ENVIRONMENTAL SCIENCE AND ENGINEERING FOR THE 21ST CENTURY

The Role of the National Science Foundation

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The Role of the National Science Foundation

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National Science Board
Committee on Programs and Plans
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The National Science Board consists of 24 members plus the Director of the National Science Foundation. Appointed by the President, the Board serves as the governing board of NSF and provides advice to the President and the Congress on matters of national science and engineering policy.

Foreword

The quality of life in the 21st century will depend in large measure on the generation of new wealth, on safeguarding the health of our planet, and on opportunities for enlightenment and individual development. The environment is a critical element of the knowledge base we need to live in a safe and prosperous world.

In August 1998, the National Science Board established the Task Force on the Environment within its Committee on Programs and Plans. The task force was created to provide guidance to the National Science Foundation (NSF) in defining the scope of its role with respect to environmental research, education, and scientific assessment and in determining the best means of implementing related activities. The task force was charged with:

- reviewing the scope of current NSF activities related to research, education, and scientific assessment on the environment; and
- developing guidance for NSF at the policy level that would be used to design an appropriate portfolio of activities consistent with the overall National Science and Technology Council strategy, the goals of the NSF Strategic Plan, and activities of other agencies and organizations that support related programs.

This report, *Environmental Science and Engineering for the 21st Century: The Role of the National Science Foundation*, presents the findings and recommendations developed by the Task Force on the Environment and approved unanimously by the National Science Board. The report is based on an extensive review of relevant policy documents and reports, a process of hearings and consultations with invested communities, invited commentary from a broad range of organizations and individuals, and feedback through a public web site (http://www.nsf.gov/nsb/tfe). The task force also examined a wide variety of environmental programs at NSF to determine the factors most likely to result in effective new research and educational activities.

On behalf of the National Science Board, I want to commend Dr. Jane Lubchenco, the chair of the task force, and the other task force members—Drs. Mary K. Gaillard, Robert M. Solow, and Warren M. Washington of the National Science Board; Dr. Mary Clutter, NSF Assistant Director for Biological Sciences; and Dr. Robert Corell, NSF Assistant Director for Geosciences—for their outstanding work in pulling together this important and complex report. Dr. Penelope Firth, Program Director for Ecosystem Studies, provided superb support as the Executive Secretary to the task force.

The Board is especially grateful for the strong support provided throughout by the Director of the National Science Foundation, Dr. Rita R. Colwell, and by NSF's Deputy Director, Dr. Joseph Bordogna.

Eamon M. Kelly
Chairman

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We also wish to thank Dr. James Edwards, Executive Officer, Directorate for Biological Sciences; Ms. Keelin Kuipers, Presidential Management Intern, Directorate for Biological Sciences; Dr. Thomas Spence, Senior Associate for Science Programs and Coordination, Directorate for Geosciences; Mr. Joseph Kull, NSF Chief Financial Officer; and Ms. Diane Weisz, Staff Associate, Office of Budget, Finance, and Award Management, who were most helpful in developing NSF-focused materials used by the task force.

Formation of the final recommendations of this report benefited greatly from comments received from representatives of U.S. Federal agencies; nongovernmental organizations — including in particular the Committee for the National Institute for the Environment; various professional science, engineering, and educational organizations; academic institutions; and members of the public.

The National Science Board is grateful to the many people who provided testimony at the hearings and symposia held by the task force, as well as those who assisted in making arrangements for these activities. The Board also thanks the diverse group of individuals who provided written comments to the task force via the web site and other mechanisms.

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Executive Summary

Context and Framework for the Study

The junction between present and future societies lies in the global commons: the shared physical, biological, and intellectual resources of the planet. The environment—specifically intact, functioning ecological systems—is essential to opportunities for individual development, the health and well-being of citizens and communities, and the generation of new wealth. Environmental science and technology are therefore a vital component of productive knowledge and thus a high priority for the Nation.

As connections between humans and the goods and services provided by the ecosystems of Earth become better understood, the scale and rate of modifications to these ecosystems are increasing. Environmental challenges are often exceedingly complex, requiring strengthened disciplinary inquiry as well as broadly interdisciplinary approaches that draw upon, integrate, and invigorate virtually all fields of science and engineering. Within the broad portfolio of science and engineering for the new century, the environment is emerging as a vigorous, essential, and central focus.

The National Science Foundation (NSF) is one of the largest supporters of environmental research in the Federal Government and the major supporter of environmental research conducted by the academic community. Consistent with NSF's mission, the agency primarily supports awards based on external, peer-reviewed national competition, and these investments drive advances in fundamental understanding of environmental systems. Therefore, because of its mission and record of accomplishment, NSF is primed to provide dynamic leadership in advancing the new insights and fundamental knowledge essential to addressing a range of emerging environmental issues.

NSF activities must complement and enhance, not duplicate or replace, the extant portfolio of other Federal activities in this area. The Foundation and other Federal agencies and interagency coordinating bodies, such as the National Science and Technology Council (NSTC), have responded to the need for research, education, and scientific assessment activities in many environmental areas. However, the scope and significance of the emerging environmental issues in our Nation and around the world suggest a need to evaluate the challenges and opportunities that these critical issues raise for NSF. Therefore, the National Science Board established a Task Force on the Environment, whose findings and recommendations are detailed in this report. The recommendations set the stage for a more vigorous NSF role in environmental research, education, and scientific assessment in the 21st century.

Strategy for the Conduct of the Study

The Board, through its Task Force on the Environment, conducted hearings and town meetings; solicited input from scientists, government agencies, and the private sector; reviewed hundreds of reports and documents related to environmental research, education, and assessments; and sought suggestions through a public web site. Hundreds of suggestions and recommendations were received and considered. Scholars in every scientific discipline participated. Comments were received from community groups, local and Federal agency officials, professional scientific and engineering societies, nongovernmental organizations (NGOs), the private sector, and concerned citizens. In addition, the Board examined a variety of programs at NSF to determine the factors most likely to result in effective research, education, and scientific assessment activities. The Board focused on the overall level, scope, robustness, balance, funding, and organization of the Foundation's environmental activities.

Principal Findings

A number of themes emerged from this diverse input. Foremost among them was a strong endorsement of the fundamental operating principles of NSF. At the same time, the Board heard many ideas that framed ways in which NSF could and should expand its environmental portfolio. The majority of these suggestions focus on enhancing both the disciplinary and interdisciplinary understanding of environmental systems and problems; improving the systematic acquisition, analysis, and synthesis of data; and improving the interpretation and dissemination of this information into understandable formats for multiple uses and users. Throughout the public input process, it was clear that citizens, government officials, other Federal agencies, professional scientific and engineering societies, and individual scientists look to NSF for leadership in environmental research, education, and scientific assessment. The strong message running through the input process was that NSF is poised and is expected to respond vigorously to the new challenges of providing and communicating the fundamental knowledge base and educating and training the workforce to meet the environmental challenges of the next century. A parallel message underscored the necessity of significant new resources to accomplish these goals and an effective organizational structure to implement NSF's total environmental portfolio.

Recommendations

NSF is supporting significantly more environmental research and education than is generally appreciated. However, the Nation's need for fundamental environmental knowledge and understanding requires further attention. To expand and strengthen the Foundation's environmental portfolio, the Board developed 12 recommendations: 2 overarching keystone recommendations addressing critical funding and organizational issues; 5 recommendations on research, education, and scientific assessment; 4 crosscutting recommendations focusing on the requisite physical, technological, and information infrastructure; and 1 recommendation emphasizing the importance of partnerships, coordination, and collaborations to NSF's programs and activities in research, education, and scientific assessment.

KEYSTONE RECOMMENDATIONS

Recommendation 1: Resources and Funding.
Environmental research, education, and scientific assessment should be one of NSF's highest priorities. The current environmental portfolio represents an expenditure of approximately $600 million per year. In view of the overwhelming importance of, and exciting opportunities for, progress in the environmental arena, and because existing resources are fully and appropriately utilized, new funding will be required. We recommend that support for environmental research, education, and scientific assessment at NSF be increased by an additional $1 billion, phased in over the next 5 years, to reach an annual expenditure of approximately $1.6 billion.
The Board expects NSF management and staff to develop budget requests and funding priorities for the coming years that are consistent with this and the following recommendations. It further expects that, consistent with its normal way of operating, NSF will involve the scientific community in identifying specific priority programmatic areas and in elaborating the specific recommendations below.

Recommendation 2: Organizational Approach.
NSF management should develop an effective organizational approach that meets all of the criteria required to ensure a well-integrated, high-priority, high-visibility, cohesive, and sustained environmental portfolio within the Foundation. These criteria include:

- **A high-visibility, NSF-wide organizational focal point with:**
  - **principal responsibility for identifying gaps, opportunities, and priorities, particularly in interdisciplinary areas;**
  - **budgetary authority for enabling integration across research, education, and scientific assessment, and across areas of inquiry;**
  - **responsibility for assembling and publicizing, within the context of the Foundation's normal reporting, a clear statement of NSF's environmental activities; and**
  - **a formal advisory process specifically for environmental activities.**
- **Continuity of funding opportunities, in particular in interdisciplinary areas.**
- **Integration, cooperation, and collaboration with and across established programmatic areas, within NSF and between NSF and other Federal agencies.**

The Board recognizes that it is a challenging task to satisfy all of the criteria specified in the organizational recommendation. Nonetheless, we are confident that it can and should be done. The Board further acknowledges the attention and priority that the Foundation recently has placed on identifying possible new organizational structures. The unprecedented emphasis on integrative, sustained, interdisciplinary activities called for in this report requires the establishment of a policy-driven strategy as well as a mechanistic approach to ensure effective implementation.

Research recommendations

As the fields of environmental research have matured intellectually, their requirements for knowledge across all scientific, engineering, and mathematics disciplines have increased. The Board finds that meeting this challenge will require increasing disciplinary research efforts across all environmental fields. Information and understanding from certain disciplines that are especially relevant to environmental problems are often lacking. Most environmental issues are interdisciplinary, and their drivers, indicators, and effects propagate across extended spatial and temporal scales. Increased resources are needed for interdisciplinary, long-term, large-scale, problem-based research and monitoring efforts. In addition, special mechanisms will be required to facilitate successful interdisciplinary programs.

Recommendation 3: Disciplinary Research.
Environmental research within all relevant disciplines should be enhanced, with significant new investments in research critical to understanding biocomplexity, including the biological/ecological and social sciences and environmental technology.

Recommendation 4: Interdisciplinary Research.
Interdisciplinary research requires significantly greater investment, more effective support mechanisms, and strengthened capabilities for identifying research needs, prioritizing across disciplines, and providing for their long-term support.

Recommendation 5: Long-Term Research.
The Foundation should significantly increase its investments in existing long-term programs and establish new support mechanisms for additional long-term research.

Education Recommendation

NSF's role is to create educational and training opportunities that enhance scientific and technological capacity associated with the environment, across both formal and informal educational enterprises. Environmental education and training should be science based, but should be given a renewed focus on preparing students for broad career horizons and should integrate new technologies, especially information technologies, as much as possible. The twin goals of learning are to gain knowledge and to acquire skills such as problem solving, consensus building, information management, communication, and critical and creative thinking.

Recommendation 6: Environmental Education.
The Foundation should encourage proposals that capitalize on student interest in environmental areas while supporting significantly more environmental education efforts through informal vehicles. All Foundation-supported education activities should at their core recognize potential and develop the capacity for excellence in all segments of society, regardless of whether they have been part of the scientific and engineering traditions.

Scientific assessment recommendation

Scientific assessment, as used here, is defined as inquiry-based synthesis, evaluation, and communication of understanding of relevant biological, socioeconomic, and physical environmental scientific information to provide an informed basis for (1) prioritizing scientific investments and (2) addressing environmental issues. Research on how to do effective, credible, and helpful scientific assessments is timely. Approaches to scientific assessment need to be refined, and made more transferable between environmental issues. In addition, the Board finds that there is an identified need for a credible, unbiased approach to defining the status and trends, or trajectory, of environmental patterns and processes. The Board acknowledges the ongoing scientific assessment activities of other agencies and urges that additional scientific assessment efforts by NSF complement present efforts.

Recommendation 7: Scientific Assessments.
The Foundation should significantly increase its research on the methods and models used in scientific assessment. In addition, NSF should, with due cognizance of the activities of other agencies, enable an increased portfolio of scientific assessments for the purpose of prioritizing research investments and for synthesizing scientific knowledge in a fashion useful for policy- and decision-making.

Infrastructure recommendations

Environmental research depends heavily on effective physical infrastructure. These include environmental observatories complemented by high-speed communications links, powerful computers, well-constructed databases, natural history collections that provide a baseline against which to measure environmental change, and both traditional and virtual centers. The Board finds that an important NSF role is to facilitate the development of instrumentation, facilities, and other infrastructure that enables discovery, including the study of processes and interactions that occur over long time scales.

Recommendation 8: Enabling Infrastructure.
NSF should give high priority to enhancing infrastructure for environmental observations and collections as well as new information networking capacity. The agency should create a suite of environmental research and education hubs, on the scale of present Science and Technology Centers and Engineering Research Centers, that might include physical and/or virtual centers, site-focused and/or problem-focused collaboratories, and additional environmental information synthesis and forecasting centers.

The Board finds that a critical NSF role is to foster research that seeks to develop innovative technologies and approaches that assist the Nation in conserving its environmental assets and services. NSF should facilitate an effort to identify technologies that represent order-of-magnitude improvements over existing environmental technologies, and—in communication with other Federal agencies, the academic community, and the private sector—define the scientific and engineering research needed to underpin these technologies.

Recommendation 9: Environmental Technology.
The Foundation should vigorously support research on environmental technologies, including those that can help both the public and private sectors avoid environmental harm and permit wise utilization of natural resources.

The Board further finds that technological advances are often keystone enabling elements that profoundly advance scientific research. The future of scientific research, education, and assessment will increasingly depend on new and advanced technological developments in instrumentation, information technologies, facilities, observational platforms, and innovative tools for science and engineering.

Recommendation 10: Enabling Technologies.
The Foundation should enable and encourage the use of new and appropriate technologies in environmental research and education.

The Board finds that the role of NSF, in partnership with other Federal agencies, is to stimulate the development of mechanisms and infrastructure to synthesize and aggregate scientific environmental information and to make it more accessible to the public.

Recommendation 11: Environmental Information.
The Foundation should take the lead in enabling a coordinated, digital, environmental information network. In addition, NSF should catalyze a study to frame a central source that compiles comparable, quality-controlled time-series measurements of the state of the environment.

Partnerships, coordination, and collaborations recommendation

The Board finds that collaborations and partnerships are essential to important and high-priority environmental research, education, and scientific assessment efforts. Furthermore, collaborations are most effective when they are based on intellectual needs. Partnerships among Federal agencies, with nongovernmental bodies (e.g., private sector entities, NGOs, and others), and with international organizations can provide the intellectual and financial leveraging to address environmental questions at the local, regional, and international levels. There are thus many opportunities to partner in bilateral/multilateral agreements or via NSTC science and engineering initiatives. The Board endorses strong NSF participation in the coordinating mechanism provided through NSTC.

The most effective partnerships involve the evolution of trust among participants, strategic thinking processes to identify and evaluate common interests and objectives, and relatively simple, flexible administrative arrangements. They also require sufficient staff, resources, and time to mature.

Recommendation 12: Implementation Partnerships.
NSF should actively seek and provide stable support for research, education, and assessment partnerships that correspond to the location, scale, and nature of the environmental issues. Such partnerships and interagency coordination should include both domestic and international collaborations that foster joint implementation including joint financing when appropriate. This report clearly establishes the need for an expanded national portfolio of environmental R&D. Therefore, the Board suggests that NSTC, with advice from the President's Committee of Advisors on Science and Technology, reevaluate the national environmental R&D portfolio, including identification of research gaps and setting of priorities, and the respective roles of different Federal agencies in fundamental environmental research, education, and scientific assessment.

Conclusion

Scientific understanding of the environment, together with an informed, scientifically literate citizenry, is requisite to improved quality of life for generations to come. As the interdependencies of fundamental and applied environmental research become more evident, NSF should capitalize on the momentum gained in its past support for premium scholarship and emerging new research areas and technologies. The time is ripe to accelerate progress for the benefit of the Nation.

With regard to the NSB report overall, we applaud the Board's recommendation that environmental research be made one of NSF's highest priorities and agree that funding should be substantially augmented. — *President's Committee of Advisors on Science and Technology, 1999 (appendix E)*

CHAPTER 1

INTRODUCTION

Within the broad portfolio of science and engineering for the new century, the environment is emerging as a vigorous, essential, and central focus. At the same time that connections between humans and the goods and services provided by the ecosystems of Earth become better understood, the scale and rate of modifications to these ecosystems are increasing. Our growing understanding of the complex connectedness and vulnerability of Earth's ecosystems and of human dependence on them is changing how we view environmental research. The environment is no longer simply a background against which research is conducted, but rather the prime target for enhanced understanding.

If in the 20th century science and technology moved to the center of the stage, in the 21st century they will command it. Quality of life will depend in large measure on the generation of new wealth, on safeguarding the health of our planet, and on opportunities for enlightenment and individual development. The contributions of research and education in science and engineering make possible advances in all these areas. — *National Science Board Strategic Plan, 1998*

THE ISSUES

New discoveries have highlighted unappreciated linkages between the environment and human health, prosperity, and well-being (e.g., Arrow et al. 1995, Lubchenco 1998, WMO/UNEP 1998). Simply put, the ecological systems of the planet—including forests, grasslands, kelp forests, deserts, wetlands, rivers, estuaries, coral reefs, lakes, and open oceans—provide us with goods and services. The goods are familiar: food, fiber, medicines, genes. Only recently have we begun to understand and appreciate the essential local, regional, and even global services provided by ecological systems (Daily 1997, Daily et al. 1997). Examples include purification of water and air, partial regulation of climate, provision of fertile soil, cycling of nutrients, decomposition, provision of pollinators, control of pests and pathogens, storage of water, and modulation of floods. Ecosystems provide yet another type of service: as places for recreation, enjoyment, inspiration, and learning. It has become clear in recent years that these services are provided as a byproduct of the functioning of intact ecological systems (see box 1). In many cases, we are becoming aware of these ecological services only because they are being disrupted or lost.

Ecological goods and services constitute the life support systems of and for life on Earth (WMO/UNEP 1998, Levin 1999). Over the last century, increased global population pressures and a broad spectrum of human activities have inadvertently resulted in substantial

The process used to produce this report

On August 12, 1998, the National Science Board established the Task Force on the Environment under its Committee on Programs and Plans. The task force was created to assist the Foundation in defining the scope of its role with respect to environmental research, education, and scientific assessment, and in determining the best means of implementing activities related to this area (NSB 1998; reprinted here in appendix A).

The task force initially carried out four parallel activities to meet the objectives of hearing from invested communities and gathering data to inform its deliberations:

1. Reviewed and considered recommendations from approximately 250 reports and policy documents concerning the scientific and engineering aspects of environmental research, education, and scientific assessment; this included outreach to underrepresented communities to ensure that the reports consulted were as balanced as possible. This literature list appears in appendix B.
2. Received input and feedback from invested communities via:
    - a public hearing in Portland, Oregon, on January 14, 1999;
    - a public National Science Board symposium in Los Angeles, February 17-18, 1999;
    - a public town hall meeting in Arlington, Virginia, on March 8, 1999; and
    - a web site launched to communicate the activities of the task force and provide a vehicle for public input and electronic registry of comments (http://www.nsf.gov/nsb/tfe).

   The task force also invited written views from a number of relevant organizations and individuals. Appendix C lists all the people and institutions that provided formal input to the task force prior to the release of the Interim Report.
3. Inventoried the current portfolio of and reviewed the current approach to environmental activities at the National Science Foundation.
4. Examined a variety of environmental programs at the Foundation to determine the factors most likely to result in effective new research and educational activities.

Information from these sources was considered by the task force and synthesized into an Interim Report that, following several iterations, was unanimously approved by the Board on July 29, 1999.

The Interim Report was then released publicly and posted on the task force web site. During the next several months, almost 7,000 hits were recorded for the web site, and several dozen specific comments were received, a number from professional organizations representing thousands of environmental scientists, engineers, and educators. Appendix D lists the people and institutions that provided formal input following the release of the Interim Report.

Presentations of the rationale, key findings, and recommendations of the Interim Report were made by members of the task force, Board, and Foundation staff to other federal agencies, the Office of Science and Technology Policy, the President's Committee of Advisors on Science and Technology, and the National Science and Technology Council's Committee on Environment and Natural Resources.

The President's Committee of Advisors on Science and Technology reviewed the Interim Report, endorsed its recommendations, and made several key suggestions that greatly improved the document. Its letter to the Chair of the National Science Board is reprinted in appendix E.

Feedback from this wide range of sources was carefully considered in revising the Interim Report to produce the final report. The National Science Board unanimously approved the report (NSB 00-22) on February 2, 2000.

Box 1. Nature's services: What ecosystems provide to people, what is at risk, and why new interdisciplinary knowledge is required

Individual organisms or species provide familiar services—trees provide shade or windbreaks, marigolds discourage garden pests. Ecosystems, too, provide a multitude of services, though they are generally less appreciated. Recent widespread conversion of many ecosystems from former forest or grassland to agricultural, industrial, or urban use has brought to light the concomitant alteration or loss of the services formerly provided by those ecosystems. In some cases, the altered system may be preferred, but a complete assessment of the tradeoffs, including services lost or gained, will enhance informed decisions.

A recent example highlights the potential threats to vital services, the economic consequences of disruption, and the potential for restoration efforts to conserve essential services (Chichilnisky and Heal 1998). Historically, the watershed of the Catskill Mountains provided a plethora of ecosystem services including air purification, flood control, pest control, nutrient recycling, carbon sequestration, the provision of places for recreation and education, as well as a particularly high-profile service—water filtration and purification. As recently as 1948, New York City had what was billed as the purest water in the world. Over time, this watershed ecosystem became overwhelmed by incremental development and the accompanying land conversion and generation of sewage, industrial waste, and agricultural runoff. As a consequence, the water quality in the city fell below Environmental Protection Agency drinking water standards. An economic analysis provided comparative costs of two alternatives for restoring water quality. The cost of purchasing and restoring the watershed so that it could continue to provide the service of purification and filtration was calculated at approximately $1 billion. The cost of building and maintaining a water purification and filtration plant was $6 to $8 billion in capital costs, plus annual operating expenses of $300 million. The city has opted to buy and restore the watershed, i.e., to let nature work for people. An additional benefit of this choice is that the watershed also provides multiple other services not included in the analysis. As this example illustrates, ecosystem services provide fertile ground for new collaborations between economists and ecologists (PCAST 1998; Dasgupta, Levin, and Lubchenco 2000).

changes to many ecosystems (Vitousek et al. 1997b; see box 2). As land is transformed, as ecosystems are fragmented, reduced in size, or lost, or as species become extinct or are transplanted, the functioning of the system is frequently disrupted or lost, and the provision of services is often impaired (UNEP 1995). Both imperceptible and broad-scale alterations to the biology, chemistry, and physical structure of the land, air, and water of the planet will continue to pose formidable challenges for the quality of human life and the environmental sustainability of the biosphere. This in turn intensifies the need to focus on the environment as an area of study, in particular to achieve a fundamental understanding of environmental systems commensurate with the consequences of alterations transforming them (Lubchenco et al. 1991).

Old Frameworks and Approaches Are Inadequate

The environmental challenges facing the Nation and the world have emerged relatively recently and rapidly. Moreover, they are often exceedingly complex, requiring strengthened disciplinary inquiry as well as broadly interdisciplinary approaches that draw upon, integrate, and invigorate virtually all fields of science and engineering. The current level of effort and existing conceptual approaches are proving to be insufficient. New approaches and frameworks are needed to provide the requisite understanding, guidance, and tools. In particular, solutions will require credible information about the rates, scales, and kinds of changes; improved understanding of the underlying dynamics of the relevant biogeophysical and social systems and their interactions; new analyses of alternative technologies or methodologies and their tradeoffs; new institutional mechanisms and conceptual frameworks for making decisions; and more. Meeting these challenges will require significant scientific and technological advances, and rapid communication of our new understandings to the private and public sectors as well as to the electorate. An improved understanding of the dynamics of complex systems, especially complex biological systems, will be essential to future progress. Finally, emerging interdisciplinary perspectives must enrich not only the research enterprise, but educational and scientific assessment approaches as well.

The problems that exist in the world today cannot be solved by the level of thinking that created them. — *Generally attributed to Albert Einstein*

BOX 2. UNPRECEDENTED ENVIRONMENTAL CHANGES: NEW CHALLENGES FOR HUMANITY

Assertions about environmental changes grab headlines. Sorting out fact from fiction, however, is frequently problematic. Fortunately, credible information is available for some important phenomena. The following summary highlights a number of global-scale changes where the information is quantitative and well-documented, the rates of change are known, and the causes are understood (Vitousek et al. 1997b and references therein). These global-scale indicators of change provide a credible platform for discussing environmental challenges.

1. **Between 40 and 50 percent of the land surface of the planet has been transformed by human action.** Examples include the conversion of wetlands and forests to urban and industrial areas or of grasslands to pastures and agricultural fields. These transformations affect climate, biodiversity, human health, and the delivery of critical ecosystem services.
2. **The concentration of carbon dioxide in the atmosphere has increased by 30 percent since the beginning of the Industrial Revolution.** Because we can “fingerprint” this heat-trapping, greenhouse gas, we are certain that the increase is a direct result of human activities, primarily the burning of fossil fuels.
3. **Humanity currently utilizes over half the available surface freshwater of the planet.** About 70 percent of that amount is used in agriculture. Diversions and impoundments have altered river systems substantially, with only 2 percent of U.S. rivers now running unimpeded. Demands for clean water are expected to rise as the human population grows exponentially.
4. **Human actions have doubled the amount of fixed nitrogen annually since the beginning of the 20th century.** This additional fixed nitrogen—produced deliberately by the making of fertilizers and inadvertently as a byproduct of fossil fuel combustion—affects human health, climate, biodiversity, urban smog, acid rain, fish kills, dead zones, and harmful algal blooms in coastal waters (see box 4).
5. **Invasions of nonnative species are increasing globally, with more than half of the plant species on islands and 20 percent or more on continental areas frequently nonindigenous.** This rearrangement of the biota of the planet is occurring at vastly greater rates due to human activities. Most biological invasions are irreversible; some have serious economic and ecological consequences.
6. **One-quarter of the bird species on the planet have gone extinct, due primarily to human actions (hunting, introduction of invasive species, and habitat destruction).** Birds are one taxon for which reliable information about extinctions exists. For lesser known taxa, credible estimates suggest that rates of species extinctions are approximately 100 to 1,000 times those before humanity’s dominance of Earth.

The Necessary Response

Today, the National Science Foundation (NSF), several other Federal agencies, and interagency coordinating bodies such as the Committee on Environment and Natural Resources (CENR) of the National Science and Technology Council (NSTC) are responding to the need for research, education, and scientific assessment activities in many environmental areas. But the magnitude of the challenges cited above and the urgent time scale required for many of these opportunities demand a whole new level of integrated activities and programs (see, for example, PCAST 1998). Implementation of such activities and programs will require significant new scientific advances, improved public understanding of environmental topics, more effective communication of new knowledge, and incorporation of new knowl-

7. **Two-thirds of the major marine fisheries are now fully exploited, overexploited, or depleted. Just over 40 years ago, this figure stood at less than 5 percent.** Currently, 22 percent are overexploited or already depleted, and 44 percent are at their limit of exploitation. In addition to the reported biomass of landed catches, an additional 27 million tons of bycatch are discarded annually, nearly one-third as much as total landings.

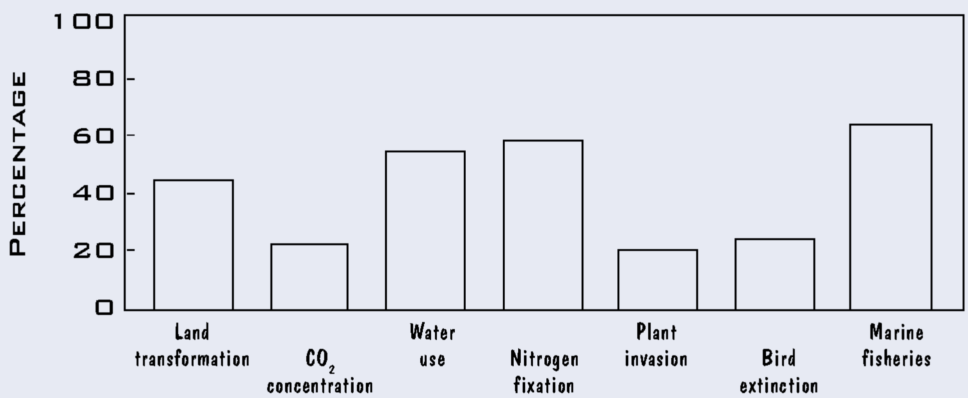

Figure 1. Human dominance or alteration of major components of the Earth system. Data are expressed as (from left to right) percentage of the land surface transformed; percentage of the current atmospheric CO_2 concentration that results from human action; percentage of accessible surface freshwater used; percentage of terrestrial N fixation that is human-caused; percentage of plant species in Canada that humanity has introduced from elsewhere; percentage of bird species on Earth that have become extinct in the past 2 millennia, almost all of them as a consequence of human activity; and percentage of major marine fisheries that are fully exploited, overexploited, or depleted. Figure is reprinted with permission from Vitousek et al. (1997b).

It is clear from these seven global-scale indicators of change that human activities are transforming the planet in new ways and combinations at faster rates, and over broader scales than ever before in the history of humans on Earth. Our activities are inadvertently changing the chemistry, the physical structure, and the biology of the planet. Accelerated efforts to understand Earth's ecosystems and how they interact with the numerous components of human-caused global changes are timely and wise.

edge into policies and practices. NSF has significant responsibilities in the first three of these areas (see figure 2).

By virtue of its mission and track record, NSF is poised to provide a more vigorous and intellectual leadership role. The Foundation can provide the fundamental understanding of the complexity of Earth's environmental envelope and its human interactions through discovery, focused education and training, information dissemination, and scientific assessment. This role is consistent with its mission, as stated in the National Science Foundation Act of 1950: "To promote the progress of science; to advance the national health, prosperity, and welfare; to secure the national defense..."

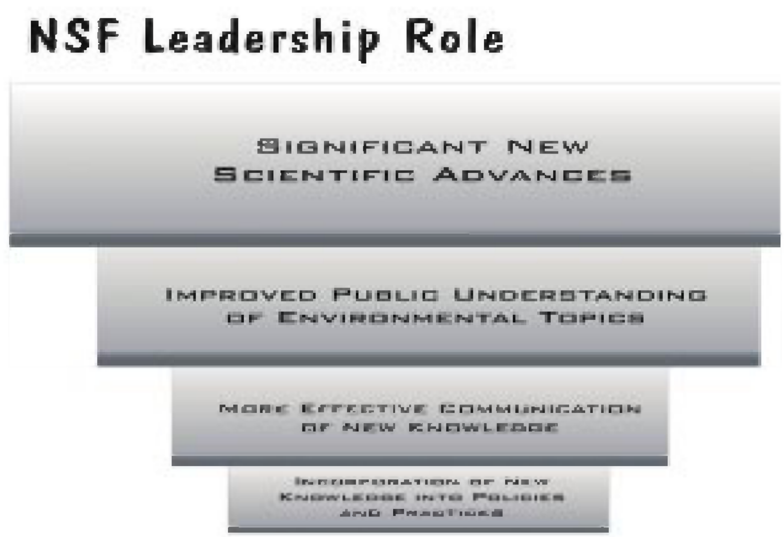

Figure 2. Of the four challenges in environmental research, education and assessment identified above, NSF makes its greatest contribution in the first three.

To this end, the National Science Board posed the question: *What should the environmental portfolio of NSF look like, in the context of external activities, in order to provide and communicate the knowledge required to respond to current and future environmental challenges?* In developing this answer, the Board focused on the overall level, balance, and organization of environmental activities within NSF and within the context of other Federal programs and activities. This report provides the answer to the question, beginning with a description of the goals to be accomplished, a summary of current and anticipated activities within the Foundation, a synopsis of suggestions and information received by the Board during its review, and the Board's findings and recommendations.

Goals for Enhancing the Environmental Portfolio

Three goals should guide the design and implementation of the Foundation's environmental portfolio (see figure 3):

- Provide an integrated understanding of the natural status and dynamics of, and the anthropogenic influences on, Earth's environmental envelope. Achieve this through *discovery* across the fields of science and engineering to elucidate the processes and interactions among the atmosphere, biosphere, cryosphere, hydrosphere, lithosphere, and socioeconomic systems.

- Provide for *education and training* that enhance scientific and technological capacity associated with the environment, across both formal and informal educational enterprises.
- *Integrate and disseminate research results* effectively to multiple audiences—including scientific, public, and policy audiences, and the private sector—via credible scientific assessments of broad environmental phenomena and the transfer of technological knowledge.

Achieving these goals will require several supporting elements:

- facilities, instrumentation, and other *infrastructure* that enable discovery, including the study of processes and interactions that occur over long time scales;
- research to develop *innovative technologies* and approaches that will help the Nation conserve and wisely use its environmental assets and services;
- mechanisms and infrastructure to synthesize and aggregate scientific environmental *information* and provide open access to these informational materials; and
- *partnerships* with other Federal agencies, state and local governments, citizens' groups, the private sector, and other nations to advance knowledge, understanding, and solutions.

In view of these goals and enabling infrastructural needs, the remainder of this report presents the Board's analysis of current and anticipated environmental activities within the Foundation.

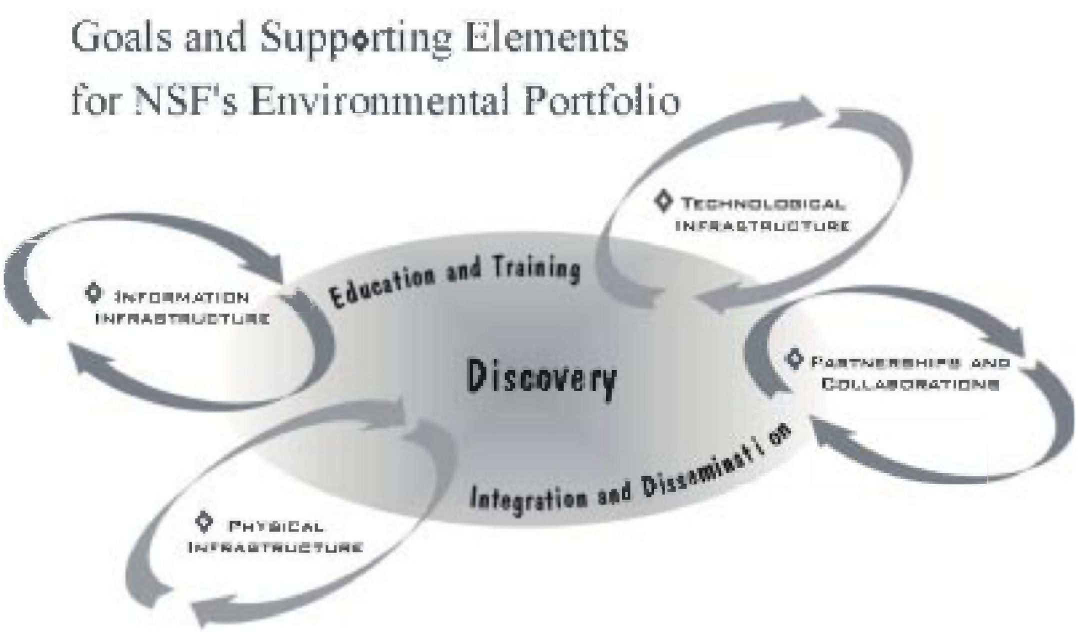

Figure 3. Goals and supporting elements for NSF's environmental portfolio.

Chapter 2

The Larger Context for NSF-Supported Environmental Research, Education, and Scientific Assessment

Research Within and Across Agencies

The national investment in science and engineering R&D produces a wide variety of benefits ranging from new knowledge and new technologies to better inform policies and practices. Many Federal agencies contribute to the national investment in environmental science and technology. Overall, the Federal Government supports an environmental R&D portfolio estimated in excess of $5 billion per year (http://www.nnic.noaa.gov/CENR/cenr.html).

Collaboration and cooperation across agencies is enabled through multiple mechanisms. Many efforts have been coordinated through the White House. NSTC's Committee on Environment and Natural Resources, operating through the President's Office of Science and Technology Policy, coordinates several interagency environmental R&D activities. The President's Committee of Advisors on Science and Technology provides complementary advice on the roles of science and technology in achieving national goals.

> Current annual Federal R&D spending on environmental research is only 5 percent of annual expenditures on environmental management. Thus the achievement of even a small improvement in management efficiency would pay for the incremental research many times over. — *CENR, 1995, Preparing for the Future Through Science and Technology (paraphrased)*

Established in 1993 and chaired by the President, the cabinet-level NSTC serves as an initiator and coordinator of interagency science and technology R&D. CENR is one of five committees under NSTC. With respect to NSF, CENR informs and influences the process by which the Foundation establishes research priorities and responds to policy concerns. NSF plays an active role in a variety of important multi-agency CENR activities, including the successful U.S. Global Change Research Program (USGCRP) (http://www.usgcrp.gov), the new Integrated Science for Ecosystem Challenges activity, and the National Biological Information Infrastructure (http://www.its.nbs.gov:8000/cbi/programs/nbii.html), a CENR effort to set standards for environmental information and make that information available to researchers, industry, and the general public.

The CENR research agenda, published in 1995, provided the initial framework for coordinating agency research programs to address environmental issues in an integrated manner (http://www.whitehouse.gov/WH/EOP/OSTP/NSTC/html/enr/enr-plan.html). CENR has sought, and continues to seek, advice from academia, industry, other private sector groups, Congress, and state and local governments. CENR seeks to involve experts from all stakeholder groups in conducting broad and credible national scientific and technical assessments of the state of knowledge. The point of these assessments is to develop consensus that explicitly acknowledges what is known, what is unknown, and what is uncertain. The consensus understanding can then be used to project the implications of alternative policy options and to involve stakeholders and policy-makers in understanding the basis, uncertainties, and likely consequences of those projections.

CENR has also encouraged increased extramural R&D in the overall mix of Federal R&D. In addition, CENR recognizes the diversity of strengths afforded by the Federal laboratories, national laboratories (government owned, contractor operated), universities, and private industry in environmental research. As CENR works to ensure that the capabilities and resources of each of these sectors are appropriately integrated, it looks to NSF for leadership in supporting fundamental academic environmental research, in ensuring that our academic institutions continue to provide an adequate supply of well-trained scientists and engineers, and in laying the foundation for a scientifically literate citizenry.

A number of bi- and multi-agency environmental activities complement the CENR initiatives (see table 1). NSF's unique relationship with the university-based science and engineering community allows it to bring a valuable outside perspective from the researchers themselves.

Table 1. Examples of NSF's multi-agency environmental activities

Activity	*Participating Agencies*
International Cooperative Biodiversity Groups	NSF, NIH, USDA
Joint Program on Bioremediation	NSF, EPA, DOE, ONR
National Earthquake Hazard Reduction Program	NSF, USGS, FEMA, NIST
Partnership for Environmental Research, including four grants competitions:	NSF, EPA, USDA
Decision-making and Valuation for Environmental Policy	NSF, EPA
Environmental Statistics	NSF, EPA
Technology for a Sustainable Environment	NSF, EPA
Water and Watersheds	NSF, EPA, USDA
U.S. Global Change Research Program	NSF, USDA, DOC/NOAA, DOE, HHS/NIH, DOI, EPA, NASA, SI
U.S. Weather Research Program	NSF, NOAA, NASA, DOD

Education and Other Knowledge Transfer

Just as the inability to read puts a child at risk of truancy and becoming a school dropout, deficiencies in mathematics and science have become a barrier to higher education and the 21st century workplace. In the recently released National Science Board report *Preparing Our Children: Math and Science Education in the National Interest* (NSB 1999), the Board urges a Nation-wide consensus on a core of knowledge and competency in mathematics and science. The Board believes it is both possible and imperative to develop national strategies that serve the national interest while respecting local responsibility for K-12 teaching and learning. NSF support for integrated environmental research and education in this context emphasizes the involvement of the science and engineering communities—both individually and through their institutions—as a special resource for local schools, teachers, and students. Together with elected officials, school administrators, classroom teachers, parents, and employers, scientists and engineers bring a valuable perspective on mathematics and science as a way of knowing, a transferable skill, and a citizenship tool as we enter a new millennium.

New knowledge is perhaps the single most important driver of economic growth and the most precious and fully renewable resource available to individuals and societies to advance their material well-being (NSB 1999). An important approach to carrying out NSF's mission is to help the Nation use new knowledge in science and engineering for the benefit of society. The transfer of such knowledge is a vital ingredient in enhancing the Nation's industrial competitiveness. NSF's knowledge transfer activities are focused on building working relationships at the research project level between academia, industry, and other potential users, such as local and state governments (NSF 1995).

Assessment Roles and Boundaries

NSF's involvement in environmental activities is directed toward discovery, with the goal of achieving a more comprehensive understanding of environmental systems. Discovery alone is insufficient, however. New knowledge must be integrated and communicated, both to other scientists and to society at large. The Foundation, as well as other agencies, thus has a role in "scientific assessment," which the Board uses to mean the synthesis, evaluation, and communication of scientific understanding.

The Board distinguishes scientific assessment from other types of assessment, including:

- *Resource assessment*, which is the evaluation of the quality and/or quantity of a particular natural resource such as timber, water, or fisheries. This type of assessment is usually done by the relevant Federal management or regulatory agencies in cooperation with the cities, states, or regional entities that are naturally involved. NSF is not routinely involved in support of resource assessments.
- *Human health risk assessment*, which refers to the process that scientists and government officials use to estimate the increased risk of health problems in people who are exposed to different amounts of specific toxic or other harmful substances, for example, persistent organic pollutants.

- *Ecological risk assessment*, which is the process of analyzing data, assumptions, and uncertainties to evaluate the likelihood of adverse ecological effects resulting from a particular activity, e.g., a chemical spill. These types of assessments are extensively used by the U.S. Environmental Protection Agency (EPA) as tools in risk management and are an integral part of EPA's regulatory approach. NSF is not involved in support of risk assessments.

These other kinds of assessments are important, but beyond NSF's scope. Many fall within the purview of other agencies or are tied explicitly to their missions.

Although scientific assessments do not constitute a major suite of activities at NSF, the Foundation does fund two kinds of assessment activity. NSF currently provides (1) support for research on the conduct of assessments and (2) grants for specific scientific assessments (often in partnership with other agencies—see "Scientific Assessment" section in chapter 3). Both activities are funded by grants to parties outside NSF, as opposed to being conducted by NSF personnel. For example, some scientific assessments are conducted by the National Research Council; others by independent panels of experts assembled for that purpose.

The purpose of a particular scientific assessment may vary. Some are intended to summarize the state of knowledge of a particular scientific field, with the goal of identifying new research opportunities and setting priorities. Other scientific assessments are designed to evaluate the knowledge about a particular topic with the goal of informing policy decisions. Scientific assessment may also be called knowledge assessment. A scientific assessment may pose a range of questions, depending on the intended purpose of the assessment. For example, it may ask:

1. What is known at present and with what degree of certainty?
2. What is not known?
3. What types of additional research would likely lead to significant scientific gains?
4. What additional knowledge would be useful for decision-makers?
5. In view of the answers to questions 1 and 2, what are the likely consequences of different alternative societal or policy options?

In many cases, a scientific assessment may combine elements of both an assessment of the state of knowledge in a scientific field as well as an assessment of the relevance of that knowledge to policy decisions and societal welfare (see box 3).

For a study analyzing the methodology of integrated assessments and their application to global environmental concerns, see the Organisation for Economic Co-operation and Development's report on a Workshop on Global-scale Issues (OECD 1998).

Some scientific assessments are particularly appropriate for an interagency partnership approach, especially when the agencies involved share responsibility for a topic or must be prepared to act on the information resulting from the assessments. NSF has a responsibility to engage in assessments, enabling the synthesis, analysis, and clear communication of research findings—particularly basic research findings—in a timely fashion. In addition, NSF can provide a valuable service to other agencies and to the scientific and engineering community by supporting the development of explicit research agendas and by providing for improved understanding of the actual process of conducting assessments.

Box 3. Scientific assessment of stratospheric ozone depletion

Some recent scientific assessments have played critical roles in summarizing the state of scientific knowledge in a fashion that allowed policy-makers to make informed decisions and that stimulated the acquisition of additional knowledge (questions 1-5 in the text). For example, a series of international scientific assessments on stratospheric ozone articulated the dimensions of a formerly unappreciated environmental problem; indicated the certainties, uncertainties, and priority areas for further research; and evaluated the likely consequences of various policy options. These assessments led to international agreements to limit production of stratospheric ozone-reducing compounds, a major environmental success story.

A series of international scientific assessments between 1985 and 1998 provided credible and integrated summaries of the state of knowledge on stratospheric ozone. During this interval and driven in part by the assessment process, significant advances were made in the understanding of the impact of human activities on the ozone layer, the influence of changes in chemical composition on the radiative balance of Earth's climate, and the coupling of the ozone layer and the climate system itself.

The fifth scientific assessment of ozone depletion was published in 1998 (WMO/UNEP 1998) in response to provisions of the 1987 Montreal Protocol on Substances That Deplete the Ozone Layer. The protocol required that future decisions be based on the available scientific, environmental, technical, and economic information as assessed by worldwide expert communities. The scientific assessment articulates 11 major scientific findings and observations, among them:

- The abundance of ozone-depleting compounds in the lower atmosphere peaked in about 1994 and is now slowly declining.
- The springtime Antarctic ozone hole continues unabated.
- Stratospheric ozone losses have caused a cooling of the global lower stratosphere and may have offset about 30 percent of the climate forcing due to increases in the well-mixed greenhouse gases such as carbon dioxide and methane.

The assessment details the supporting scientific evidence for its findings and discusses related issues and needed research. It then provides an analysis of implications for policy formulation, including discussion of the following:

- The Montreal Protocol is working.
- The ozone layer is currently in its most vulnerable state.
- The ozone layer will slowly recover over the next 50 years.
- Few policy options are available to enhance the recovery of the ozone layer.
- The issues of ozone depletion and climate change are interconnected; hence, so are the Montreal and Kyoto Protocols.

The scientific assessment of ozone depletion is an excellent example of a scientific assessment whose outcome was a significant benefit to the world.

The scale and nature of the problem or information being assessed should dictate the scale of the assessment. Some scientific assessments need to be performed at an international level, while others can and should be conducted at the national level. NSF has a role in both. In the international arena, NSF should award grants to the coordinating entity as well as allocate funds to sponsor U.S. scientists to participate in assessments. A number of international and national scientific assessments would be beneficial; many would involve partnerships with other agencies or international bodies. One international scientific assessment that has been proposed and that is well within the purview of NSF's mission is the Millennium Assessment of the World's Ecosystems (Ayensu et al. 1999).

Infrastructure in Context

In addition to physical infrastructure provided directly by NSF, an international array of research sites, facilities, centers, and platforms provide immense benefit for the NSF-supported researchers who use them. These physical infrastructure capabilities are provided by a variety of entities: other nations; other U.S. Federal agencies; tribal, state, and local governments; and, in some cases, NGOs and the private sector. For example, several Federal agencies are committed to maintaining infrastructure and monitoring efforts that provide long-term data sets for our lands and waters.

Information infrastructure is a special type of physical infrastructure (see box 4). The recent report of the President's Information Technology Advisory Committee (PITAC 1998) highlights not only the inadequacy of Federal information technology R&D investment, but also the drawback that it is focused too heavily on near-term problems. In the environmental area, the information infrastructure has been tuned to several different needs and opportunities. For example, the National Biological Information Infrastructure and the National Spatial Data Infrastructure represent critical pieces of a larger need. Similarly, the National Aeronautics and Space Administration's (NASA's) Earth Observing System Data and Information System provides important lessons on the efficiency and effectiveness of a centralized mechanism for collecting and providing specific information. NSF has a legitimate role, in partnership with other agencies, to support the infrastructure needed to synthesize and aggregate environmental information and make it more accessible to the public. Further, NSF can focus on the long-term, fundamental environmental information infrastructure needs that more mission-focused agencies are unable to support.

Numerous initial efforts have identified the kinds of information infrastructure required to track environmental topics. For example, the Heinz Center (1999) has recently released "Designing a Report on the State of the Nation's Ecosystems," which takes important steps toward identifying and describing environmental indicators in a scientifically credible, nonpartisan way for use by decision-makers. This kind of synthetic activity depends heavily on information infrastructure.

Investments in Environmental Technology

Immense advances in science and engineering have been made possible by national policies that promote research at the frontiers of knowledge. A concomitant policy is to ensure that discovery in science and engineering is used to benefit all citizens, promote economic growth, improve the quality of life, and ensure national security. In many areas of science and engineering, the interval between discovery and industrial innovation is becoming shorter. As a consequence, there is a need for stronger university-industry partnerships in order to

Box 4. The information explosion and the technology revolution

Understandable, credible, and easily accessible information is essential for managing our environment and natural resources. Recent revolutionary changes in computation and communications capabilities have opened up previously unimagined possibilities in the field of information technology. These trends are expected to continue for the foreseeable future. Simultaneously, the amount of data beaming down from satellites, emerging from laboratories, and arriving from environmental research of all kinds is exploding—the equivalent of more than a Library of Congress worth of data every day. Research and development are needed to harness the power of the new information technologies, capture the wealth of new information, and provide new and invaluable information for decision-making and future research (PCAST 1998).

Acquiring data is no longer the major hurdle—managing, validating, and understanding the data are the new challenges. The web and Internet connectivity have fueled expectations by citizens, policy-makers, scientists, and managers for ready access to on-line data and metadata (i.e., documentation essential for understanding the who, what, where, and how of the data). While knowledge about environmental systems, even though incomplete, is a vast and complex information domain, a second source of complexity in this information is sociologically generated. This type of complexity includes problems of communication and coordination—between agencies; between divergent interests; and across groups of people from different regions, different backgrounds (academia, industry, government), and different views and requirements. The kinds of data that have been collected vary in precision, accuracy, and numerous other ways. New methodologies for converting raw data into comprehensible information are now feasible.

The relatively new field of informatics is developing tools to manage the complexity of scope of modern databases. The biodiversity databases in museums, for example, are an untapped rich source of knowledge, representing more than 750 million specimens of animals and plants nationwide and 3 billion worldwide. A "next generation" National Biological Information Infrastructure is presently being planned to address the needs of this community of scientists (Frondorf and Waggoner 1996, PCAST 1998). High-performance computer tools that could integrate access to information from museum collections with ecological, genomic, weather, and geographical data would be immediately useful for studies of emerging diseases, exotic species, and ecological restoration.

Much of the talent needed to invent better means of converting data to useful information is currently employed in the private sector. The potential benefit arising from public-private partnerships that would bring together software and hardware designers with environmental scientists and engineers is prodigious.

exploit new opportunities that will arise in environmental technologies and supporting fields. At the same time, a rich base of fundamental research in science and engineering must be maintained to ensure future innovations in environmental technology (see box 5). Overall, industry sees strength in its ability to link inventions to markets and to commercialize new technologies (Resetar et al. 1999).

The environmental market is increasingly technology-driven, indicating that suppliers must make continuing substantial R&D expenditures. The large multinational environment companies are most R&D intensive, spending 8 to 10 percent of turnover on research; smaller firms in lower technology environmental sectors may spend less than 2 percent of turnover on R&D (OECD 1998). According to Resetar et al. (1999), from a company's point of view, collaborative research on environmental technologies may be an opportunity to share expenses for technologies necessary to comply with environmental regulations. They may also be a way to reduce the risks associated with introducing new technologies to comply with regulations and the risks of environmental liability.

The Federal role in fostering R&D to advance environmental technologies was articulated by NSTC (1994):

- Appropriately balance avoidance, monitoring, control, and remediation technologies, stressing the need for a shift toward technologies that emphasize sustainable use of natural resources and avoidance of environmental harm while still maintaining the commitment to remediate past environmental damages.
- Focus Federal R&D support on viable technologies that require assistance to attract private sector investment because of high technical risk, long payback horizons, or instances in which the anticipated returns are not evident to individual firms or distinct industrial sectors.
- Foster international cooperation on understanding, monitoring, and assessing environmental changes and impacts on a global or multinational scale.

Box 5. Learning before doing: New goals for environmental technology

For many years, the dominant environmental paradigm has been learning too late. Waste streams from every sector of society have necessitated after-the-fact treatment and remediation, often at tremendous cost and effort. Ozone-destroying chlorofluorocarbons, brain-damaging metals such as mercury and lead, reproductive-system-impairing persistent organic pollutants such as DDT and PCBs are a few familiar examples of learning too late. A new goal for environmental technology is to "learn more before doing."

For example, the development of microarray technology for simultaneously analyzing the total component of genome-encoded messenger RNA holds promise in allowing biologists to evaluate gene expression, protein function, and metabolism at the whole-genome level. Microarray analysis is being adapted to evaluate microbial community diversity and speciation. Research is needed to couple this technology to quantitative models so that it can be used to help understand the likely responses of microorganisms to environmental perturbations, how compounds travel through ecosystems, and how species interact.

In another example, as the rate of synthesis of new chemicals grows, screening compounds early and anticipating possible environmental interactions will be key. Presently we are able to learn about potential environmental impacts as a part of production. Can we use computer simulation modeling together with an increasingly sophisticated understanding of atmospheric, aquatic, and terrestrial systems to "learn more before doing"? Scientists and engineers would like to explore virtual prototyping, molecular modeling, and retrosynthesis in order to help design environmentally benign production processes and products.

The integration of informatics, molecular biology, robotics, and ecology also has rich potential for environmental technologies that increase efficiency, dematerialization, and recyclability and may drop costs substantially. A new and vigorous fundamental science and engineering research agenda that highlights the promise and the priorities emerging from the intersection of systems and complexity theory, quantitative modeling, and environmentally benign technology development would be a smart investment.

Chapter 3

Scope of NSF's Current Environmental Activities

NSF is a Federal funding agency that provides support to enable and facilitate scientific and engineering research and education. The Foundation makes merit-based awards to individual researchers and groups in partnership with colleges, universities, and other institutions—public, private, local, state, and Federal—throughout the Nation. These awards are made based on peer-reviewed national competition.

NSF plays a pivotal role in the Nation's investment in environmental R&D. It is one of the largest supporters of environmental research in the Federal Government and the major supporter of environmental research conducted by the academic community. About 20 percent of NSF's total 1998 budget—$542 million—was dedicated to environmental activities in a broad range of disciplines. The FY 1999 investment in this area totaled $595 million; $659 million is estimated for environmental activities in FY 2000. Consistent with NSF's primary mission, the majority of these funds go to integrated research and education projects, with scientific assessment receiving more modest support. By way of context, the larger Federal investment in environmental R&D was approximately $5.3 billion in FY 1995 according to the most recent budget crosscut published by CENR (1995).

In the environmental arena, the Foundation works with outside experts, primarily representing the academic community, to identify the Nation's most important environmental research needs. A cogent argument for maintaining a vigorous fundamental research effort in environmental science and engineering is for the country to have information available that can be used to address as yet unknown environmental problems likely to arise. Moreover, the significance of particular research in advancing specific fields of study has been a prime criterion for inclusion in the agency's portfolio. The relevance of such research to societal issues is also vital.

In line with these objectives, NSF has recently promulgated revised review criteria that address both the intellectual merit as well as the broader impacts of work it supports:

1. **What is the intellectual merit of the proposed activity?** How important is the proposed activity to advancing knowledge and understanding within its own field or

across different fields? How qualified is the proposer (individual or team) to conduct the project? To what extent does the proposed activity suggest and explore creative and original concepts? How well conceived and organized is the proposed activity? Is there sufficient access to resources?

2. **What are the broader impacts of the proposed activity?** How well does the activity advance discovery and understanding while promoting teaching, training, and learning? How well does the proposed activity broaden the participation of underrepresented groups (in terms of gender, ethnicity, disability, geography, etc.)? To what extent will it enhance the infrastructure for research and education, such as facilities, instrumentation, networks, and partnerships? Will the results be disseminated broadly to enhance scientific and technological understanding? What might be the benefits of the proposed activity to society?

As discussed in the previous sections, the challenges and opportunities required to study and understand the environment demand a broad range of disciplinary and interdisciplinary research approaches. This diversity is reflected in NSF's broad environmental portfolio and in the multiple approaches it employs for funding work in this area. These include:

- *Ongoing core programs* that define areas of interest and are continually revitalized by new ideas from individuals or small groups of investigators whose proposals are subjected to the rigors of the merit review process.
- *Special competitions* that respond to new topical areas, are often interdisciplinary in nature, and provide opportunities for interagency cooperation (see table 2). NSF's approach has been to enable these topical areas to mature and to foster connections among participating investigators; it may then fold the area into ongoing programs, allowing new areas to emerge.
- *Center or large group activities* that provide a framework for long-term studies of complex, cutting-edge topics. NSF supports several centers that have environmental work as all or part of their portfolio (appendix F).

Table 2. Examples of interdisciplinary special competitions

Special Competition	*Objective*
Environmental Geochemistry and Biogeochemistry	Supports research on the chemical processes that determine the behavior and distribution of inorganic and organic materials in environments near Earth's surface
Life in Extreme Environments	Addresses such fundamental questions as determining the evolutionary and physiological processes that led to the formation and adaptation of life on Earth
Water and Watersheds (with EPA and USDA)	Integrated socioeconomic, physical, and ecological research that takes a systems approach to questions of pattern and process at the whole-watershed scale

Research

As in other scientific and engineering arenas, NSF's environmental research activities serve as the fulcrum for advances by other Federal agencies, state and local governments, the private sector, and individual citizens. The knowledge derived from NSF-sponsored research fosters advances in our fundamental understanding of environmental systems. This knowledge in turn drives new technologies and other applications; enables sound policy and management decisions; and provides the basis for improved human health, prosperity, and well-being.

A diverse portfolio across the Foundation

From the search for understanding microbial processes in Antarctic ice to tracing contaminant effects in the Arctic ocean, from investigation of nanoscale interactions on mineral surfaces to the influence of solar flares, from the turnings of DNA to changes in animal migration patterns, researchers supported by NSF attempt to understand Earth's life forms and their complex relationship to their physical habitat. In the last few years, that search has been augmented by new tools for discovery—including new genomic methods, increased computational capacities, and more sensitive and versatile analytical instrumentation—and by increasing interest in interdisciplinary research. Concerns about the effects of human activity have focused greater attention on the development of environmentally benign advanced technologies and a deeper understanding of the socioeconomic dimensions of environmental systems.

Terrestrial, freshwater, and marine ecosystems around the world are probed, sometimes through interdisciplinary approaches. Of note in this area are the opportunities for long-term studies essential to understanding ecosystem dynamics and the impact of stressors. Many long-term studies are carried out under the Long Term Ecological Research (LTER) program (http://lternet.edu/), which is celebrating its 20th anniversary. NSF also supports a multiplicity of biological and biogeochemical research areas, including but not limited to: the patterns and causes of biological diversity at levels of organization ranging from genes to the biosphere; experimental, theoretical, and modeling studies on the structure and functioning of complex biotic-abiotic associations; the conceptual and synthetic linkages between scales of organization; and molecular evolution and organismal adaptation to changing environments.

Research on *physical processes in the environment* is a major current effort. Cycling of carbon, nitrogen, and other elements is under active investigation and is driven not only by curiosity but also by societal concerns about biogeochemical and climatic changes (see box 6). New space-based and remote-sensing technologies have enabled large-scale measurement and informative visualization. NSF supports research in integrated interagency programs such as Climate Modeling, Analysis and Prediction, and the World Ocean Circulation Experiment (http://www.nsf.gov/geo/egch/). Ongoing programs support studies of ocean, Earth, and atmospheric systems.

NSF is interested in the *role that humans play in contributing to changes in the environment and to mitigating the effects of environmental harm*. Engineering, computational and mathematical sciences, materials, and chemistry programs at NSF support work on environmentally friendly industrial processes, materials synthesis, natural hazards, and development of environmentally relevant sensors, simulation methods, and database strategies (http://

Box 6. Nutrients: Newly discovered links between agriculture, energy, health, fisheries, tourism, and climate

After thousands of years of stability, the chemistry of the surface of the Earth is changing rapidly (Schlesinger 1997). Changes in the cycles of nitrogen and phosphorus are substantial and linked in complex ways to changes in agriculture and energy (Vitousek et al. 1997a and 1997b, Carpenter et al. 1998a and 1998b).

Until the beginning of this century, microbes and lightning were the primary sources of fixed nitrogen (the form usable by plants), and human contributions were negligible. These non-anthropogenic sources currently generate approximately 140 TG fixed N/y. Humans contribute to nitrogen fixation by making fertilizers, burning fossil fuels, and planting legumes widely. Human activities now produce more than an additional 140 TG fixed N/y. As a result, the total amount of terrestrial nitrogen fixed each year has more than doubled.

Until the advent of extensive mining activity, new phosphorus was made available primarily through weathering of rock. Mining and land disturbances have now more than tripled the rate of phosphorus mobilization (from about 10 to more than 30 Tg/y) and the rate of phosphorus flow from the continents to the coastal oceans (from about 8 to 22 Tg/y).

When nitrogen and phosphorus were only scantily available to the biological world, they served as limiting factors that controlled the dynamics, biodiversity, and functioning of many ecosystems. Ecosystems now flush with excess fixed nutrients are changing rapidly. Nutrients unused by crops and lawns, livestock waste and sewage, and airborne nitrogen resulting from the burning of fossil fuels are disrupting a wide range of downstream and downwind systems. Excess nutrients stimulate the growth of algae and can lead to eutrophication, harmful algal blooms, loss of oxygen ("dead zones") in lakes and coastal waters, fish kills, loss of seagrass beds, degradation of coral reefs, and loss of commercial and sport fisheries and shellfish industries (Carpenter et al. 1998a and 1998b). In addition, the chemistry of the atmosphere is being altered by human-driven changes in the nitrogen cycle, with serious implications for the greenhouse effect, smog, and acid precipitation. Nitrate contamination is also a potential concern for human health, particularly in drinking water drawn from relatively shallow aquifers in agricultural areas (USGS 1999a).

Scientific uncertainties include the controls on nitrogen fixation and denitrification processes in ocean waters; triggers of harmful algal blooms; transport of nutrients across the landscape and among air, soil, and water; evolutionary consequences of long-term nutrient enrichment; and controls of nutrient-retention processes in ecosystems. Particularly important questions address the control points that could allow us to mitigate the flows or effects of excess nutrients. For example, how can floodplains and shorelines be configured to minimize nutrient flow to surface waters? Also, we need to understand the role of large reservoirs of nutrients in the control of regional and global cycles. For example, what is the rate of phosphorus buildup in agricultural soils, and what are the implications of this buildup for freshwaters and coastal oceans?

www.nsf.gov/home/crssprgm/be/). Some special initiatives in these areas take advantage of opportunities to collaborate with other agencies. A joint NSF-EPA venture on environmental statistics is developing algorithms for use on environmental problems (see box 7); another competition on decision-making and valuation focuses on choices made by humans about the environment. Research on urban communities attempts to identify the set of complex factors that give rise to vigorous, healthy communities and sustainable growth.

A growing trend is the synthetic *integration of data sets and greater use of modeling*. Such integration takes place both at large NSF-funded centers such as the National Center for Atmospheric Research (NCAR) (http://www.ncar.ucar.edu/)and the National Center for Ecological Analysis and Synthesis (NCEAS) (http://www.nceas.ucsb.edu), and increasingly within individual investigator projects. These trends are facilitated by high-speed computers,

Box 7. Statistical prevention models for wildfire suppression

Some of the most devastating natural disasters in the history of the United States have been caused by wildfires. Environmental statistical research models fire occurrence as a marked spatial-temporal point process whose conditional rate depends not only on the record of previous fires, but on other covariates including environmental factors such as temperature, altitude, humidity, precipitation, vegetation, and soil characteristics. Using advanced statistical research, investigators are constructing quantitative predictions of local fire hazard accompanied by estimates of uncertainties in these predictions. In particular, research in the Los Angeles basin will integrate these predicted hazards into detailed, regularly updated maps of risk that are available to the public. The strategy is to exploit local trends in fire occurrence and the relationships between the incidence of fires and other environmental factors. This basic research could have important public policy implications relating to more aggressive fire suppression and prescribed burning.

new software and modeling methodologies that allow integration of disparate data sets, and the use of integrated assessment techniques. New software and hardware for computational analysis, modeling, and simulation are leading to more reliable models for ecosystem complexity across scales, integrated assessments, forecasting, and analysis of management options (see box 8).

Importance of partnerships and collaborations

As NSF and other organizations move into a new era that calls for greater contributions to national and global well-being and more efficient use of resources, the potential for a more effective use of partnerships is extraordinary. NSF presently cooperates with other Federal agencies, state and local governments, private sector firms, organizations and foundations, nongovernmental organizations (NGOs), and scholarly associations in carrying out its science and engineering portfolio. Outside the United States, NSF works with counterpart agencies of foreign governments, intergovernmental organizations such as the United Nations, and NGOs such as the International Council of Scientific Unions.

NSTC/CENR provides a mechanism to facilitate and foster interagency research. CENR has highlighted the importance of coordinating research relevant to national initiatives and priorities, environmental statutes, and regional and global agreements and conventions. CENR also notes areas for improvement for such research, including the need to strengthen extramural academic research programs, encourage external peer review of all Federal R&D programs, and invest in future human resource and technical research capabilities.

Building on the success of the U.S. Global Change Research Program in developing a successful interagency initiative, NSTC is overseeing similar efforts in several other areas. Two of these are the Federal Geographic Data Committee, which is developing common standards for geographically based research and observation; and Integrated Science for Ecosystem Challenges, which features multidisciplinary approaches to such problems as invasive species and harmful algal blooms. NSF has also developed a wide range of bi- and multilateral interagency environmental activities that are not specifically part of the larger NSTC efforts. Additionally, the Foundation has helped other agencies develop NSF-style peer review systems.

The need to understand our global environment, its natural variability, and the changes imposed on it through human activities is recognized internationally. Environmental processes occur over a wide range of spatial scales. Some environmental problems are local

Box 8. Complexity theory and ecosystems

Ecologist Gene Likens recently said that a major intellectual limitation for environmental studies is the false assumption that there will be simple, all-inclusive answers (Pace and Groffman 1998). He went on to say that we must confront the complexity of ecosystems and incorporate that complexity into our scientific endeavors.

Ecological systems are highly nonlinear, characterized by abrupt thresholds in dynamics and possibly chaotic behavior. It is unreasonable to expect consistently accurate predictions for these systems—even with additional resources for generating scientific information combined with the prodigious computing power now available. On the other hand, conceptual and analytical progress is accelerating, and we can increasingly expect serviceable forecasts of the range of likely behaviors and the probabilities of various outcomes. The key in this regard lies in viewing systems as complex and not as the simple sum of their parts.

Ecosystem theory encompasses a wide range of approaches to understanding complex systems: Empirical work, including experimental manipulation of natural and model systems, as well as mathematical methods drawn from other disciplines such as cybernetics, control theory, information theory, network theory, thermodynamics, self-organization, and emergence and hierarchy theory (Muller 1992, 1997). A fundamental issue is to integrate systems behavior across levels of resolution in space and time to address the generation and maintenance of biological complexity across multiple spatio-temporal levels of resolution.

Scientists have learned that even simple rules can generate very complex behaviors and that systems can be very sensitive to initial conditions. This means that making precise long-term or large-scale predictions may be much more difficult than we initially thought—if not impossible in some cases. Complex systems are probably not understandable in the same way as simple systems, although sometimes complex rules can generate simple behavior, arguing the need to extract the “knowable” from the “unknowable” (Levin 1999). Also, small variations may lead to large changes that are not always predictable. So-called “exceptional” events turn out to be not all that rare. This new understanding is leading to fundamentally new approaches that will provide essential insight and guidance to members of the public and policy-makers. Improved understanding of the behavior of complex biological systems will greatly facilitate ecological forecasting and environmental decision-making.

(waste disposal), some are regional (loss of migratory species due to habitat destruction in one seasonal habitat), and some are global (stratospheric ozone depletion). Therefore, certain environmental research and scientific assessment efforts demand international collaboration and cooperation.

New directions

NSF’s activities in environmental science and engineering reflect the evolution of the Foundation’s thinking as to how agency activities can best exploit opportunities provided by recent research advances and best contribute to the overall program of Federal activities related to the environment. The full portfolio of environmental science and engineering activities at NSF is described on the web at http://www.nsf.gov/home/crssprgm/be/.

NSF’s FY 2000 budget for an initiative in Biocomplexity in the Environment represents the beginning of an increased investment in environmental science and engineering. This initiative will build on the broad environmental portfolio by addressing specific areas of opportunity in both disciplinary and interdisciplinary studies that promise to advance our ability to understand the complex interactive processes that occur in environmental systems. These opportunities will emphasize the use and further development of cutting-edge technologies such as genomics, molecular sequencing, informatics, robotics, remote sensing, new computational algorithms, newly developed x-ray scattering and surface spectroscopic methods, and advanced mathematics and modeling to enable new approaches to understanding these interrelationships (see box 9).

The term "biocomplexity" refers to phenomena that arise as a result of dynamic interactions that occur within living systems, including human beings, and between these systems and the physical environment, both natural and human-made. These systems, which range from microscopic to global in scale, exhibit properties that depend not only on the individual actions of their components, but also on the interactions among these components. Biocomplexity in the Environment is a timely area for intensified research because understanding of many system components is sufficiently advanced to provide the intellectual platform for addressing how these components interact in complex systems. Studying biocomplexity in investigations of the environment will engender a more complete understanding of natural processes and the interactions between humans and their environment (see box 10). Individual research and education activities in NSF's broad environmental science and engineering portfolio contribute knowledge toward the understanding of biocomplexity at all levels of aggregation.

Box 9. Genomics and environmental research

The first sequence of the entire genome of an organism was published in 1995. Since then, more than 20 entire genomes have been published; many more are in progress. With the exception of one nematode worm, all of the published sequences have been from microbes. But what scientists are learning from the analysis of these microbes is fueling a scientific revolution.

Some of the unanticipated findings were that in the genomes sequenced thus far, about 40 to 60 percent of the putative genes encode proteins that had not been seen or studied before, and approximately 25 percent of the putative genes in each organism were unique to that organism. The large number of unknown and unique genes led to the realization that the number of microbial species thought to exist on Earth had been vastly underestimated: At most, we have identified only about 0.01 percent of them.

Another startling finding is that relatively large pieces of DNA may be transmitted from microbe to microbe—even across distantly related phylogenetic domains such as the bacteria and the archaea (Nelson et al. 1999). Movement of DNA between these groups shatters the long-held assumption of strict linear descent during species evolution. Systemacists and evolutionary biologists are now developing new algorithms to analyze microbial evolution that will take into account the lateral transfer of DNA (Pennisi 1999). Scientists are also reevaluating the evolution of genetic processes and metabolism in this new light. Inclusion of lateral gene transfer may help us understand the evolution of complex biological processes as well as multicellular organisms.

Thus far, the genomic revolution has touched only the tip of microbial life. We have at least as much to learn from the genomic analysis of more complex organisms—work that is only now just beginning—plants, fungi, and animals, including humans. For environmental biologists, the ability to understand how an organism responds at the level of the whole genome will open up new areas of analysis of host-pathogen interactions, environmental stress, evolution of complex traits, population dynamics, and signal transduction at all levels. Ultimately, genomic-scale analysis should allow us to dramatically improve some predictive models, including those dealing with community dynamics as a function of environment and genotype:phenotype relationships.

Box 10. Human dimensions of environmental questions

Humans have always played a large role in forming and modifying the environment. Environmental degradation, in turn, usually carries a high human cost. In this regard, historical ecology is emerging as a field of study that can provide lessons applicable to current problems (DieffenbacherKrall 1996, Hammett 1992). Historical evidence records past human choices and responses in which the effects of environmental change can be understood. While unfamiliarity with environmental patterns and processes can lead to disastrous choices and actions, local knowledge about the environment, culture, and history can serve both as a practical basis for regionally appropriate solutions and as a means of increasing familiarity with and support for eventual policies (Crumley 1993).

Studies of the biosphere and society also reach to the future to address such topics as system dynamics; growth, regulation, and sustainable consumption; and participatory processes in the management of natural resources. For example, to better understand the human dimensions of deforestation and reforestation, an interdisciplinary team of demographers, geographers, earth scientists, ecologists, anthropologists, and political scientists has combined theories of human decision-making about land cover conditions with detailed analyses of field sites. In a careful empirical design focusing on three major types of forest ownership, the researchers can identify the differential impact of social processes on sites. Preliminary findings include the identification of key variables associated with rates of forest regrowth and more extensive understanding of the relationship between forest conditions and property rights systems (Sohn, Moran, and Gurri 1999).

All societies face decisions about the relationship between environmental protection and economic development—and all societies differ in the cultural, historical, and political context in which those decisions must occur. Attempts to generalize across systems have been illuminating but inconclusive, in part because study designs often have focused on comparisons across similar systems or because underlying theory was poorly addressed. To complement and energize interdisciplinary empirical studies of society and biosphere, investigators must develop a strong theoretical framework for such research (Ostrom et al. 1999, Low et al. 1999).

Education

As part of its mission to promote the progress of science and engineering, NSF supports individuals and groups working to ensure a scientifically literate populace and a well-trained cadre of scientists and engineers to study present and future environmental issues. Some of these activities take place in the context of projects aimed at advancing the frontiers of knowledge; others take the form of projects dedicated to education and human resource development.

Education through research

Many—if not most—NSF-supported environmental research projects support graduate students and/or postdoctoral fellows. Many also support undergraduates via NSF's Research Experiences for Undergraduates program (NSB 1999). Moreover, a growing number of activities primarily focused on research are adding education components. For example:

- The Long Term Ecological Research program has begun a broad-scale, long-term effort to combine scientific research and K-12 science education. Projects include using LTER resources to enhance hands-on science learning for students; developing long-term research sites on or near schoolyards; and facilitating communication between scientists, science educators, and school teachers.

- The National Center for Ecological Analysis and Synthesis has established a partnership based on a science curriculum developed by the Santa Barbara, California, school system called Los Marineros (Spanish for "The Mariners"). Under this partnership, NSF-supported scientist volunteers from NCEAS adopt a fifth grade class and develop an ecology experiment which the class conducts during the school year.
- The Environmental Molecular Science Institutes were established in 1997 through an NSF Division of Chemistry and U.S. Department of Energy competition to support collaborative research on the molecular behavior of complex, dynamic environmental systems (NSF 1997). The proposals were evaluated, in part, on the quality of their education and training components, especially their plans to involve students and underrepresented groups including women, minorities, and people with disabilities.
- The NSF-EPA-U.S. Department of Agriculture Water and Watersheds special competition has added an education and outreach element. Investigators are encouraged to include involvement of local school groups in field sampling, lab analyses, or other project activities. In addition, projects must demonstrate involvement of local governments and/or community groups from inception (developing the research questions) to completion of the project and dissemination of the results.

Informal and formal education

Beyond the education accomplished through research project support, approximately $29 million was spent in FY 1998 on environment-related projects funded by NSF's Directorate for Education and Human Resources (EHR). In line with an increasing public awareness of environmental issues, more environmental courses and placement exams at the secondary school level, and a growing demand for undergraduate environmental science degrees, EHR has been receiving an increasing number of education proposals related to the environment. These trends have also fueled an increase in the number of teachers seeking professional development in the field.

EHR provides support for science and mathematics education across all levels of formal education as well as for informal education approaches. Funds are not targeted at specific topical areas, such as the environment; however, a significant number of environment-related projects are funded via the standard proposal process. Types of activities funded by EHR that relate to the environment include:

- teacher preparation and professional development projects;
- development and dissemination of educational materials and experiences such as textbooks, CD-ROM interactive programs, classroom science kits, laboratory and field equipment, web-based curricula, video lessons, and exercises; and
- informal education projects such as the development of museum exhibits, video documentaries, radio programs, large-format IMAX films, and television series.

Other NSF directorates have been joining with EHR to fund education projects—a trend that has been increasing in recent years. For example, EHR collaborates with the Directorate for Geosciences, along with NASA and the National Oceanic and Atmospheric Administration, in funding the Global Learning and Observations to Benefit the Environment (GLOBE) program. GLOBE is a worldwide network of students, teachers, and scientists from over 6,000 schools working together to study and understand the global environment. Scientists use GLOBE data in their research and provide feedback to the students to enrich their science education. NSF invests approximately $2 million per year on GLOBE awards (http://globeint.org/).

A project on Arctic Connections, co-funded by EHR and the Office of Polar Programs, will produce a CD-ROM that incorporates an inquiry-based approach designed to stimulate interest in science among Alaskan Native middle school students. The CD-ROM will contain story modules that discuss both scientific and Native ways of understanding, teaching modules with classroom lessons followed by adventure stories with scientific content and problem-solving activities relevant to Arctic communities, and laboratory activities.

Additionally, a joint effort between EHR and the Plant Genome Venture Fund in NSF's Biology Directorate is developing instructional kits to help biology students in grades 6-12 make the conceptual connection between molecular genetics and gene expression in plants. The kits will let students make a visual connection between the results of DNA analysis and observations of plant morphology.

Scientific Assessment

Scientific assessment, as used by the Board, refers to the synthesis, evaluation, and communication of scientific understanding. Such activities are vital to the effective integration and communication of scientific research findings, since the results of individual and team research efforts rarely themselves provide the synthesis needed to set research priorities or provide guidance for environmental policy or management decisions. Scientific assessment is particularly desirable where there are complex data sets and results from multiple research sites, disparate time intervals, or varying environmental conditions. Scientific analysis, synthesis, and modeling—all proven techniques of scientific assessment—provide rational mechanisms for integrating and evaluating results or for defining the most productive research avenues to pursue.

NSF currently funds only a small number of assessment activities, totaling about $4 million annually (see table 3). Some of these focus on the science of assessments—they provide grants to analyze the process of conducting effective assessments (i.e., the USGCRP Methods and Models for Integrated Assessments special competition). Other activities involve grants to groups of recognized experts with the goal of synthesizing information and reporting it in a credible and useful fashion. In this regard, it is useful to remember that the traditional audience for the vast majority of scientific research has been the scientific community, and publication in scientific journals has been the communication vehicle of choice. Alternative avenues of communication also can be employed, taking findings from peer-reviewed journals and making them accessible to a broader audience.

Most of the innovative science and engineering research funded by NSF is by its nature anticipatory. Pioneering research often identifies environmental problems that later—in the

Table 3. Recent scientific assessments supported by NSF

Assessment	*Scope*	*Description*
USGCRP National Assessment	United States; interagency	To analyze and evaluate the potential consequences of global change for the United States. Focuses on the consequences of climate variability and change; timed to provide input to the third Assessment Report of the Intergovernmental Panel on Climate Change.
Habitat Conservation Plan Assessment	Nationwide graduate seminar funded through NCEAS: 106 graduate students & 13 faculty advisors at 8 universities	To examine the role of science in habitat conservation plans (HCPs). Private landowners are legally required to provide HCPs that outline how they intend to minimize the impact of planned activities on endangered species and habitats. The 90,000-entry peer-reviewed HCP database was used by the U.S. Fish and Wildlife Service in revising its HCP handbook.
Grand Environmental Challenges	Interdisciplinary; National Research Council Project	To identify and prioritize grand challenge research opportunities in environmental sciences. Focuses on identifying on a scientific basis the most important and challenging questions in environmental sciences, including social sciences and engineering.

short or long term—become established as specific research areas (e.g., carbon dioxide increase, ozone hole, acid rain, species extinction rates, exotic species invasions). The ability to anticipate future environmental problems can help prevent them from happening or keep them from becoming prohibitively expensive and difficult to address. NSF has just begun to tap opportunities for coupling its support of anticipatory research to scientific assessment activities.

CHAPTER 4

INPUT RECEIVED ABOUT UNMET NEEDS AND OPPORTUNITIES

GENERAL THEMES

The Board reviewed and considered hundreds of recommendations from reports and policy documents; from scholars in every scientific discipline and a broad range of professional societies; from local and Federal agency officials; and from nongovernmental organizations, community groups, and concerned citizens (see appendices B, C, and D). Many of the suggestions transcend NSF's mission and relate more properly to the entire Federal portfolio of environmental activities. Nonetheless, we include them as a record of those points made repeatedly and as a basis for many of the findings and recommendations presented in this report. In addition, the Board examined a variety of programs at NSF to determine the factors most likely to result in effective research, education, and scientific assessment activities.

Several themes emerged from this diverse input. Foremost among them was a strong endorsement of NSF's fundamental operating principles. In particular, the following strengths were highlighted:

- **Credibility.** NSF's merit review approach is considered key to the credibility of its environment portfolio.
- **Program flexibility.** The ability of core NSF programs to evolve over time as different fields of study emerge, change, and combine is widely supported.
- **Emphasis on education.** NSF gets positive marks for its support of education and the integration of education with research.
- **Leadership.** One of NSF's major strengths is its ability to activate the intellectual assets of the research and education communities and to mobilize resources for addressing substantive scientific and engineering challenges.

A NOTE OF THANKS

The Board is grateful to all of the individuals and organizations that provided comments during the process of developing this report. The thought and care that went into these responses were obvious, and this report has benefited accordingly. The Board does not endorse all of the comments received, but appreciates the intent behind them and the perspectives that were brought to the table. The findings and recommendations offered in this report reflect a careful process of developing coherent policy guidance for the Foundation that has necessitated difficult choices. The context for this consideration is evident throughout the report.

- **Flexible funding.** The ability of program officers to allocate funds to facilitate the early development of emerging fields is both beneficial to nascent disciplines and an excellent mechanism for attracting outstanding scientists to serve in the critical role of program officers.

These strengths place the Foundation in a unique position to expand its efforts to enable a broad spectrum of advances in the research community and to strengthen and expand its partnerships with other Federal agencies in support of environmental research, education, and scientific assessment.

Also from this input, the Board heard many ideas that framed ways in which NSF could and should develop its environmental portfolio. The repeated suggestions are summarized below.

Input Received During the Hearing Process*

Enable significantly more interdisciplinary and multidisciplinary research to address environmental issues and problems

This recommendation has been repeated frequently over a number of years as researchers have grappled with the extraordinary complexity of environmental systems and the factors influencing those systems. For example, the Corson Report (NRC 1993) notes that "the research establishment is poorly structured to deal with complex, interdisciplinary research…" Expertise from multiple disciplines—including the physical, biological, and social sciences and engineering—is required to advance understanding and solve environmental problems. Many of the individuals who spoke to the Board in its public events or via its web site emphasized this as an area that NSF needs to strengthen, and a sizable fraction of the approximately 250 reports in appendix B also mentions this issue. Many also emphasized the inherent difficulties in establishing interdisciplinary and multidisciplinary projects within the context of disciplinary programs through which funding is presently available.

The best interdisciplinary science must be firmly grounded in rigorous disciplinary research. Enabling productive interdisciplinary efforts, however, requires significantly more than simply assembling outstanding disciplinary researchers. Successful interdisciplinary research requires different ways of conceptualizing problems; an openness and respect for other disciplines; and the availability of time for the development and maturation of new interactions, language, understanding, methodologies, and concepts. Fostering interdisciplinary research thus needs to occur in parallel to the conduct of disciplinary research. The report of the USGS Workshop on Enhancing Integrated Science explores this area and suggests a draft set of principles for the conduct of interdisciplinary science endeavors (USGS 1999b).

The Board heard that interdisciplinary grant competitions at NSF suffer from weak continuing institutional commitment and planning. Environmental research takes at least a 2- or 3-year startup period to become fully effective. Once a competition is announced, program officers within NSF and researchers in outside communities must assemble new alliances and learn to work together. It takes a couple of times through the process to learn it well. The

*Prior to the July 1999 release of the Interim Report.

Board heard that by the time the process becomes well focused, changes within the Foundation shift budgets to other priorities and personnel rotate out or are reassigned elsewhere. Many NSF interdisciplinary programs operate in only startup or lame duck mode, and this obstructs real progress toward addressing important, interdisciplinary environmental issues.

The Board also heard endorsements of the core programs at NSF and was urged to secure funding for environmental research that complements and expands existing activities. There has been, and continues to be, a tremendous amount of important knowledge that has been generated by the solid foundation that the core programs at NSF provide. Environmental research that has major political elements has the potential to substantially diminish the stability of NSF's environmental research efforts. While it would be very helpful to strengthen and expand existing NSF programs and to increase the capacity for interdisciplinary environmental research, such expansions should not be made at the cost of the long-term stability of disciplinary environmental research at the Foundation.

Recognize the inherent complexity and nonlinearity of most environmental systems

Many individuals suggested that NSF's new focus on biocomplexity is timely and urgently needed, but felt that support for a far greater effort in this area is required. They pointed out the importance of recognizing the inherent differences between reductionist approaches (which focus on smaller and smaller units of a process or system) and more synthetic approaches (which emphasize interactions among components, complex behaviors, and emergent properties). Significant advances in synthetic, holistic approaches are required to understand environmental systems.

Environmental issues are often characterized by both interdisciplinarity and complexity. For example, scholars concerned with conservation of biodiversity must synthesize advances in evolutionary systematics, biogeography, and ecological genetics in order to understand genetic diversity and how it can be conserved.

In another example, the Board learned that synthesis of advanced process understanding in atmospheric science, hydrology, and geology is necessary to quantify mass flux and energy balance in certain natural systems. This is specifically important to our understanding of the complexities of flow in the "vadose zone": the region of soil and fractured rock where we are intentionally (Yucca Mountain) and inadvertently (Hanford and other sites) storing high-level radioactive waste.

The Board also heard testimony urging NSF not to make biocomplexity the lens through which all environmental research should be focused. The concern was that it risks making the term so broad as to be meaningless and could devalue disciplinary research not central to understanding biocomplexity.

Consider questions at the appropriate temporal and physical scale by taking into account long-term and large-scale research needs

The Board heard from a variety of sources that the need for long-term research, monitoring, and assessment of environmental trends far exceeds what is generally being delivered. A whole new level of effort is needed to complement the excellent examples of long-term, large-spatial-scale research that were identified (e.g., certain Global Change Research endeavors and the LTER program).

The vast majority of field studies are of insufficient duration or spatial scale, or both, to capture important phenomena. For example, in a survey of the duration of research projects published in the journal *Ecology* between 1977 and 1987, Tilman (1989) found that 40 percent of those studies had time periods of less than 1 year and that more than 92 percent of experimental field studies had durations of 5 years or fewer. Given that many organisms require more than a few years to complete their life span and that most ecological processes require a long period to exhibit their potential range, an emphasis on shorter term projects can substantially constrain the development of environmental understanding. Similarly, the spatial scale of most research projects does not approach the scale at which whole system patterns and processes begin to emerge.

The idea of environmental research and education hubs—physical and/or virtual centers, or collaboratories—was advanced as one way by which researchers could synthesize the findings from long-term and large-scale research. A parallel goal for such hubs could be the integration of research with education.

The Board also heard that long-term and large-scale research offers opportunities for partnerships with other Federal agencies as well as state, tribal, and local agencies and NGOs. The LTER program could serve as a model for how such partnerships might be established and maintained.

Include appropriate human components (e.g., economics and social sciences) in environmental research and education

Over the last decade or so, an increasing number of environment-related reports have noted that great leaps in our understanding of environmental systems will be made as system paradigms expand to include human sciences. New areas encompass theoretical and empirical research to develop measures of sustainable consumption levels; quantitative studies on the efficient use of resources; research on the relationships between environmental regulations, private sector investment decisions, and productivity growth; and research on participatory processes, scientific and technological innovation, and resource management.

A particularly critical area of study, research on environmental valuing and decision-making, has shown that humans weigh concerns for social justice, aesthetics, history, and economic factors in assessing the merits of policy and practice. Further research is needed to identify the kinds of participatory processes and educational approaches that enhance human ability to make good use of scientific information in developing stable, sustainable environmental policies, frequently in the face of substantial scientific uncertainty (see box 11).

The Board heard testimony that the human sciences have developed with impoverished spatial information, in part because until recently the capacity to create such large data sets was constrained by enormous costs and the capacity to analyze such data was poor. Information technology has now advanced to the point that spatially explicit problem solving in the human sciences can be integrated meaningfully with similar approaches in ecology, the

Box 11. Integrated natural-socioeconomic sciences: Some priorities for investigation

Challenges of understanding integrated natural-socioeconomic systems are neither purely ecological nor purely economic. Each discipline has essential knowledge, but each discipline alone is insufficient. To understand and predict natural-socioeconomic systems, we require genuine interdisciplinary collaboration, which builds from the foundations of the individual disciplines to create a new, integrative body of knowledge. In studies of water quality, for example, an interdisciplinary team comprised of an ecologist, an economist, and a mathematician has discovered that economically optimal management goals are radically different from the status quo when the economic analyses account for nonlinear dynamics of lakes (Carpenter et al. 1999b). Integrated ecological-socioeconomic models of watersheds behave in ways that are similar to case histories of watershed management, yet unexpected from the behavior of isolated models of ecosystems or social systems (Carpenter et al. 1999a). This example shows remarkable new insights sparked by an interdisciplinary collaboration rooted firmly in the knowledge of the parent disciplines.

Ecology has made great strides in understanding complex interactions among processes that change slowly or infrequently (such as evolution, soil development, or populations of long-lived organisms like trees and whales) and processes that change rapidly (such as pest outbreaks, some species invasions, and blooms of toxic algae). Yet integrating people into an ecological understanding of nature in a rigorous fashion remains a challenge. Economists have made enormous progress in understanding how decisions made by vast numbers of people lead to equilibrial patterns of markets and economies that shape our lives. Yet economic theory has so far been unable to account for the slow dynamics, multiple stable cycles, contingent evolution, and intrinsic variability of ecological systems. The time is right to build on the strengths of the two disciplines and bridge the gaps between them. Some research priorities include:

- identification and quantification of ecosystem services and natural capital, including their contributions to human welfare and their economic valuation (see box 1);
- management of complex systems characterized by interactions across scales of time and space, multistable oscillatory attractors, and the capacity to create novelty;
- improved capacity to forecast ecological dynamics under given management scenarios, with explicitly quantified uncertainties;
- analysis of the role of uncertainty and its dynamics in environmental decision-making, including the reduction of uncertainty via experimental management; and
- dynamics of learning and the role of bounded rationality in ecological-socioeconomic systems.

geosciences, and other fields. For example, these capabilities could be applied to concerted, long-term research into the historical effects of human communities on local environments. This type of research could provide fine-grained, spatially explicit, historical data on changing ecosystems and on the dynamic relationship of human communities and ecosystems.

Create a more effective information infrastructure to facilitate significant advances in informatics, data management, modeling, synthesis, and dissemination of information

It is generally acknowledged that effectively addressing environmental issues requires utilizing the powerful new tools of information technology to manage, use, and communicate the scientific data and information already in existence and to be generated by future research and monitoring.

The Board learned that approximately $600 million per year is spent on environmental information generation through research, data collected by monitoring efforts, and the storage and analysis of data (PCAST 1998). But existing high-quality information is not currently being incorporated into management decisions because of lack of electronic availability of the information and inadequate capabilities to interpret, synthesize, and analyze that information.

For example, the United States possesses approximately 750 million biological specimens in its natural history museums and herbaria. The georeferenced data (geographic coordinate data attached to the biological information) from these specimens are urgently needed as a tool to study the status and trends of ecological systems, but the vast majority of this information has not been digitized.

The Committee for the National Institute for the Environment, in testimony to the Board, called for an overarching electronic network for this spectrum of information activities. This network would feature the combined use of Internet-centered information technology, services, products, existing organizations and systems, and information specialists organized into an environmental information infrastructure. The recommended network would facilitate linkage of distributed information and databases, improved quality control of databases, increased support for data standardization and information management, and improved access to information for the public.

Today we speak easily of collaborations between molecular biosciences and ecology. What we quickly forget is the sometimes long period of incubation before such collaborations take hold and lead environmental science in new directions. To realize the Nation's environmental research agenda, we need to understand the process of scientific collaboration better. Perhaps the vehicle here is information. Therefore, the Board could well explore how we bring information technology more fully to the environmental research agenda. — *W. Franklin Harris, University of Tennessee*

The Digital Library Interoperability project at the University of California–Santa Barbara, Stanford University, and the University of California–Berkeley may provide lessons. The Internet allows computers to exchange data, and the web gives computer users interactive access to information. But users of digital libraries and information grids need services to help them manage raw information and organize data. This NSF-NASA-Defense Advanced Research Projects Agency-supported project is building tools and services to allow people to exploit the remarkable opportunities for collaborative creation and sharing of knowledge that a digital world makes possible.

Develop and exploit state-of-the-art technology to advance environmental studies and address environmental problems

New computational algorithms, remote sensing, new kinds of sensors, genome sequencing, laser technologies, and other advanced approaches are moving environmental research into a new era. Previously inconceivable advances are being suggested. A variety of tools from molecular biology (e.g., oligonucleotide probes) are letting us interrogate microbial assemblages to find out what microbial types are present, what they can do, and what they are doing. One scientist testified to the Board, for example, that genomic bar-coding of the pathogen *Pfiesteria* in the Chesapeake Bay may become a reality thanks to microchips that will identify the organism's genome as quickly as a supermarket scanner. Tools from molecular chemistry (e.g., advanced x-ray methods) allow scientists to collect unprecedented kinds of information about geochemical environments at the microbe scale.

Powerful new computers and algorithms are letting scientists construct models that include the true complexity of biogeochemical systems. We are beginning to access the information processing capability to connect the many processes of environmental and human systems coherently so that we achieve a comprehensive understanding. But the kinds of profound advances that we foresee require integrated research and application of these advanced tools across a broad front of fundamental questions and environmental issues.

Other kinds of advances should be supported in the newly emerging environmental technology area of industrial ecology, a field that takes a systems view of the use and environmental implications of materials, energy, and products in industrial societies. Specifically, it places industrial activity in its environmental context and draws on nature as a model for the processes involved in industrial activity. The rich research agenda for industrial ecology has grown from more traditional research on particular materials and economic sectors to include needs for cross-sector and multiscale approaches.

The Board also heard that fundamental research is needed to enable the shift from waste management and remediation to avoidance of environmental harm. For example, fundamental studies in chemistry and engineering have led to environmentally benign alternatives to chlorinated hydrocarbons for use in the synthesis of chemicals and pharmaceuticals and in manufacturing processes. Industries have been quick to adopt new products such as these, as well as new approaches to polymer production, drycleaning, and paint application that prevent pollution and thereby avoid environmental harm.

Support inventory and monitoring programs to characterize animal and plant resources and to determine their status and trends

Plant, animal, and microbial species provide the basis for economically productive enterprises, including crop and timber agriculture, livestock husbandry, fishing, and consumptive and nonconsumptive wildlife recreation. The Board learned that protecting the basis of these endeavors calls for a more extensive understanding of the wild relatives of these species (as rich sources of new genes), of threats from invasive species including pests and pathogens, and of the ways in which the relevant ecosystems will respond to the plethora of ongoing global changes. In addition, studies of genetic diversity and the rich array of chemicals and structures found in plants, animals, and microbes contribute directly to many facets of the biotechnology industry and biomedical research. The need for evaluation of patterns and causes of change goes beyond the need for information on individual species. Assessing the status and trends of ecosystems providing essential services is increasingly recognized as vital to economic and health interests. Ecosystem services of particular interest include pollination, pest control, water purification, and flood control (PCAST 1998).

Support research that connects more effectively with decision-making (policy, regulatory, management, institutional, and individual)

There has been a growing interest over the last decade in improving the scientific basis of environmental decision-making. Several recommendations the Board heard and read on this topic are of relevance here: (1) research results should be communicated to potential users in a useful and understandable form; (2) research should include a focus on those environmental problems where users need better information (see box 12); and (3) public understanding of science, in particular in the environmental area, needs to be improved.

Knowledge assessments are one route toward providing a common base of understanding. A model for such knowledge assessments might be the *Issues in Ecology* series produced by the Ecological Society of America. These peer-reviewed publications report, in lay language, the consensus of a panel of scientific experts on issues relevant to the environment.

Unlocking Our Future, the Report to Congress of the House Committee on Science (1998), emphasizes that the role for science in helping society make good decisions will take on increasing importance, particularly as we face difficult decisions related to the environment.

The Corson Report, the Committee for the National Institute for the Environment, the American Institute of Biological Sciences, and the Ecological Society of America, among others, suggest specific ways to improve the use and usefulness of knowledge resulting from the research enterprise (see e.g., NRC 1993, CNIE 1994, Blockstein 1997). Suggestions include: improved coordination across the environmental research portfolio; setting priorities to produce a more comprehensive knowledge base; better mechanisms for the communication of urgent societal needs to the research community; better communication of research results to multiple audiences; improved mechanisms for organization, management, and distribution of data; and improved public understanding of science and environmental issues.

Include educational elements in environmental programs and plans

The Board heard that education and training in the Nation's universities are strongly disciplinary, whereas solution of environmental problems also requires broadly trained

Box 12. Atmospheric chemistry

The chemistry of the atmosphere, Earth's ecosystems, human health, and economic systems are inextricably linked, often in complex ways. Research supported by NSF and other Federal agencies has created tremendous progress in understanding stratospheric chemistry. However, many questions remain unresolved, such as the exact nature of stratospheric aerosols and the detailed linkages between their chemistry and dynamics. Current areas of interest also include the connection between stratospheric ozone depletion and climate change—the stratosphere is actually cooling. The lower stratosphere/upper troposphere—previously not easily accessible to direct observation—has recently come into focus since much of its chemistry and dynamics, including stratosphere/troposphere exchange, are poorly understood. Tropospheric chemistry remains full of challenges: defining its oxidative capacity (which in turn determines the ozone depletion potentials and global warming potentials of harmful compounds); understanding the factors affecting regional and global air quality; feedback mechanisms between global climate change and the chemical processes; and a complete understanding of biogeochemical cycles that link atmospheric, oceanic, and biological processes.

people and multidisciplinary approaches. Opportunities for broadly based interdisciplinary graduate degrees are few, and faculty are often not as well rewarded for interdisciplinary activities as they are for disciplinary work. Additionally, environmental scientists are often not appropriately trained to address pressing needs and fill positions in career paths outside academe.

Complexity, and biocomplexity in particular, offers roadmaps for training the next generation of scientists. Creativity in building the educational support system for this new integrative environmental science is an especially important challenge. It will require new models of institutional cooperation and new degrees of freedom on the part of NSF program officers to assess and build creative, integrative research/educational programs.

Improve coordination among programs and agencies

The need for good communication and coordination across agencies was highlighted as an ongoing challenge (see box 13). CENR provides a mechanism for this coordination and has overseen a variety of highly successful interagency activities. For example, USGCRP has for a decade focused multiple Federal agencies on understanding the components of the Earth system and modeling at the global scale. Within a coordinated framework, progress has been made in understanding the loss of stratospheric ozone, the important roles of terrestrial and marine ecosystems in the overall carbon cycle, and past changes in the Earth's environment that provide a context for anthropogenic changes now ongoing. USGCRP has also provided predictive information about El Niño that has been useful to natural resource management and agencies concerned with human health and safety.

Not all testimony supported coordination of Federal agency activities through a committee structure. The Board heard testimony that interagency programs may lack the necessary ownership within each agency and can lead to renaming of existing activities rather than major new initiatives.

The Board also learned of excellent examples of interagency coordination that have not involved CENR. One example is NSF's interaction with universities and other Federal agencies to develop and implement the network of LTER sites. Many of these projects involve complex partnerships with mission agencies, and the scientific yield has been extraordinary. The Board heard that NSF must continue its leadership role and its partnering efforts with other agencies.

Finally, the Board heard that scientific assessments, by establishing and communicating a base of scientific knowledge on a given topic, can provide a mechanism for improving collaborations between Federal agencies and between the Federal and private sectors.

Improve predictive capabilities in a variety of environmental areas

Our ability to predict the behavior of environmental systems has grown steadily with an increase in understanding of many of these complex systems. For example, interdisciplinary paleoclimatic research is improving our understanding of the Holocene climate. This is important because it is within the Holocene that the boundary conditions for modern natural climate variability can be identified and from which the relative importance of

Box 13. New insight into infectious diseases: An emerging interface between health and the environment

In the early 1960s, Machupo virus, a new pathogen transmitted directly from rodents to humans, ultimately infected over one-third of the population of San Joaquin, Bolivia, and killed hundreds before it subsided.

Considered endemic to developing countries, Machupo virus and its sister pathogens remained more or less unstudied until 1993, when an outbreak of the related Hantavirus Cardio-Pulmonary Syndrome occurred in the Southwestern United States (Parmenter et al. 1993).

Hantaviruses are a group of RNA viruses, many of which are highly pathogenic to humans (Keller et al. 1998). This new virus was found to use the deer mouse as its primary reservoir and to be fatal in almost 50 percent of human cases. Since this discovery, almost 30 new Hantaviruses have been found in the New World, half of which are known to be pathogenic to humans (Hjelle et al. 1995). The specific origins of these new viruses and the cause of the 1993 outbreak appear to be due to a complex set of evolutionary and ecological factors. For example, El Niño events are now known to trigger population explosions of host rodent populations and eventually an increased incidence of infection in mice—and increased risk of infection in humans. Data from NSF-supported long-term ecological and biodiversity research have played a significant role in our growing understanding of these emerging viruses. This new understanding, improved remote-sensing capabilities, and modeling of complex systems are enabling improved prediction and prevention of Hantavirus outbreaks in the Western United States.

This understanding and other similar studies have led to a fundamental change in how we approach the study of diseases and is leading to the emergence of a field of study in the ecology of infectious diseases (Anderson and May 1991, Dobson and Carpenter 1996, Real 1996). These studies are multidisciplinary by design and require long-term data to be robust (Parmenter et al. 1999). They hold great potential for allowing the development of predictive models, not just for Hantaviruses, but for many other diseases. A clear understanding of the ecology and evolution of these pathogens will be needed if we are to respond effectively to emerging biological threats.

natural versus anthropogenic climate forcing can be assessed. Understanding of modern climate and prediction of future climate will require a detailed understanding of Holocene climate forcing and response.

Most environmentally related scientific inquiry focuses on components of the environment or the individual effects of one component on others. Simulation and other models provide a framework within which to place our understanding of all the components simultaneously as they occur in nature. This framework allows quantitative accounting of the interaction of the component parts with factors outside the system and the sometimes surprising responses resulting from feedback among interacting components. For example, at the Central Plains Experimental Range LTER site, scientists have studied and modeled the long-term effects of grazing on vegetation succession dynamics. Surprisingly, heavy grazing in this system resulted in little change in annual net primary production, increased plant density, and decreased abundance of exotic invading species. LTER scientists speculate that this response reflects the importance of native herbivores in these ecosystems over evolutionary time. This particular response to grazing has not been generalizable to all grassland ecosystems, however: Sensitivity to grazing varies with gradients of productivity and environmental conditions.

Comparison of model output with data from environmental experiments indicates how much confidence can be placed in the models. And models that have been tested successfully in a variety of situations permit more robust predictions about the complex behavior of the environment. Modeling experiments can be conducted to help design research in unexplored areas. Additionally, sets of environmental drivers can be used in models to represent management or impact scenarios of particular interest to scientists or society. Simulation models have thus become tools of necessity for environmental research.

Get input on priority setting from people and organizations familiar with research, education, and assessment issues

No multifaceted program can be accomplished without setting priorities. The Board examined several examples where research or education agendas were defined in an inclusive and integrated manner. For example, the Freshwater Imperative Research Agenda (Naiman et al. 1995) was developed with NSF support over a 2-year period of study and consensus building involving a broadly interdisciplinary array of scientists, managers, and educators. This research agenda sets priorities and develops detailed research questions as well as makes recommendations for implementation. Such research agendas are the exception rather than the rule, however, and it became clear to the Board that this is an area that needs much more attention, in particular where priorities are set in interdisciplinary areas.

Throughout the public input process, it became increasingly clear that citizens, government officials, representatives of other Federal agencies and of professional scientific and engineering societies, and individual scientists look to NSF for leadership in environmental research, education, and scientific assessment. The expectation that NSF will play a key role was highlighted for the Board in a number of ways and by groups ranging from National Research Council committees to advocacy groups. The strong message running throughout the hearings was that NSF can, and is expected to, respond vigorously to the new challenges of providing and communicating the fundamental knowledge base, and educating and training the workforce to meet the environmental challenges of the new century. A parallel message underscored the requirement for significant new resources to accomplish these goals.

Input Received in Response to the Interim Report

After the release of the report as an interim document in July 1999, the Task Force on the Environment web site received almost 7,000 “hits.” The Task Force also received comments on the Interim Report from a variety of individuals and professional organizations representing several thousand environmental scientists, engineers, and educators (see appendix D). The vast majority of these comments were quite positive, reinforcing the input received earlier and supporting the recommendations. A number of the suggestions were very helpful to the task force in strengthening and clarifying the report. Several additional points were made by multiple respondents:

The report should be implemented in a way that is recognizable as a new approach in order to be successful in receiving funding and providing scientific information that will make a difference

In addition to this explicit point, several organizations commented that the report should be implemented as a cohesive program, not treated as a menu from which selections might be made. Several organizations were interested in how NSF would collaborate with interested parties to pursue implementation and in how NSF would integrate research, assessment, education, and information. The point was also made that outcome assessment tools should be developed by which the success of the report could be measured.

In recommending a unique implementing entity, multiple respondents suggested that interdisciplinary programs be established and separated from disciplinary units to most effectively nurture interdisciplinary approaches. The underlying concern expressed was that as long as interdisciplinary programs compete for resources within a single budgetary organization, they will be at a disadvantage for the simple reason that interdisciplinary proposals will be perceived as less relevant to the core goals of the disciplinary unit. This point was coupled to the observation that most interdisciplinary activities cannot be sustained over the necessary time periods without an organizational home within NSF. It was of interest to the Board that these comments were made multiple times and across virtually all disciplines.

NSF should consider different approaches to establishing research priorities

Several respondents suggested that NSF include stakeholders—established environmental groups, scientists, policy-makers at all levels of government, and NGOs—in the process of determining research priorities. Others suggested that priorities should be developed in large part through a series of scientific assessments. Several respondents advised NSF to place the discussion of research needs into a broader national context and fully consider leveraging opportunities.

With regard to the NSB report overall, we applaud the Board's recommendation that environmental research be made one of NSF's highest priorities and agree that funding should be substantially augmented, particularly in five specific areas emphasized in the report: interdisciplinary research; environmental education; economic valuation of ecological goods and services; long-term, large-scale research; and improving environmental assessment capabilities.—*President's Committee of Advisors on Science and Technology, 1999 (appendix E)*

NSF should work to break down the barrier between applied and basic environmental research

Many respondents commented on what has emerged as a continuum between applied and basic research, and several suggested that NSF allow policy-relevant basic research to flourish alongside more traditional approaches. It was pointed out that the illustrative boxes in the Interim Report concentrated on problem-focused science and engineering, while the text emphasized fundamental research. Several respondents wondered if this was a disconnect or an intentional effort to highlight where the most exciting advances were occurring. Others asked if NSF would now support science that meets intellectual merit criteria but is primarily directed toward environmental improvement rather than scientific advancement.

CHAPTER 5

FINDINGS AND RECOMMENDATIONS

Three interrelated conclusions provide a compelling rationale for making the environmental portfolio a central activity of the Foundation: (1) environmental issues are significant to national health, prosperity, equity, and well-being; (2) environmental research, education, and scientific assessment are essential to environmental problem solving; and (3) within the family of Federal agencies, NSF is positioned to play a leadership role in providing and communicating the fundamental knowledge base on environmental topics. To be effective in this role, NSF's activities must complement and enhance, not duplicate or replace, the extant portfolio of Federal activities in this area.

Environmental sciences and engineering have matured significantly over the last decade. New knowledge and new technologies have combined to bring the environmental sciences to an unprecedented threshold of discovery and understanding. Although NSF already supports more environmental research and education than is generally realized, the Nation's need for fundamental environmental knowledge and understanding requires further attention. To expand and strengthen the Foundation's environmental portfolio, environmental activities within NSF must:

- be organized more effectively, and
- receive greater funding.

The growing frustration with the lack of adequate scientific information about environmental issues has led to a plethora of reports and suggestions. The majority of these focus on enhancing the disciplinary and interdisciplinary fundamental understanding of environmental systems and problems, improving the systematic acquisition of data, the analysis and synthesis of these data into useful information, and the dissemination of this information into understandable formats for multiple uses. A number of these reports and policy documents examined by the Board made specific recommendations regarding the level of funding required to meet the Nation's needs in these areas (see appendix B). The Board received additional testimony during the hearing process on the scale and scope of the needed investments. These substantial inputs—together with a thorough review of NSF's current investment—form the basis for the Board's budget recommendation.

Suggestions for Federal organizational changes have included the creation of a new Federal National Institute for the Environment, a strengthened interagency environmental committee that would involve NSF, an environmental institute within NSF, and a new directorate inside NSF. These suggestions have been tremendously helpful in promoting dialogue and raising awareness of the issues, and the Board considered these carefully in light of its immediate focus on environmental research, education, and scientific assessment within NSF. The suggestion of a new institute within NSF, for example, was deemed less desirable than a new mechanism that would simultaneously retain and strengthen existing disciplinary units but at the same time provide more effective integration, cooperation, visibility, and continuity across the Foundation.

Based on these reports and the broad input received by the task force, the Board identified the following characteristics as necessary for an effective organizational structure. NSF's environmental portfolio should be well-integrated, high priority, highly visible, cohesive, and sustained. It must work effectively with and enhance the current disciplinary structure and, simultaneously, provide more and more effective interdisciplinary efforts. Moreover, NSF's activities should continue to complement and enhance those of other Federal agencies. To this end, the Board made two overarching recommendations.

Keystone Recommendations

1 Resources and Funding

Environmental research, education, and scientific assessment should be one of NSF's highest priorities. The current environmental portfolio represents an expenditure of approximately $600 million per year. In view of the overwhelming importance of, and exciting opportunities for progress in, the environmental arena, and because existing resources are fully and appropriately utilized, new funding will be required. We recommend that support for environmental research, education, and scientific assessment at NSF be increased by an additional $1 billion, phased in over the next 5 years, to reach an annual expenditure of approximately $1.6 billion.

The Board expects NSF management and staff to develop budget requests and funding priorities for the coming years that are consistent with this and the following recommendations. It further expects that, consistent with its normal way of operating, NSF will involve the scientific community in identifying specific priority programmatic areas and in elaborating the specific recommendations below.

2 Organizational Approach

NSF management should develop an effective organizational approach that meets all of the criteria required to ensure a well-integrated, high-priority, high-visibility, cohesive, and sustained environmental portfolio within the Foundation. These criteria include:

- A high-visibility, NSF-wide organizational focal point with:
  - principal responsibility for identifying gaps, opportunities, and priorities, particularly in interdisciplinary areas;

- – budgetary authority for enabling integration across research, education, and scientific assessment, and across areas of inquiry;
- – responsibility for assembling and publicizing, within the context of the Foundation's normal reporting, a clear statement of NSF's environmental activities; and
- – a formal advisory process specifically for environmental activities.

- Continuity of funding opportunities, in particular in interdisciplinary areas.
- Integration, cooperation, and collaboration with and across established programmatic areas, within NSF and between NSF and other Federal agencies.

The Board acknowledges the attention and priority that the Foundation recently has placed on identifying possible new organizational structures. The Board further recognizes that it is a challenging task to satisfy all of the criteria specified in the organizational recommendation. At the same time, it stresses the importance of doing so in order to respond effectively to the unprecedented emphasis on integrative, sustained, interdisciplinary activities called for in this report.

Specific Findings and Recommendations

The above keystone recommendations are complemented by 10 more specific findings and recommendations. These are organized into three basic activity categories (research, education, and scientific assessment) and four crosscutting categories (physical infrastructure, technological infrastructure, information infrastructure, and partnerships).

Research

The fundamental understanding of environmental pattern and process requires analysis in balance with synthesis to provide a foundation of knowledge upon which paradigm development and predictive modeling can be based. As the field of environmental research has matured intellectually, its requirements for knowledge across all scientific, engineering, and mathematics disciplines have increased. The Board finds that meeting this challenge will require increasing disciplinary research efforts across all environmental areas.

The role of the research component of NSF's environmental portfolio is to foster discovery across the fields of science and engineering that seeks to elucidate environmental processes and interactions, thereby providing an integrated understanding of the natural status of, and the anthropogenic influences on, Earth's environment. Information and understanding from certain disciplines are especially relevant to environmental problems, but are often lacking. The Board finds that lack of knowledge in biological/ecological and social sciences and environmental technology is limiting. Specific research areas needing enhancement in the NSF environment portfolio include ecosystem services, integrated environmental systems, biosphere and society, and strategic environmental technologies (see table 4). Note that these specific areas do not represent a comprehensive list of all high-priority unmet research needs. Rather, they illustrate examples of exciting, emerging areas ripe for advance and immediately relevant to environmental needs that were identified repeatedly in the task force's inquiry.

Most environmental issues are interdisciplinary, and their drivers, indicators, and effects propagate across extended spatial and temporal scales. Increased resources are needed for interdisciplinary, long-term, large-scale, problem-based research and monitoring efforts. In addition, special mechanisms may be required to facilitate successful interdisciplinary programs. The current mechanism of establishing special competitions to address interdisci-

Table 4. Programmatic gaps or areas needing enhancement in the current NSF environment portfolio identified by the Board

Programmatic Area	*Description*
Ecosystem Services	The interface between ecology and economics, especially mechanisms for incorporating ecosystem services into market systems.
	Relationship between biological diversity, the area occupied by the ecosystem, and the delivery of critical services.
	Biogeochemical cycles.
	Discovery of unknown species, understanding their relationships to known organisms, and evaluation of their genetic and other potential for ecosystem functioning and services to humans.
Integrated Environmental Systems	Carbon cycle connections: terrestrial-atmospheric-oceanic. Emphasis to improve balance of knowledge among components.
	Coastal zone research and other interface areas: watersheds, coastal waters and estuaries, large rivers.
	Ecosystem experimentation and the systems theory/complexity theory interface.
	Spatially explicit studies of biogeochemistry, land cover, and land use.
	Ecology of infectious diseases.
	Integration of systematic biology with molecular and evolutionary approaches to improve predictive understanding of invasive species, human disease, and other areas.
	Climate and the hydrological cycle.
Biosphere and Society	Valuation and decision-making research on risk, existence values, ethics, and intergenerational tradeoffs of well-being.
	Historical ecology: e.g., tracing human-environment relations by integrating evidence from physical, biological, and social sciences and the humanities over space and time.
	Social ecology: e.g., studies of social, cultural, and economic processes, societal institutions, and public policies in relation to the environment and its spatial context.
	Research on the innovation process for environmentally benign materials, designs, and processes.
Strategic Environmental Technologies	Integration of classic environmental technologies with new capabilities in molecular biology, informatics, gene expression, robotics, observing capabilites, and other enabling technologies.
	Industrial ecology: e.g., materials flow accounting, scale issues research including the scale of human perturbations to natural material flows, studies of urbanization/ transportation and land use, and product/process life-cycle assessment research.
	Energy and environmental implications of emerging 21st century patterns: e.g., service economies, movement of certain production processes to lesser developed countries, and remanufacturing.

plinary needs is useful to initiate programs, but does not address the need to provide long-term stability of interdisciplinary efforts.

The Board acknowledges that the time scales of environmental phenomena are much longer than funding cycles and program durations. Long-term databases, observations, and experiments are necessary to provide understanding of many environmental problems, yet insufficient support exists for sustained research efforts.

3 Disciplinary Research

Environmental research within all relevant disciplines should be enhanced, with significant new investments in research critical to understanding biocomplexity, including the biological/ecological and social sciences and environmental technology.

4 Interdisciplinary Research

Interdisciplinary research requires significantly greater investment, more effective support mechanisms, and strengthened capabilities for identifying research needs, prioritizing across disciplines, and providing for their long-term support.

5 Long-Term Research

The Foundation should significantly increase its investments in existing long-term programs and establish new support mechanisms for additional long-term research.

Education

The twin goals of learning are to gain knowledge and to acquire skills such as problem solving, consensus building, information management, communication, and critical and creative thinking. Environmental issues offer excellent vehicles for developing and exercising many of these skills using a systems approach. Moreover, environmental education and training should be science based, but should be given a renewed focus on preparing students for broad career horizons; they should also integrate new technologies, especially information technologies, as much as possible. Finally, changes should be made in the formal educational system to help all students, educators, and education administrators learn about the environment, the economy, and social equity as they relate to all academic disciplines and their daily lives.

To this end, NSF should create educational and training opportunities that enhance scientific and technological capacity associated with the environment. These opportunities should be made available not only through formal education channels, but also through more informal education channels such as science centers, aquariums, and similar facilities; television and radio programs; web sites; and other learning foci that are attractive to the public. In this way, the agency can help enhance the public's ability to deal with complex information in the environmental area and encourage access to information on, and opportunities to learn and make informed decisions about, the environment as it relates to citizens' personal, work, and community lives.

6 Environmental Education The Foundation should encourage proposals that capitalize on student interest in environmental areas while supporting significantly more environmental education efforts through informal vehicles. All Foundation-supported education activities should at their core recognize potential and develop the capacity for excellence in all segments of society, regardless of whether they have been part of the scientific and engineering traditions.

Scientific assessment

Scientific assessment, as used here, is defined as inquiry-based synthesis, evaluation, and communication of understanding of relevant biological, socioeconomic, and physical environmental scientific information to provide an informed basis for (1) prioritizing scientific investments and (2) addressing environmental issues. The Board finds that NSF's role is to facilitate the development of methods and models of scientific assessment and foster scientific assessment, both domestically and internationally.

Research on how to do effective, credible, and helpful scientific assessments is timely. Approaches to scientific assessment need to be refined, standardized, and made more transferable between environmental issues. In addition, the Board finds that there is an identified need for a credible, unbiased approach to defining the status and trends, or trajectory, of environmental patterns and processes. The Board acknowledges the ongoing scientific assessment activities of other agencies, and urges that additional scientific assessment efforts by NSF complement present efforts.

7 Scientific Assessments The Foundation should significantly increase its research on the methods and models used in scientific assessment. In addition, NSF should, with due cognizance of the activities of other agencies, enable an increased portfolio of scientific assessments for the purpose of prioritizing research investments and for synthesizing scientific knowledge in a fashion useful for policy- and decision-making.

Physical infrastructure

Environmental research depends heavily on effective physical infrastructure. Environmental observatories, ranging from telescopes to undersea platforms to LTER sites are complemented by high-speed communications links, powerful computers, and well-constructed databases. Another category of physical infrastructure is natural history collections that provide a baseline against which to measure environmental change and provide essential resources for biology and biotechnology. Finally, centers—both traditional and virtual—are magnets for interdisciplinary teams that can address problem-focused issues and complement the types of activities that individual investigators perform. Consequently, NSF must foster the development of facilities, instrumentation, and other infrastructure that enable discovery, including the study of processes and interactions that occur over long time scales.

The physical and virtual infrastructure required for an effective environmental program should be enhanced. Some of this enhancement can be done in partnership with other agencies; some is primarily NSF's responsibility. In addition to traditional areas of physical infrastructure, more attention is needed to informatics, web accessibility of data sets, and maintenance of natural history specimens (extracted genetic, living, and preserved) to ensure that researchers and educators can leverage past and future investments.

8
Enabling Infrastructure

NSF should give high priority to enhancing infrastructure for environmental observations and collections as well as new information networking capacity. The agency should create a suite of environmental research and education hubs, on the scale of present Science and Technology Centers and Engineering Research Centers, that might include physical and/or virtual centers, site-focused and/or problem-focused collaboratories, and additional environmental information synthesis and forecasting centers.

Technological Infrastructure

The Board finds that a critical NSF role is to foster research that seeks to develop innovative technologies and approaches that help the Nation conserve its environmental assets and services.

The convergence of 21st century science and technology with emerging paradigms of ecological understanding provides an unprecedented opportunity. Wholly new fields of inquiry and analysis that address complex ecosystem processes and resource stewardship have emerged in just the past few years. The Board finds that the thoughtfully planned integration of these sciences offers great promise for accelerating fundamental understanding of environmental principles and injecting contemporary science and technology into the study and management of ecological systems. Table 5 presents examples of technologies with promise for environmental research.

Table 5. Examples of technologies with promise for environmental research

Technology	*Description*
Genome sequencing and derivative technologies	DNA chips and other new biotechnologies to increase understanding of how biological processes are controlled by genetic limitations and environmental variables; design principles borrowed from biological systems to guide biocatalysis and bioremediation
Networked observational systems	Data provided by robust sensors, autonomous ecological monitoring devices, biochemical tracers, and satellite-based imaging of landscapes and bodies of water are networked for better integrated and more accessible information
Smart technology	New molecular design methods and smart technology can lead to environmentally benign materials, device miniaturization, and advanced processing methods
Software and statistics	New software for computational analysis, modeling, and simulation combined with new statistical approaches to provide a better basis for comparison of patterns emerging from data at different levels of detail

NSF can play an important role in facilitating innovation and stimulating a shift from relatively small incremental advances to bold technological transformation in response to environmental problems. The Foundation should facilitate an effort to identify technologies that represent order-of-magnitude improvements over existing environmental technologies, and—in cooperation with other Federal agencies, the academic community, and the private sector—support the scientific and engineering research needed to underpin these technologies.

9 Environmental Technology

The Foundation should vigorously support research on environmental technologies, including those that can help both public and private sectors avoid environmental harm and permit wise utilization of natural resources.

10 Enabling Technologies

The Foundation should enable and encourage the use of new and appropriate technologies in environmental research and education.

Information infrastructure

Lack of knowledge and poor communication of existing information constrain both the progress of discovery and the processes of society. As good stewardship of environmental systems becomes increasingly vital, the need for ease of analysis and synthesis of information about them will become ever more important. NSF should, in partnership with other Federal agencies, stimulate the development of mechanisms and infrastructure to synthesize and aggregate scientific environmental information and make it more accessible to the public. A coordinated electronic network linking distributed information and databases at all levels is vital; this network must ensure efficient and effective information access by and transfer to the public.

The state of environmental monitoring is imperfect; even the data that exist are not routinely checked for comparability and quality, nor are they made conveniently available for analysis in the way in which labor statistics, for example, are managed by the Bureau of Labor Statistics. A central source of comparable, quality-controlled time-series measurements of the environment is needed.

11 Environmental Information

The Foundation should take the lead in enabling a coordinated, digital, environmental information network. In addition, NSF should catalyze a study to frame a central source that compiles comparable, quality-controlled time-series measurements of the state of the environment.

Partnerships, Coordination, and Collaborations

Collaborations and partnerships are essential to high-priority environmental research, education, and scientific assessment efforts. Furthermore, collaborations are most effective when they are based on intellectual needs. The collective results should be greater than what could have been achieved independently. Partnerships among federal agencies, with nongovernmental bodies (e.g., private sector entities, NGOs, and others), and with international organizations can provide the intellectual and financial leveraging to address environmental questions at the local, regional, and international levels.

Within the Federal Government, many mission agencies conduct research, education, and assessment activities in the environmental arena. There are thus many opportunities to partner in bilateral agreements or via National Science and Technology Council science and engineering initiatives. In addition to bridging common interests and objectives, partnerships should provide for more effective coordination of complementary expertise and experience, and broadening of perspectives among participants. The Board endorses strong NSF participation in the NSTC coordinating mechanism.

On the international front, many of NSF's environmental research collaborations address fundamental scientific questions at the root of current environmental issues (e.g., the role the equatorial ocean plays in controlling the timing and magnitude of El Niño) and reflect the drive to develop an international scientific consensus for consideration by policy-makers (e.g., the scientific basis for the depletion of stratospheric ozone and the international policies within the Montreal Protocol). Just as research informs the policy dialogue within the United States, so research in which national policy-makers have confidence undergirds international policy negotiations. By collaborating with scientists from around the world—including those in countries with limited means—NSF-funded projects help expand the knowledge base needed for scientific consensus.

The most effective partnerships involve the evolution of trust among participants, strategic thinking processes to identify and evaluate common interests and objectives, and relatively simple, flexible administrative arrangements. They also require sufficient staff, resources, and time to mature.

12 Implementation Partnerships

NSF should actively seek and provide stable support for research, education, and assessment partnerships that correspond to the location, scale, and nature of the environmental issues. Such partnerships and interagency coordination should include both domestic and international collaborations that foster joint implementation including joint financing when appropriate. This report clearly establishes the need for an expanded national portfolio of environmental R&D. Therefore, the Board suggests that NSTC, with advice from the President's Committee of Advisors on Science and Technology, reevaluate the national environmental R&D portfolio, including identification of research gaps and setting of priorities, and the respective roles of different Federal agencies in fundamental environmental research, education, and scientific assessment.

Chapter 6

Conclusion

Scientific understanding of the environment, together with an informed, scientifically literate citizenry, are requisite to improved quality of life for generations to come. As the interdependencies of fundamental and applied environmental research become more evident, NSF should capitalize on the momentum gained in its past support for premium scholarship and emerging new research areas and technologies. The time is ripe to accelerate progress.

This report provides guidance at the policy level for NSF. The 2 overarching and 10 topical recommendations frame a timely agenda for the Foundation's research, education, and scientific assessment activities. Fleshing out the specific new agendas will require intense effort by NSF staff, close coordination and communication with sister agencies and the Office of Science and Technology Policy, and vigorous participation by the scientific community. The Board eagerly awaits the construction of this new portfolio.

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APPENDIX A

CHARGE TO TASK FORCE ON THE ENVIRONMENT

NSB-98-161
August 12, 1998
revised

CHARGE
COMMITTEE ON PROGRAMS AND PLANS
TASK FORCE ON THE ENVIRONMENT

On March 19, 1998, the National Science Board approved a resolution (NSB-98-65) in which it noted the need for expanded environmental research, education, and assessment. The resolution stated that NSF has a legitimate role in these activities, and that this role can be exercised most constructively in the context of a strategy coordinated by the White House agencies and the National Science and Technology Council (NSTC).

The Task Force on the Environment is established to assist the Foundation in defining the scope of its role with respect to environmental research, education, and assessment, and in determining the best means of implementing activities related to this area. The task force will report to the Committee on Programs and Plans (CPP) and will consist of Dr. Jane Lubchenco, Chair, Dr. Mary K. Gaillard, Dr. Solow, and Dr. Warren Washington, and will also include Dr. Mary Clutter, Assistant Director for Biological Sciences and Dr. Robert Corell, Assistant Director for Geosciences. Dr. John Hopcroft, NSB consultant, will serve as consultant to the task force.

The Task Force will:

Review the scope of current NSF activities related to research, education, and assessment on the environment;

Develop guidance for the National Science Foundation at the policy level that will be used for designing an appropriate portfolio of activities, consistent with the overall NSTC strategy, the goals of the NSF Strategic Plan, and activities of other agencies and organizations that support related programs; and

Complete a report, with final recommendations, to be submitted to the Board no later than its May 5–7, 1999 meeting.

Eamon M. Kelly
Chairman

Appendix B

Literature Compiled and Considered by the Board

The literature list illustrates the broad range of environmental concerns considered by the Board. Works are listed alphabetically by title, beginning with the most recent publications. Where available, the initiator/sponsor and publication information is provided to assist in locating the document. Although all documents are in the public domain, convenient access varies. The number of references on a particular issue should not be interpreted as a measure of the Board's priority for that issue.

	Title	*Date*	*Initiator/Sponsor*	*Publication Information*
1	Benefits of Biodiversity	1999	Council for Agricultural Science and Technology, Ames, IA	http://www.cast-science.org
2	Bioinformatics in the 21st Century	1999	NSTC: Committee on Science: Subcommittee on Biotechnology: Research Resources and Infrastructure Working Group	Krasnow Institute for Advanced Study, George Mason University, Fairfax, VA
3	Bioregional Assessments: Science at the Crossroads of Management Policy	1999		K. N. Johnson, F. Swanson, M. Herring, and S. Greene, Washington, DC: Island Press
4	Designing a Report on the State of the Nation's Ecosystems	1999	Initiated by the Heinz Center. Multiple Federal and private sponsors	The H. John Heinz III Center, Washington, DC; http://www.us-ecosystems.org/
5	Discounting and Intergenerational Equity	1999		P.R. Portney and J.P. Weyant, Washington, DC: Resources for the Future
6	Ecological Risk Assessment in the Federal Government	1999	NSTC: CENR	CENR/5-99/001
7	Environmental Engineering and Science Research Frontiers	1999	Association of Environmental Engineering and Science Professors; NSF; and The Pennsylvania State University	B.E. Logan and F.S. Cannon, eds., University Park, PA: Association of Environmental Engineering Professors

	Title	*Date*	*Initiator/Sponsor*	*Publication Information*
8	Evolution, Science, and Society: Evolutionary Biology and the National Research Agenda	1999	A.P. Sloan Foundation and NSF	Thomas R. Meagher, Rutgers, The State University of New Jersey; http://www.amnat.org/
9	Fragile Dominion, Complexity and the Commons	1999		Simon A. Levin, Cambridge: Perseus Publishing
10	Global Environmental Change: Research Pathways for the Next Decade	1999	NRC: Board on Sustainable Development	Washington, DC: National Academy Press
11	Hormonally Active Agents in the Environment	1999	NRC: Commission on Life Sciences: Board on Environmental Studies and Toxicology	Washington, DC: National Academy Press
12	Nature's Numbers	1999	NRC: Commission on Behavioral and Social Sciences and Education: Committee on National Statistics: Panel on Integrated Environmental and Economic Accounting	W.D. Nordhaus and E.C. Kokkelenberg, eds., Washington, DC: National Academy Press
13	Our Common Journey: A Transition Toward Sustainability	1999	NRC: Board on Sustainable Development	Washington, DC: National Academy Press
14	Preparing Our Children: Math and Science Education in the National Interest	1999	NSB	NSB 99-31; http://www.nsf.gov/pubs/1999/nsb9931/start.htm
15	Sharing the Fish, Toward a National Policy on Individual Fishing Quotas	1999	NRC: Commission on Geosciences, Environment and Resources: Ocean Studies Board	Washington, DC: National Academy Press
16	Sustaining Marine Fisheries	1999	NRC: Commission on Geosciences, Environment and Resources: Ocean Studies Board	Washington, DC: National Academy Press
17	Technology Forces at Work: Profiles of Environmental Research and Development at DuPont, Intel, Monsanto, and Xerox	1999	OSTP and RAND Science and Technology Policy Institute	S. Resetar, B. Lachman, R. Lempert, and M. Pinto; RAND, Science and Technology Policy Institute; #MR-1068-OSTP; http://www.rand.org/publications/MR/MR1068/
18	Toward Environmental Justice: Research, Education and Health Policy Needs	1999	IOM: Committee on Environmental Justice	Washington, DC: National Academy Press

	Title	Date	Initiator/Sponsor	Publication Information
19	Towards a Sustainable America: Advancing Prosperity, Opportunity and a Healthy Environment for the 21st Century	1999	President's Council on Sustainable Development	http://www.whitehouse.gov/PCSD
20	Air Quality Research Subcommittee Strategic Plan	1998	NSTC: CENR	CENR Executive Secretariat, 202-482-5916
21	Basic Research Needs to Achieve Sustainability: The Carbon Problem	1998	NSF and DOE	P. Eisenberger, Columbia University, and M. Knotek, DOE, Conference organizers; conference held October 22-24, 1998 in Tucson, AZ
22	Community-Based Research in the United States	1998	The Loka Institute	R.E. Sclove, M.L. Scammell, and B. Holland; http://www.loka.org/crn/pubs/comreprt.htm
23	Consilience: The Unity of Knowledge	1998		Edward O. Wilson, New York: Alfred A. Knopf, Inc.
24	Endocrine Disruptors: Research Needs and Priorities	1998	NSTC: CENR	CENR Executive Secretariat, 202-482-5916
25	Enhancing Integrated Science	1998	Ecological Society of America; Geological Society of America; U.S. Geological Survey	Report of USGS Workshop; http://www.usgs.gov/integrated_science/
26	Entering the Century of the Environment: A New Social Contract for Science	1998		J. Lubchenco, Science 279:491
27	Excellence in Ecology: The Globalization of Ecological Thought	1998		O. Kinne, Germany: Ecology Institute
28	Federal Funds for Research and Development: FY 1996, 1997, and 1998	1998	NSF: Division of Science Resources Studies	NSF 97-335, Arlington, VA
29	Food Safety, Sufficiency, and Security	1998	Council for Agricultural Science and Technology	http://www.cast-science.org/
30	Foodborne Pathogens: Review of Recommendations	1998	Council for Agricultural Science and Technology	http://www.cast-science.org/
31	Future of Ocean Chemistry in the U.S. (FOCUS)	1998	NSF	Workshop report; http://www.joss.ucar.edu/joss_psg/project/oce_workshop/focus/

	Title	*Date*	*Initiator/Sponsor*	*Publication Information*
32	Future of Physical Oceanography (APROPOS)	1998	NSF	Workshop report; http://www.joss.ucar.edu/joss_psg/project/oce_workshop/apropos/
33	Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB)	1998	Intergovernmental Oceanographic Commission: Scientific Committee on Oceanic Research	Workshop report; http://www.phys.ocean.dal.ca/~jhurst/SCOR/GEOHAB/GEOHAB.html
34	Global Environmental Change: Research Pathways for the Next Decade	1998	NRC: Policy Division: Board on Sustainable Development: Committee on Global Change Research	Washington, DC: National Academy Press
35	Global Ocean Observing System (GOOS): Prospectus 1998	1998	UNESCO: Joint Scientific and Technical Committee for the Global Ocean Observing System	Paris: Intergovernmental Oceanographic Commission; ISBN 0-904175-39-1; 168 pp.
36	Hydrologic Sciences: Taking Stock and Looking Ahead	1998	NRC: Commission on Geosciences, Environment, and Resources: Water Science and Technology Board	Washington, DC: National Academy Press; 138 pp.
37	International Environmental Law and Policy	1998	University Casebook Series	D. Hunter, J. Salzman, and D. Zaelke, New York: Foundation Press
38	Is Coastal Eutrophication out of Control?	1998		J. Pelly, Environmental Science & Technology 3(10):462-66
39	Linking Industrial Ecology to Public Policy: Report of a Workshop	1998	NSF	C. Andrews, D. Rejeski, R. Socolow, and V. Thomas, RU/EJBS Working Paper 4; http://policy.rutgers.edu/projects/ie.htm
40	Major U.S. Oceanographic Research Programs: Impacts, Legacies and the Future	1998	Marine Technology Society	Marine Technology Society Journal 32(3)
41	Monitoring for Fine Particulate Matter	1998	OSTP and RAND: CTI	Elisa Eiseman, Santa Monica: Critical Technologies Institute, RAND
42	Ocean Ecology: Understanding and Vision for Research (OEUVRE)	1998	NSF	Workshop report; http://www.joss.ucar.edu/joss_psg/project/oce_workshop/oeuvre/report/
43	Opportunities in Ocean Sciences: Challenges on the Horizon	1998	NRC: Ocean Studies Board (Kenneth Brink, Chair)	Washington, DC: National Academy Press

	Title	*Date*	*Initiator/Sponsor*	*Publication Information*
44	Our Changing Planet: The FY 1999 U.S. Global Change Research Program	1998	NSTC: CENR: Subcommittee on Global Change Research	Washington, DC: OSTP; 130 pp.
45	Park Science: Integrating Research & Resource Management	1998	DOI: National Park Service	http://www.nature.nps.gov/parksci/
46	Program Guide to Federally Funded Environment and Natural Resources R&D	1998	NSTC: CENR	CENR Executive Secretariat, 202-482-5916 U.S. GPO
47	Protecting Our Planet, Securing Our Future: Linkages Among Global Environmental Issues and Human Needs	1998	UNEP; NASA; and the World Bank	Robert Watson et al.; UNEP
48	Report of U.S. Southern Ocean GLOBEC Planning Workshop	1998	NSF	Workshop report; http://www.ccpo.odu.edu/Research/globec/dcmeeting/dcrept.html
49	Research Frontiers in Environmental Engineering	1998	NSF and Association of Environmental Engineering Professors	B.E. Logan, C.R. O'Melia, and B.E. Rittman, eds., Monterey, CA: Association of Environmental Engineering Professors
50	Russian-American Initiative on Shelf-Land Environments in the Arctic (RAISE) Program Plan	1998	Arctic Research Consortium of the U.S.	http://www.arcus.org/Publications/index.html
51	Strategic Directions for the U.S. Geological Survey Ground-water Resources Program	1998	USGS	A Report to Congress; http://water.usgs.gov/ogw/gwrp/stratdir/
52	Successes, Limitations, and Frontiers in Ecosystem Science	1998		M.L. Pace and P.M. Groffman, eds., New York: Springer-Verlag; 499 pp.
53	Teaming With Life: Investing in Science to Understand and Use America's Living Capital	1998	PCAST: Panel on Biodiversity and Ecosystems	http://www.whitehouse.gov/WH/EOP/OSTP/html/OSTP_Home.html
54	The Atmospheric Sciences: Entering the Twenty-first Century	1998	NRC: Board on Atmospheric Sciences and Climate (John Dutton, Chair)	http://www.nap.edu/books/0309064155/html/R1.html
55	The Global Observing Systems	1998	ICSU	http://www.icsu.org/

	Title	*Date*	*Initiator/Sponsor*	*Publication Information*
56	The National Report Card on Environmental Knowledge, Attitudes and Behaviors: The Seventh Annual Survey of Adult Americans	1998	National Environment Education & Training Foundation and Roper Starch Worldwide	http://www.neetf.org/
57	The OECD Megascience Forum: Workshop on Global-scale Issues	1998	OECD	Summary of workshop held March 4-6, 1998, in Sweden; http://www.oecd.org/
58	The Regional Impacts of Climate Change: An Assessment of Vulnerability	1998	WMO and UNEP: IPCC	R.T. Watson, M.C. Zinyowere, and R.H. Moss, eds., Cambridge University Press
59	The TOGA Decade: Reviewing the Progress of El Niño Research and Prediction	1998	American Geophysical Union	D.L.T. Anderson, E.S. Sarachik, and P.J. Webster, eds., Washington, DC: American Geophysical Union, Journal of Geophysical Research
60	Toward Prediction of the Arctic System: Predicting States of the Arctic System on Seasonal-to-Century Time Scales by Integrating Observations, Process Research, Modeling, and Assessment	1998	Arctic Research Consortium of the U.S.	http://www.arcus.org/Publications/index.html
61	Unlocking Our Future: Toward a New National Science Policy ("Ehlers Report")	1998	U.S. House of Representatives: Committee on Science	Report to Congress; http://www.house.gov/science/science_policy_study.htm
62	Visions for Natural Resource Education and Ecosystem Science for the 21st Century	1998	Northwest Center for Sustainable Resources; Chemeketa Community College, Salem, OR	Interim unpublished report
63	Weaving a Web of Wealth: Biological Informatics for Industry, Science, and Health	1998	Australian Academy of Science	GPO Box 783, Canberra ACT 2601; ISBN 0 85847 2147
64	Year of the Ocean: Discussion Papers	1998	U.S. Federal agencies with ocean-related programs	NOAA: Office of the Chief Scientist (W.S. Wilson, Coordinator)
65	A Research Programme on Climate Variability and Predictability for the 21st Century (CLIVAR)	1997	ICSU: World Climate Research Programme (H. Grassl, Director)	World Climate Research Programme No. 101, WMO/TD No. 853, ICPO No.10

	Title	Date	Initiator/Sponsor	Publication Information
66	Arctic Pollution Issues: A State of the Arctic Environment Report	1997	Arctic Monitoring and Assessment Programme	http://www.grida.no/amap/
67	Atmospheric Nitrogen Deposition to Coastal Wetlands	1997	Ecological Society of America: Sustainable Biosphere Initiative	Workshop report; http://esa.sdsc.edu/sbindep1.htm
68	Building a Foundation for Sound Environmental Decisions	1997	NRC	Washington, DC: National Academy Press
69	Climate Change: State of Knowledge	1997	OSTP	http://www.whitehouse.gov/WH/EOP/OSTP/html/OSTP_Home.html
70	Climate, Ecology, and Human Health	1997	NOAA; NASA; and NSF	Paul R. Epstein, Consequences 3(2); http://www.gcrio.org/CONSEQUENCES/introCON.html
71	Contribution of Animal Products to Healthful Diets	1997	Council for Agricultural Science and Technology	http://www.cast-science.org/
72	Cooperative Ecosystem Studies Units: Concept Paper	1997	Cooperative Ecosystem Studies Units: Implementation Working Group	Gary Machlis, Chair
73	Critical Issues in K-12 Environmental Education	1997	Morgan State University: EPA Teacher Institute	Unpublished workshop report, July 11, 1997
74	East Central Europe: An Environment in Transition	1997		J.L. Schnoor, J.N. Galloway, and B. Moldan, Environmental Science & Technology 31(9):412-416
75	Environmentally Significant Consumption: Research Directions	1997	NRC: Committee on the Human Dimensions of Global Change	P.C. Stern, T. Dietz, V.W. Ruttan, R.H. Socolow, and J.L. Sweeney, eds., Washington, DC: National Academy Press
76	Federal Energy Research and Development for the Challenges of the 21st Century	1997	PCAST	OSTP; http://www.whitehouse.gov/WH/EOP/OSTP/html/OSTP_Home.html
77	Federal Environmental Research and Development: Status Report With Recommendations	1997	Carnegie Commission on Science, Technology, and Government (David Z. Robinson, Task Force Chair)	Carnegie Commission on Science, Technology and Government, Memorandum Author: Dan Sarewitz. Washington, DC; 25 pp.

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78	From Classroom to Community and Beyond: Educating for a Sustainable Future	1997	President's Council on Sustainable Development: Public Linkage, Dialogue, and Education Task Force	http://www.whitehouse.gov/PCSD
79	Fuels Decarbonization and Carbon Sequestration: Report of a Workshop	1997	DOE	Robert Socolow, ed., Report No. 302; Princeton: Center for Energy & Environmental Studies, Princeton University; http://www.princeton.edu/~ceesdoe/
80	Global Ocean Ecosystem Dynamics (GLOBEC) Science Plan	1997	ICSU: Scientific Committee on Oceanic Research	The International Geosphere-Biosphere Programme Report 40; B.J. Rothschild, Chair
81	Human Alteration of the Global Nitrogen Cycle: Causes and Consequences	1997	Ecological Society of America	Issues in Ecology, No. 1 (Spring); http://www.sdsc.edu/~ESA/
82	Integrating the Nation's Environmental Monitoring and Research Networks and Programs: A Proposed Framework	1997	NSTC: CENR: Environmental Monitoring Team (M. Ruggiero and D. Scavia, Team Leaders)	CENR Executive Secretariat, 202-482-5916
83	Lessons From the Montreal Protocol	1997	Environment Canada	Colloquium findings; http://www.ec.gc.ca/ozone/tenthann/coll_e.htm
84	Linking Sustainable Community Activities to Pollution Prevention: A Sourcebook	1997	OSTP and RAND: CTI	Beth E. Lachman, Critical Technologies Institute, RAND
85	Modeling the Arctic System	1997	Arctic Research Consortium of the U.S.	http://www.arcus.org/Publications/index.html
86	Nature's Services: Societal Dependence on Natural Ecosystems	1997		Gretchen C. Daily, Washington, DC: Island Press
87	Organizing for Research and Development in the 21st Century	1997	NSF and DOE	P.M. Eisenberger, A.R. Faust, and M. Knotek, eds., Princeton: Princeton Materials Institute, Princeton University. http://pmi.princeton.edu/
88	Our Changing Climate	1997	NOAA and UCAR	Reports to the Nation, NOAA Office of Global Programs and UCAR

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89	People and the Arctic: A Prospectus for Research on the Human Dimensions of the Arctic System	1997	Arctic Research Consortium of the U.S.	http://www.arcus.org/Publications/index.html
90	Science & Engineering Degrees 1966-1995	1997	NSF: Division of Science Resources Studies	NSF 97-335, Arlington, VA; http://www.nsf.gov/sbe/srs/nsf97335/start.htm
91	Science and Technology Shaping the Twenty-first Century	1997	OSTP	Report to Congress; http://www.whitehouse.gov/WH/EOP/OSTP/html/OSTP_Home.html
92	The Global Ocean Observing System: Users, Benefits, and Priorities	1997	NRC: Ocean Studies Board	Washington, DC: National Academy Press
93	The Microbial World: Foundation of the Biosphere	1997	NSF; NOAA; DOE; and American Society for Microbiology	Colloquium report of the American Academy of Microbiology; J.T. Staley, R.W. Castenholz, R.R. Colwell, J.G. Holt, M.D. Kane, N.R. Pace, A.A. Salyers, and J.M. Tiedje; 32 pp.
94	Valuing Ground Water: Economic Concepts and Approaches	1997	NRC: Commission on Geosciences, Environment, and Water (L.W. Canter, Chair)	Washington, DC: National Academy Press
95	A Geography of Hope: America's Private Land	1996	USDA: Natural Resources Conservation Service	USDA Program Aid 1548 (C. Cox and M. Schnepf, Project Managers)
96	A Plan for a Research Program on Aerosol Radiative Forcing and Climate Change	1996	NRC: Board on Atmospheric Sciences and Climate	Washington, DC: National Academy Press
97	An International Programme of Biodiversity Science: Operational Plan	1996	DIVERSITAS	http://www.icsu.org/DIVERSITAS/Plan/index.html
98	Climate Change and Human Health	1996	WHO; WMO; and UNEP	A.J. McMichael, A. Haines, R. Sloof, and S. Kovats, Geneva
99	Common Future for Long-Term Ecological Research, Land Margin Ecosystem Research and Joint Global Ocean Flux Study	1996	NSF	Workshop report; http://atlantic.evsc.virginia.edu/~bph/LTER_LMER/NSFreport.html
100	Ecological Resource Monitoring: Change and Trend Detection	1996	Ecological Society of America: Sustainable Biosphere Initiative	Workshop report; http://esa.sdsc.edu/sbi_bull8.htm

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101	Ecologically Based Pest Management, New Solutions for a New Century	1996	NRC: Board on Agriculture: Committee on Pest and Pathogen Control Through Management of Biological Control Agents and Enhanced Cycles and Natural Processes	Washington, DC: National Academy Press; 144 pp.
102	Freshwater Ecosystems: Revitalizing Educational Programs in Limnology ("Brezonik Report")	1996	NRC: Commission on Geosciences, Environment, and Resources: Water Science and Technology Board: Committee on Inland Aquatic Ecosystems (P. Brezonik, Chair)	Washington, DC: National Academy Press; 364 pp.
103	Frontiers of Illusion, Science, Technology, and the Politics of Progress	1996		Daniel Sarewitz, Philadelphia: Temple University Press
104	FUMAGES: Future of Marine Geology and Geophysics	1996	NSF and ONR: Coastal Dynamics Program	Workshop report (P. Baker and M. McNutt, compilers); http://www.joss.ucar.edu/joss_psg/project/oce_workshop/fumages/
105	Functional Roles of Biodiversity: A Global Perspective. SCOPE 55	1996	SCOPE	H.A. Mooney, J.H. Cushman, E. Medina, O.E. Sala, and E-D Schulze, Chichester: John Wiley
106	Global Change and Terrestrial Ecosystems	1996	International Geosphere-Biosphere Programme and ICSU	B. Walker and W. Steffen, UK: Cambridge University Press
107	Global Change: Effects on Coniferous Forests and Grasslands. SCOPE 56	1996	SCOPE	A.I. Breymeyer, D.O. Hall, J.M. Melillo, and G.I. Agren, Chichester: John Wiley
108	Global Climate Change & Sustainability: Enhancing the Policy/Science Dialogue	1996	Dutch & U.S. Governments	Proceedings of the 27th International Conference of the International Simulation & Gaming Association; J.H.G. Klabbers, C. Bernabo, B. Moomaw, T. Carter, S.P. Hammond, and M. Hisschemoller
109	Grazing on Public Lands	1996	Council for Agricultural Science and Technology	http://www.cast-science.org/
110	Integrated Animal Waste Management	1996	Council for Agricultural Science and Technology	http://www.cast-science.org/

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111	Linking Science & Technology to Society's Environmental Goals ("Ahearne-Stever Report")	1996	NRC: Policy Division: Committee on the National Forum on Science and Technology Goals: Environment	Washington, DC: National Academy Press; 530 pp.
112	National Acid Precipitation Assessment Program (NAPAP)	1996	NAPAP	Report to Congress, Washington, DC: U.S. GPO
113	Natural Disaster Reduction: A Plan for the Nation	1996	NSTC: CENR: Subcommittee on Natural Disaster Reduction	CENR Executive Secretariat, 202-482-5916
114	Nitrogen Cycling in the North Atlantic Ocean and Its Watersheds	1996	SCOPE	Robert W. Howarth, Netherlands: Kluwer Academic Publishers
115	Nuclear Science: A Long Range Plan	1996	DOE/NSF Nuclear Science Advisory Committee	http://pubweb.bnl.gov/~nsac/
116	Oceans 2000: Bridging the Millennia: Partnerships for Stakeholders in the Oceans	1996	Consortium for Oceanographic Research and Education (CORE)	Interagency Partnership Initiative, CORE, 1755 Massachusetts Avenue, NW, Suite 800, Washington, DC 20036-2102; core@brook.edu
117	Particle Flux in the Ocean. SCOPE 57	1996	SCOPE	V. Ittekkot, P. Schafer, S. Honjo, and P.J. Depetris, Chichester: John Wiley
118	Sustainable America: A New Consensus for Prosperity, Opportunity, and a Healthy Environment for the Future	1996	President's Council on Sustainable Development	D.T. Buzzelli and J. Lash, Co-chairs; Washington, DC: U.S. GPO; ISBN 0-16-048529-0
119	The MATE Forum: Critical Issues in Marine Advanced Technology Education	1996		MATE Center, Monterey Peninsula College, 980 Fremont Street, Monterey, CA 93940; 831-645-1393; info@marinetech.org
120	U.S. GLOBEC Northeast Pacific Implementation Plan	1996	NSF	http://cbl.umces.edu/fogarty/usglobec/reports/rep17/nepip.contents.html
121	Understanding Our Planet	1996	ICSU	http://www.icsu.org/
122	Upstream: Salmon and Society in the Pacific Northwest	1996	NRC: Board on Environmental Science and Technology	Washington, DC: National Academy Press
123	Vision to 2001: Science and Technology for Canada's Future	1996	National Research Council Canada	http://www.nrc.ca/corporate/english/tools/nrcvise.pdf

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124	Wetland and Aquatic Ecosystem Research: Science Plan	1996	European Commission: Directorate General XII: Science, Research & Development	Workshop report: EUR 17452; H.J. Laanbroek, E. Maltby, P. Whitehead, B. Faafeng, H. Barth, eds.
125	When We Don't Know the Costs or the Benefits: Adaptive Strategies for Abating Climate Change	1996		R.J. Lempert, M.E. Schlesinger, and S.C. Bankes, Climactic Change 33:235-74
126	Allocating Federal Funds for Science and Technology	1995	National Academy of Sciences; National Academy of Engineering; IOM; NRC: Committee on Criteria for Federal Support of Research and Development	Washington, DC: National Academy Press; 97 pp.
127	Arctic Ocean Research and Supporting Facilities: National Needs and Goals	1995	NRC: Ocean Studies Board	Washington, DC: National Academy Press
128	Basic Research Needs for Vehicles of the Future	1995	NSF; DOE; Chrysler; Ford; and GM	P.M. Eisenberger, ed., Princeton: Princeton Materials Institute, Princeton University; http://pmi.princeton.edu/
129	Beyond the Horizon: Using Foresight to Protect the Environmental Future	1995	EPA Science Advisory Board: Environmental Futures Committee	EPA-SAB-EC-95-007, Washington, DC
130	Biotechnology for the 21st Century: New Horizons	1995	NSTC: Committee on Fundamental Science: Biotechnology Research Subcommittee	Washington, DC: OSTP; 89 pp.
131	Bridge to a Sustainable Future	1995	NSTC	Washington, DC: U.S. GPO; 87 pp.
132	Building a Scientific Basis to Ensure the Vitality and Productivity of U.S. Ecosystems	1995	NSTC: CENR: Ecosystem Working Group	http://www.cop.noaa.gov/pubs/ewgfn2.txt
133	Ecology and Oceanography of Harmful Algal Blooms (ECOHAB): A National Research Agenda	1995	NSF and NOAA	Workshop report; Woods Hole Oceanographic Institution
134	Enhancing the Effectiveness of Research to Assist International Climate Change Policy Development	1995	Dutch National Research Programme on Global Air Pollution and Climate Change	C. Bernabo, M. Hisschemoller, and J. Klabbers, Report No. 410 100 090, NRP Programme Office

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135	Extinction Rates	1995		J.H. Lawton and R.M. May, Oxford, UK: Oxford University Press
136	Global Biodiversity Assessment	1995	UNEP	V.H. Heywood and R.T. Watson, UK: Cambridge University Press
137	Islands, Biological Diversity and Ecosystem Function	1995	SCOPE	P.M. Vitousek, L.L. Loope, and H. Adsersen, Berlin: Springer Verlag
138	Managing Global Genetic Resources (4 vols.)	1995	National Academy of Sciences	Washington, DC: National Academy Press
139	Methods to Assess the Effects of Chemicals on Ecosystems. SCOPE 53	1995	SCOPE	R.A. Linthurst, P. Bourdeau, and R.G. Tardiff, Chichester: John Wiley
140	Microbial Diversity and Ecosystem Function	1995	UNEP (sponsor) and other international organizations	D. Allsopp, R.R. Colwell, and D.L. Hawksworth, UK: CAB International
141	Molecular Biology in Marine Science: Scientific Questions, Technological Approaches, and Practical Implications	1995	NRC: Ocean Studies Board	Washington, DC: National Academy Press
142	NSF in a Changing World: The National Science Foundation's Strategic Plan	1995	NSF	NSF 95-24, Arlington, VA. http://www.nsf.gov/cgi-bin/getpub?nsf9524
143	Partnering to Build a Quality Workforce: Critical Issues in Environmental Technology Education at Two-Year Colleges	1995	NSF	Report on national forum; http://ateec.eiccd.cc.ia.us/ci1.html
144	Phosphorus in the Global Environment. SCOPE 54	1995	SCOPE	Holm Tiessen, Chichester: John Wiley
145	Preparing for the Future Through Science and Technology: An Agenda for Environmental and Natural Resources Research	1995	NSTC: CENR	CENR Executive Secretariat, 202-482-5916
146	Priorities for Coastal Ecosystem Science	1995	NRC: Ocean Studies Board	Washington, DC: National Academy Press

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147	Research Restructuring and Assessment: Can We Apply the Corporate Experience to Government Agencies?	1995	NRC: Commission on Physical Sciences, Mathematics and Applications	Workshop report; Washington, DC: National Academy Press
148	Science and the Endangered Species Act	1995	NRC: Board on Environmental Science and Technology	Washington, DC: National Academy Press
149	Science, Policy, and the Coast: Improving Decisionmaking	1995	NRC: Ocean Studies Board	Washington, DC: National Academy Press
150	Setting a New Course for U.S. Coastal Ocean Science	1995	NSTC: CENR: Subcommittee on U.S. Coastal Ocean Science	CENR Executive Secretariat, 202-482-5916
151	Sustainable Agriculture and the 1995 Farm Bill	1995	Council for Agricultural Science and Technology	http://www.cast-science.org/
152	The Conservation Reserve: A Survey of Research and Interest Groups	1995	Council for Agricultural Science and Technology	http://www.cast-science.org/
153	The Ecosystem Approach: Healthy Ecosystems and Sustainable Economies, Vol. 1-Overview	1995	Interagency Ecosystem Management Task Force	NTIS, U.S. DOC, PB95-265583
154	The Ecosystem Approach: Healthy Ecosystems and Sustainable Economies, Vol. 2-Implementation Issues	1995	Interagency Ecosystem Management Task Force	NTIS, U.S. DOC, PB95-265591
155	The Freshwater Imperative Research Agenda	1995	NSF	R.J. Naiman, J.J. Magnuson, D.M. McKnight, and J.A. Stanford, eds., Washington, DC: Island Press; 165 pp.
156	The Population-Environment Connection: What Does It Mean for Environmental Policy?	1995	EPA: Office of Policy Planning and Evaluation	C.E. Orians and M. Skumanich, Seattle: Battelle Seattle Research Center
157	Understanding Marine Biodiversity: A Research Agenda for the Nation	1995	NRC: Ocean Studies Board: Board on Biology: Committee on Biological Diversity in Marine Systems	Washington, DC: National Academy Press
158	Waste Management and Utilization in Food Production and Processing	1995	Council for Agricultural Science and Technology	http://www.cast-science.org/

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159	Assigning Economic Value to Natural Resources	1994	NRC: Commission on Geosciences, Environment and Resources; and Commission on Behavioral and Social Sciences and Education	Washington, DC: National Academy Press
160	Atomic, Molecular, and Optical Science—An Investment in the Future	1994	NRC	Washington, DC: National Academy Press
161	Biochemistry of Small Catchments: A Tool for Environmental Research. SCOPE 51	1994	SCOPE	B. Moldan and J. Cerny, Chichester: John Wiley
162	Changes in Land Use and Land Cover: A Global Perspective	1994		W.B. Meyer and B.L. Turner II, UK: Cambridge University Press
163	Defining Soil Quality for a Sustainable Environment	1994	American Society of Agronomy; Crop Science Society of America; and Soil Science Society of America	SSSA Special Publication #35. http://www.asa-cssa-sssa.org/
164	El Niño and Climate Prediction	1994	NOAA and UCAR	Reports to the Nation (Spring); http://hilo.pmel.noaa.gov/toga-tao/el-nino-report.html
165	Environmental Science in the Coastal Zone	1994	NRC: Water Science and Technology Board	Washington, DC: National Academy Press
166	Foodborne Pathogens: Risks and Consequences	1994	Council for Agricultural Science and Technology	http://www.cast-science.org/
167	How Much Land Can Ten Billion People Spare for Nature?	1994	Council for Agricultural Science and Technology	http://www.cast-science.org/
168	Implications of the Convention on Biological Diversity: Management of Animal Genetic Resources and the Conservation of Domestic Animal Diversity	1994	UN Food and Agriculture Organization: Informal Working Group: Animal Production and Health Division	M.S. Strauss, ed., Washington, DC: American Association for the Advancement of Science
169	Life in the Soil: Soil Biodiversity: Its Importance to Ecosystem Processes	1994	NSF and UK Natural Environment Research Council	Workshop report; Diana W. Freckman, ed., Colorado State University; 24 pp.

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170	Restoring and Protecting Marine Habitat: The Role of Engineering and Technology	1994	NRC: Marine Board	Washington, DC: National Academy Press
171	Science and Judgment in Risk Assessment	1994	NRC: Board on Environmental Science and Technology	Washington, DC: National Academy Press
172	Scientific Plan for a Regional Research Programme in the Arctic on Global Change	1994	NRC: Polar Research Board	Washington, DC: National Academy Press
173	Solar Influences on Global Change	1994	NRC: Board on Sustainable Development	Washington, DC: National Academy Press
174	Strategies and Mechanisms for Field Research in Environmental Bioremediation	1994	Oak Ridge National Laboratory	Colloquium report of the American Academy of Microbiology; R.V. Miller & J.S. Poindexter
175	Systematics Agenda 2000	1994	NSF	J. Cracraft, M. Denton, H. Eshbaugh, M. Novacek, and N. Platnick, Co-chairs; 34 pp.
176	Technology for a Sustainable Future	1994	NSTC	Washington, DC: U.S. GPO; 154 pp.
177	Ten-Year Review of the NSF Long Term Ecological Research (LTER) Program	1994	NSF: Biological Sciences Directorate	Arlington, VA
178	The Long View	1994	NSF: Directorate for Engineering	Arlington, VA
179	The National Biodiversity Information Center	1994	The National Biodiversity Information Center Advisory Planning Board	Thomas Lovejoy, Chair
180	The Role of Terrestrial Ecosystems in Global Change: A Plan for Action	1994	NRC: Board on Sustainable Development	Washington, DC: National Academy Press
181	Valuing the Environment: Proceedings of the First Annual International Conference on Environmentally Sustainable Development	1994	The World Bank	Environmentally Sustainable Development Proceedings Series No. 2, Washington, DC

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182	A Biological Survey for the Nation ("Raven Report")	1993	NRC: Commission on the Formation of the National Biological Survey: Committee on the Formation of the National Biological Survey	Washington, DC: National Academy Press; 205 pp.
183	A Proposal for a National Institute for the Environment: Need, Rationale, Structure	1993	CNIE	Washington, DC
184	Agricultural Ecosystem Effects on Trace Gases and Global Climate Change	1993	American Society of Agronomy; Crop Science Society of America; and Soil Science Society of America	ASA Special Publication #55 http://www.asa-cssa-sssa.org/
185	Assessment of the U.S. Outer Continental Shelf Environmental Studies Program. IV: Lessons and Opportunities	1993	NRC: Board on Environmental Science and Technology	Washington, DC: National Academy Press
186	Biodiversity and Ecosystem Function, Ecological Studies Vol. 99	1993	SCOPE	E-D Schulze and H.A. Mooney, Berlin: Springer Verlag
187	Biodiversity in Marine Systems: A Proposed National Research Initiative	1993	NSF	Workshop report; C.A. Butman, J.T. Carlton, organizers, Denver
188	Biodiversity on Private Lands	1993	President's Commission on Environmental Quality: Biodiversity Steering Committee	Washington, DC: Executive Office of the President
189	Biotechnology for the 21st Century: Realizing the Promise	1993	FCCSET: Committee on Life Sciences and Health: Biotechnology Research Subcommittee	Washington, DC: OSTP; 90 pp.
190	Biotic Interactions and Global Change	1993		P.M. Kareiva, J.G. Kingsolver, and R.B. Huey, Sunderland, MA: Sinauer Associates Inc.
191	Choosing a Sustainable Future	1993	World Wildlife Fund	National Commission on the Environment, Washington, DC: Island Press
192	Compass and Gyroscope: Integrating Science and Politics for the Environment	1993		Kai N. Lee, Washington, DC: Island Press

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193	Earth System Responses to Global Change: Contrasts Between North and South America	1993		H.A. Mooney, E.R. Fuentes, and B.I. Kronberg, San Diego: Academic Press
194	Global Marine Biological Diversity: A Strategy for Building Conservation into Decision Making	1993	Center for Marine Conservation; World Conservation Union; World Wildlife Fund; UNEP; and the World Bank	E.A. Norse, ed., Washington, DC: Island Press; 383 pp.
195	Incorporating Biodiversity Considerations Into Environmental Impact Analysis Under the National Environmental Policy Act	1993	President's Council on Environmental Quality; EPA; DOD; DOI; and DOT	R. O'Malley, L. Langstaff, and M. Southerland
196	National Center for Ecological Synthesis: Scientific Objectives, Structure, and Implementation	1993	Ecological Society of America; Association of Ecosystem Research Centers	Joint committee report; S.R. Carpenter, ed.
197	National Center for Synthesis in Ecology: A Design Study	1993	NSF	Unpublished workshop report
198	New Perspectives on Environmental Education and Research: A Report on the University Colloquium on Environmental Research and Education	1993	Sigma Xi	Research Triangle Park, NC
199	Norway/UNEP Expert Conference on Biodiversity: Proceedings	1993	Norwegian Ministry of Environment and UNEP	O.T. Sandlund and P.J. Schei, eds., Trondheim, Norway
200	Radioecology After Chernobyl: Biogeochemical Pathways of Artificial Radionuclides. SCOPE 50	1993	SCOPE	Sir Frederick Warner and R.M. Harrison, Chichester: John Wiley
201	Report of the NSB/CPP Task Force on the Environment	1993	National Science Board: Committee on Programs and Plans	NSB/ENV 93-9, Arlington, VA: NSF
202	Report of the Technology and Sustainable Development Workshop	1993	NSF	Program for Environmental Engineering Education and Research Publication No. 94-1: MIT

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203	Research Opportunities in Oceanic Biology	1993	NRC: Ocean Studies Board	Washington, DC: National Academy Press
204	Research Opportunities in Remote Sensing	1993	NRC: Ocean Studies Board	Washington, DC: National Academy Press
205	Research to Protect, Restore, and Manage the Environment ("Corson Report")	1993	NRC: Commission on Life Sciences: Committee on Environmental Research	Washington, DC: National Academy Press; 242 pp.
206	Risk and the Environment: Improving Regulatory Decision Making	1993	Carnegie Commission on Science, Technology, and Government	http://www.carnegie.org/science_tech/reg.txt
207	Science and Stewardship in the Antarctic	1993	NRC: Polar Research Board	Washington, DC: National Academy Press
208	Science, Technology, and the Federal Government: National Goals for a New Era ("Griffiths Report")	1993	National Academy of Sciences, National Academy of Engineering, IOM: Committee on Science, Engineering, and Public Policy	Washington, DC: National Academy Press; 54 pp.
209	Statistics and Physical Oceanography	1993	NRC: Committee on Applied and Theoretical Statistics: Panel on Statistics and Oceanography	Washington, DC: National Academy Press
210	Understanding and Predicting Atmospheric Chemical Change	1993	NRC: Board on Atmospheric Sciences and Climate	Washington, DC: National Academy Press
211	A Science and Technology Agenda for the Nation: Recommendations for the President and Congress	1992	Carnegie Commission on Science, Technology, and Government	New York; 37 pp.
212	An Agenda of Science for Environment and Development Into the 21st Century (ASCEND 21)	1992	ICSU	http://www.icsu.org/
213	Assessment of the U.S. Outer Continental Shelf Environmental Studies Program. II: Ecology	1992	NRC: Board on Environmental Science and Technology	Washington, DC: National Academy Press
214	Biotechnology and Genetic Resources	1992	U.S.-European Community Task Force on Biotechnology Research	Workshop report; October, Airlie, VA

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215	Enabling the Future: Linking Science & Technology to Societal Goals	1992	Carnegie Commission on Science, Technology, and Government: Task Force on Establishing and Achieving Long-Term Goals	H.G. Stever, Chair, New York; 72 pp.
216	Environmental Research and Development: Strengthening the Federal Infrastructure	1992	Carnegie Commission on Science, Technology, and Government: Task Force on the Organization of Federal Environmental R&D Programs	R.W. Fri and H.G. Stever, Co-chairs, New York; 143 pp.
217	EPA's Research Agenda: Strengthening Science for Environmental Decisions	1992	EPA	Washington, DC
218	Federal Funding of Environmental R&D	1992	American Association for the Advancement of Science: Directorate for Science and Policy Programs	K.M. Gramp, A.H. Teich, and S.D. Nelson, AAAS Pub. No. 92-48S, Washington, DC; 72 pp.
219	Federal Ground-Water Science and Technology Programs	1992	FCCSET: Committee on Earth and Environmental Sciences: Subcommittee on Water Resources	S. Ragone (USGS), Chair
220	Federal Research on Environmental Biology	1992	FCCSET: Committee on Life Sciences and Health: Subcommittee on Environmental Biology	M.E. Clutter (NSF), Chair; 72 pp.
221	Global Environmental Change: Understanding the Human Dimensions	1992	NRC: Commission on the Behavioral and Social Sciences and Education: Committee on the Human Dimensions of Global Change	P.C. Stern, O.R. Young, and D. Druckman, eds., Washington, DC: National Academy Press; 308 pp.
222	Methods to Assess Adverse Effects on Pesticides on Non-target Organisms. SCOPE 49	1992	SCOPE	Robert G. Tardiff, Chichester: John Wiley
223	Oceanography in the Next Decade: Building New Partnerships	1992	NRC: Ocean Studies Board	C. Wunsch, Chair, Washington, DC: National Academy Press
224	Our Living Oceans: Report on the Status of U.S. Living Marine Resources	1992	NOAA: National Marine Fisheries Service	NOAA Technical Memo NMFS-F/SPO-2, Washington, DC

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225	Our Ozone Shield	1992	NOAA and UCAR	Reports to the Nation, No.2 (Fall); http://newnos.nos.noaa.gov/ogp/OGPFront/mono2.html
226	Population, Technology, and Lifestyle	1992		R. Goodland, H.E. Daly, and S.E. Serafy, eds., Washington, DC: Island Press
227	Predicting Our Weather: A Strategic Plan for the U.S. Weather Research Program	1992	FCCSET: Committee on Earth and Environmental Sciences: Subcommittee on Atmospheric Research	Washington, DC: OSTP; 36 pp.
228	Preparing U.S. Agriculture for Global Climate Change	1992	Council for Agricultural Science and Technology	P. Waggoner, Chair, Task Force Report No. 119; http://www.cast-science.org
229	Report of a Workshop for a National Park Service Ecological Research Program	1992	National Park Service	Unpublished report
230	Restoration of Aquatic Ecosystems: Science, Technology, & Public Policy ("Cairns Report")	1992	NRC: Commission on Geoscience, Environment, and Resources: Water Science and Technology Board: Committee on Restoration of Aquatic Ecosystems	Washington, DC: National Academy Press; 552 pp.
231	Safeguarding the Future: Credible Science, Credible Decisions	1992	EPA	R.C. Loehr, Chair, Expert Panel Report; EPA/600/9-91/050, Washington, DC
232	Science and the National Parks	1992	NRC: Board on Environmental Science and Technology	Washington, DC: National Academy Press
233	Science, Technology, and the States in America's Third Century	1992	Carnegie Commission on Science, Technology, and Government	P. Firth and S. Fiske, eds., Washington, DC
234	Soil and Water Quality: An Agenda for Agriculture	1992	NRC: Board on Agriculture	Washington, DC: National Academy Press
235	Sulphur Cycling on the Continents, Wetlands, Terrestrial Ecosystems, and Associated Water Bodies. SCOPE 48	1992	SCOPE	R.W. Howarth, J.W.B. Stewart, and M.V. Ivanov, Chichester: John Wiley

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236	The Atmospheric Sciences in the 1990s: Accomplishments, Challenges, and Imperatives	1992		J.A. Dutton, Bulletin of the American Meteorological Society 73(10):1549-62
237	The Atmospheric Sciences: Entering the Twenty-first Century	1992	NRC: Board on Atmospheric Sciences and Climate	Washington, DC: National Academy Press
238	Water Quality: Agriculture's Role	1992	Council for Agricultural Science and Technology	http://www.cast-science.org/
239	A Sustainable Biosphere: The Global Imperative	1991	MacArthur Foundation and Universidad Autonoma de Mexico	B.J. Huntley et.al., Ecology International 20:1-14
240	Biogeochemistry: An Analysis of Global Change	1991		William H. Schlesinger, San Diego: Academic Press
241	Ecosystem Experiments. SCOPE 45	1991	SCOPE	H. Mooney, E. Medina, D. Schindler, E-D Schulze, and B. Walker, Chichester: John Wiley
242	Environmental Engineering Education in the Year 2000	1991	NSF; American Academy of Environmental Engineers; Association of Environmental Engineering Professors; and Western Region Hazardous Substance Research Center	K.J. Williamson and M.R. Miller, eds., NSF 91-98
243	Federally Funded Research: Decisions for a Decade	1991	Office of Technology Assessment	Washington, DC: U.S. GPO
244	From Genes to Ecosystems: A Research Agenda for Biodiversity	1991	SCOPE-UNESCO supported by NSF and U.S. Committee for the MAB Program	Workshop report; Otto T. Solbrig, ed., Paris: International Union of Biological Sciences; 124 pp.
245	Implementation: Science and Technology	1991	Sigma Xi	J.H. Gibbons, in Global Change and the Human Prospect: Issues in Population, Science, Technology and Equity, Sigma Xi Forum Proceedings, Research Triangle Park, NC: Sigma Xi, pp. 183-201
246	Justification and Criteria for the Monitoring of Ultraviolet Radiation	1991	National Research Initiative Competitive Grants Program; USDA Cooperative State Research Service; Colorado State University	J.H. Gibbons, coordinator; Ft. Collins, CO: Natural Resource Ecology Laboratory, Colorado State University

	Title	*Date*	*Initiator/Sponsor*	*Publication Information*
247	Long-term Ecological Research: An International Perspective. SCOPE 47	1991	SCOPE	Paul G. Risser, Chichester: John Wiley
248	Opportunities and Priorities in Arctic Geoscience	1991	NRC: Commission on Geosciences: Committee on Arctic Solid-Earth Geosciences	Washington, DC: National Academy Press; 67 pp.
249	Opportunities in the Hydrologic Sciences ("Eagleson Report")	1991	NRC: Commission on Geosciences, Environment, and Resources; NRC: Water Science and Technology Board: Committee on Opportunities in the Hydrologic Sciences	P. Eagleson, Chair, Washington, DC: National Academy Press
250	Technology Development in the LTER Network: Status Report on GIS, Remote Sensing, Internet Connectivity, Archival Storage & Global Positioning Systems	1991	NSF	D. Foster and E. Boose, LTER Pub. No. 12, Seattle: LTER Network Office
251	The Sustainable Biosphere Initiative	1991		J. Lubchenco et al., Ecology 72(2):371-412
252	The Uses of Ecology: Lake Washington and Beyond	1991		W.T. Edmondson, Seattle: University of Washington Press
253	Transforming Technology: An Agenda for Environmentally Sustainable Growth in the 21st Century	1991	World Resources Institute	G. Heaton, R. Repetto, and R. Sobin, Washington, DC
254	1990's Global Change Action Plan: Utilizing a Network of Ecological Research Sites	1990	NSF	Workshop report; Seattle: LTER Network Office, University of Washington
255	Climate Change: The IPCC Scientific Assessment	1990	IPCC	Cambridge, UK: Cambridge University Press
256	Climate Variability and Ecosystem Response	1990	NSF and U.S. Forest Service	LTER workshop report; D. Greenland and L.W. Swift, Jr., eds.
257	Conserving the World's Biological Diversity	1990	IUCN; WRI; CI; WWF-US; and the World Bank	J.A. McNeely, K.R. Miller, W.V. Reid, et al., Washington, DC

	Title	*Date*	*Initiator/Sponsor*	*Publication Information*
258	Ecological Impacts of Federal Conservation and Cropland Reduction Programs	1990	Council for Agricultural Science and Technology	http://www.cast-science.org/
259	Forestry Research: A Mandate for Change	1990	NRC	Washington, DC: National Academy Press
260	Global Stewardship: A Review of the Context and Challenges Facing Science and Economics Research Related to Global Change	1990	NRC	Proceedings of a White House conference, Washington, DC: National Academy Press
261	Reducing Risk: Setting Priorities and Strategies for Environmental Protection	1990	EPA Science Advisory Board	SAB-EC-90-021, Washington, DC: EPA
262	The Preservation and Valuation of Biological Resources	1990		G.H. Orians, G.M. Brown, Jr., W.E. Kunin, and J.E. Swierzbinski, eds., Seattle: University of Washington Press
263	Arctic Social Science: An Agenda for Action	1989	NRC: Commission on Physical Sciences, Mathematics, and Resources: Polar Research Board: Committee on Arctic Social Sciences	Washington, DC: National Academy Press; 75 pp.
264	Biological Invasions: A Global Perspective. SCOPE 37	1989	SCOPE	J.A. Drake, H. Mooney, F. di Castri, R.H. Groves, F.J. Kruger, M. Rejmanek, and M. Williamson, Chichester: John Wiley
265	Ecotoxicology: Problems and Approaches	1989		S.A. Levin, M.A. Harwell, J.R. Kelly, and K.D. Kimball, Berlin: Springer Verlag
266	Environmental Accounting for Sustainable Development	1989	The World Bank	Y.J. Ahmad, S.E. Serafy, and E. Lutz, eds., Washington, DC
267	Global Change and Our Common Future: Papers From a Forum	1989	NRC: Committee on Global Change	R.S. DeFries and T.F. Malone, eds., Washington, DC: National Academy Press
268	Intellectual Property Rights Associated With Plants	1989	American Society of Agronomy; Crop Science Society of America; and Soil Science Society of America	ASA Special Publication #52; http://www.asa-cssa-sssa.org/

	Title	Date	Initiator/Sponsor	Publication Information
269	Investing in Research: A Proposal to Strengthen the Agricultural, Food, and Environmental System	1989	NRC: Board on Agriculture	Washington, DC: National Academy Press; 155 pp.
270	Loss of Biological Diversity: A Global Crisis Requiring International Solutions	1989	NSB: Committee on International Science: Task Force on Global Biodiversity	C.C. Black, Chair; NSB-89-171, Arlington, VA: NSF; 19 pp.
271	Opportunities in Biology	1989	NRC: Commission on Life Sciences: Board on Biology: Committee on Research Opportunities in Biology	Washington, DC: National Academy Press; 448 pp.
272	Research Priorities for Conservation Biology	1989	NSF and University of Michigan	M.E. Soule and K.A. Kohm, eds.; Society for Conservation Biology
273	Chemistry and the Environment	1988	NSF: Chemistry Division	J.W. Frost, and D.M. Golden, eds.
274	Cross-disciplinary Research in the Statistical Sciences	1988	NSF	I. Olkin and J. Sacks, Co-chairs; Institute of Mathematical Statistics
275	Future Risk: Research Strategies for the 1990s	1988	EPA Science Advisory Board	SAB-EC-88-040, Washington, DC: EPA
276	Research Priorities for Single Species Conservation Biology	1988	NSF and National Zoological Park	Workshop report; D.E. Wildt and U.S. Seal, eds.
277	Water 2020: Sustainable Use for Water in the 21st Century	1988	Science Council of Canada	G.A.K. Wallace, Chair; Report 40; ISBN 0-662-16220-X
278	Directions in Engineering Research: An Assessment of Opportunities and Needs	1987	NRC: Commission on Engineering and Technical Systems: Engineering Research Board	Washington, DC: National Academy Press; 331 pp.
279	Environmental Impacts on Human Health: The Agenda for Long-term Research and Development	1987	President's Council on Environmental Quality	S. Draggan, J.J. Cohrssen, and R.E. Morrison, eds., Praeger Publishers, ISBN 0-275-92338-X; 228 pp.
280	Environmental Monitoring, Assessment and Management: The Agenda for Long-term Research and Development	1987	President's Council on Environmental Quality	S. Draggan, J.J. Cohrssen, and R.E. Morrison, eds., Praeger Publishers, ISBN 0-275-92336-3; 128 pp.

	Title	*Date*	*Initiator/Sponsor*	*Publication Information*
281	Geochemical and Hydrologic Processes and Their Protection: The Agenda for Long-term Research and Development	1987	President's Council on Environmental Quality	S. Draggan, J.J. Cohrssen, and R.E. Morrison, eds., Praeger Publishers, ISBN 0-275-92339-8; 210 pp.
282	Infrastructure for the 21st Century: Framework for a Research Agenda	1987	NRC: Commission on Behavioral and Social Sciences and Education; NRC: Commission on Engineering and Technical Systems; and Transportation Research Board: Committee on Infrastructure Innovation	Washington, DC: National Academy Press; 100 pp.
283	Our Common Future	1987	The World Commission on Environment and Development	Oxford, UK: Oxford University Press
284	Preserving Ecological Systems: The Agenda for Long-term Research and Development	1987	President's Council on Environmental Quality	S. Draggan, J.J. Cohrssen, and R.E. Morrison, eds., Praeger Publishers, ISBN 0-275-92337-1; 191 pp.
285	Status and Future of Ecosystem Science	1987	Institute of Ecosystem Studies	Occasional Publication No. 3, Millbrook, NY: New York Botanical Garden
286	Technologies to Maintain Biological Diversity	1987	Office of Technology Assessment	Washington, DC: U.S. GPO
287	Global Change in the Geosphere-Biosphere: Initial Priorities for an IGBP ("Eddy Report")	1986	NRC: Commission on Physical Sciences, Mathematics, and Resources; U.S. Committee for an International Geosphere-Biosphere Program	J.A. Eddy, Chair; Washington, DC: National Academy Press; 91 pp.
288	Environmental Consequences of Nuclear War. SCOPE 28	1985	SCOPE	A.B. Pittock, T.P. Ackerman, P.J. Crutzen, M.C. MacCracken, C.S. Shapiro, and R.P. Turco, Chichester: John Wiley
289	Organic Farming: Current Technology and Its Role in a Sustainable Agriculture	1984	American Society of Agronomy; Crop Science Society of America; and Soil Science Society of America	ASA Special Publication #46; http://www.asa-cssa-sssa.org/
290	A Patron for Pure Science: The National Science Foundation's Formative Years, 1945-57	1982	NSF	J.M. England, NSF 82-24, Arlington, VA

	Title	*Date*	*Initiator/Sponsor*	*Publication Information*
291	Planning Future Land Uses	1981	American Society of Agronomy; Crop Science Society of America; and Soil Science Society of America	ASA Special Publication #42; http://www.asa-cssa-sssa.org/
292	Planning the Uses and Management of Land	1979	American Society of Agronomy; Crop Science Society of America; and Soil Science Society of America	Agronomy Monograph #21; http://www.asa-cssa-sssa.org/
293	Impact of Climatic Fluctuation on Major North American Food Crops	1976	C.F. Kettering Foundation	D. Hinckley, Project Manager; The Institute of Ecology
294	Environmental Science: Challenge for the Seventies	1971	NSB	H.E. Carter, Chair; NSB 71-1, Washington, DC: U.S. GPO, 50 pp.
295	The Universities and Environmental Quality—Commitment to Problem Focused Education	1969	President's Office of Science & Technology	Report to the President's Environmental Quality Council; J.S. Steinhart and S. Cherniack, Washington, DC: U.S. GPO; 22 pp.
296	Science—The Endless Frontier	1945	NSF	Vannevar Bush Report to President Franklin D. Roosevelt; NSF 90-8 (reprint), Arlington, VA

Appendix C

Sources of Public Comment: Before Release of Interim Report

The Board actively solicited public comments about wide-ranging environmental concerns through a variety of outreach efforts, including public hearings, invitations to organizations with environmental interests and to NSF advisory committees, and a web site. Over 162 written comments were received by e-mail, fax, and regular mail; some individuals submitted more than one set of comments. The name and affiliation of senior authors are listed below. Comments submitted by individuals did not necessarily represent organizational positions. However, if an organization's position was represented by an individual's comments, this is indicated by an asterisk (*) next to the organization's name. Note that some individuals provided multiple affiliations.

Name	*Organizational Affiliation*
Abedon, David	University of Rhode Island, Community Planning Department
Alessio, Julie	Affiliation Unknown
Allenby, Braden R.	AT&T, Environment, Health and Safety
Applegate, David	*American Geological Institute, Government Affairs
Bales, Roger	University of Arizona–Tucson, Department of Hydrology and Water Resources
Banks, Darryl	CH2M Hill
Barber, Mary	*Ecological Society of America
Barker, Alex	Dallas Museum of Natural History, Division of Collections and Research
Barlaz, Mort	North Carolina State University, Department of Civil Engineering
Bartlett, Richard C.	Committee for the National Institute for the Environment Mary Kay Inc. Nature Conservancy of Texas National Environmental Education and Training Foundation
Bencala, Ken	U.S. Geological Survey, Water Resources Division Research
Benedick, Richard	Battelle Pacific Northwest Laboratory
Benoit, Gaboury	Yale University, Environmental Studies, Greeley Laboratory
Bernabo, Chris	*RAND, Environmental Science and Policy Center
Bierbaum, Rosina	*White House, Office of Science and Technology Policy
Blockstein, David E.	*American Ornithologists' Union Committee for the National Institute for the Environment Ornithological Council
Boersma, P. Dee	University of Washington, Department of Zoology Society for Conservation Biology
Boyle, Ed	Affiliation Unknown
Brakke, David F.	Towson University, College of Science and Mathematics

Braverman, Hy	Affiliation Unknown
Breit, Luke	*California Democratic Party, Environmental Caucus
Brigham, L.W.	University of Cambridge (UK), Scott Polar Research Institute
Broadbent, Jeffrey	Affiliation Unknown
Brody, Michael	U.S. Environmental Protection Agency, Office of Strategic Planning
Carpenter, Steven	University of Wisconsin–Madison, Limnology and Geology
Chichilnisky, Graciela	Columbia University, Program on Information and Resources
Chuang, Liu-hsiung	U.S. Department of Agriculture, Natural Resources Conservation Service
Clark, William	Harvard University
Cochran, Patricia	*Alaska Native Science Commission
Cook, Richard	Allegheny College
Courtney, Mark	National Science Foundation, Division of Environmental Biology
Crovello, Ted	University of California–Los Angeles
Crumley, Carole	University of North Carolina–Chapel Hill
Dabbert, Walter	National Center for Atmospheric Research
Devitt, Mary-Ellen	*SAES/USDA-CSREES National Environmental Initiative
Douglas, James L.	National Science Foundation, Division of Earth Sciences
Drake, T.	North Carolina State University
Durett, Dan	DANhIKO International
Eisenberger, Peter	Columbia University, Columbia Earth Institute
Elgar, Steve	Woods Hole Oceanographic Institution
Ellman, George	Affiliation Unknown
Entekhabi, Dara	Massachusetts Institute of Technology
Fawley, Marvin	North Dakota State University, Department of Botany
Fein, Jeremy	Affiliation Unknown
Field, Christopher	The Carnegie Institution of Washington
Filippone, Ella	Passaic River Coalition
Fiscus, Dan	University of Maryland, Center for Environmental Science
Flint, Warren	Five E's Unlimited
Folger, Peter	American Geophysical Union
Friedrich, Otto	Affiliation Unknown
Frost, Tom	National Science Foundation, Division of Environmental Biology
Gallagher, E.	Naval Postgraduate School
Gautier, Catherine	University of California–Santa Barbara
Getzinger, Richard	*American Association for the Advancement of Science, Directorate for International Programs
Gibb, James G.	Affiliation Unknown
Glasener, Karl M.	*American Society of Agronomy *Crop Science Society of America *Soil Science Society of America
Groat, Charles	U.S. Geological Survey
Guza, R.	Scripps Institution of Oceanography
Haas, Charles N.	Drexel University, Environmental Engineering
Haas, Peter M.	University of Massachusetts, Department of Political Science
Harris, W. Franklin	*National Science Foundation Biosciences Advisory Committee University of Tennessee, Division of Biology
Hartwell, Penny	Affiliation Unknown

Harvey, Francis	University of Kentucky, Department of Geography
Hasbrouck, Bruce	National Association of Environmental Professionals
Hay, A.	Dalhousie University
Hayden, Bruce	National Science Foundation, Division of Environmental Biology
Heal, Geoffrey	Columbia University
Heil, Kathleen	Chesapeake Biological Lab
Hirsch, Robert	U.S. Geological Survey, Water Resources Division
Hoagland, K. Elaine	*Council on Undergraduate Research
Hollander, Rachelle	National Science Foundation, Division of Social and Economic Sciences
Hood, Laura	Defenders of Wildlife
Huberty, Brian	U.S. Department of Agriculture, Natural Resources Conservation Service
Hyps, Brian	*American Society of Plant Physiologists
Ignatenko, "Alescam" L.	Kamchatka, Russia
Jensen, Deborah	The Nature Conservancy
Kanivetsky, Roman	University of Minnesota, Minnesota Geological Survey
Kauffman, Terry	Lancaster, PA, Board of County Commissioners
Kaufman, Les	Boston University, Department of Biology
Kirby, J.	University of Delaware
Kirk, Elizabeth J.	*American Association for the Advancement of Science, Directorate for International Programs
Kutz, Frederick W.	U.S. Environmental Protection Agency, Environmental Science Center
Lashutka, Greg	City of Columbus, OH, Office of the Mayor
Levin, Simon	Princeton University
Lippmann, T.	Scripps Institution of Oceanography
Liverman, Diana	University of Arizona
Maconochie, Rosemary	*New England Board of Higher Education
Malone, Thomas	Connecticut Academy of Science and Engineering Sigma Xi
Manheim, Frank T.	U.S. Geological Survey Coastal & Marine Geology Center, Woods Hole, MA
Mann, Curt	Association of American Veterinary Medical Colleges
Mathews-Amos, Amy	*Marine Conservation Biology Institute
Matson, Pamela	Stanford University
McClintock, James	University of Alabama at Birmingham, School of Natural Sciences and Mathematics
McCreedy, Cliff	Oceanwatch
McGillivary, Phillip	U.S. Coast Guard Icebreakers
McHenry, John	North Carolina Supercomputing Center Committee on Atmospheric Chemistry of the American Meteorological Society
McKee, Art	Oregon State University, Department of Forest Science
Melillo, Jerry	The Ecosystems Center, Woods Hole, MA
Moberly, Heather	Pennsylvania State University
Moffett, James	Woods Hole Oceanographic Institution
Mooney, Harold	Stanford University, Department of Biological Sciences
Moore, Berrien	University of New Hampshire, Institute for the Study of Earth, Oceans, and Space
Moran, Emilio F.	*American Anthropological Association Task Force on the Environment
Morel, Francois	Princeton University

Morin, Nancy	*American Association of Botanical Gardens and Arboreta *Flora of North America Project
Newman, Arnold	International Society for the Preservation of the Tropical Rainforest
Norse, Elliott A.	*Marine Conservation Biology Institute
O'Grady, Richard	*American Institute of Biological Sciences
Oberle, Mark	Affiliation Unknown
Orians, Gordon	University of Washington, Department of Zoology National Research Council, Board of Environmental Studies and Toxicology
Orme, Thomas	Council for Agricultural Science and Technology
Orr, Wilson	Prescott College
Ostfeld, Richard	Institute of Ecosystem Studies, Millbrook, NY
Overbey, Mary Margaret	American Anthropological Association
Paradise, T.	University of Hawaii at Hilo, Geography & Environmental Sciences
Parker, Thornton	Affiliation Unknown
Patz, Jonathan	Johns Hopkins School of Public Health, Department of Environmental Health Sciences
Pfirman, Stephanie	Columbia University, Barnard College, Environmental Science Department
Portney, Paul	Resources For The Future
Powers, Julian	Affiliation Unknown
Press, Daniel	University of California–Santa Cruz, Environmental Studies Department
Preuss, Peter	U.S. Environmental Protection Agency, National Center for Environmental Research and Quality Assurance
Raney, Jay	University of Texas at Austin, Bureau of Economic Geology
Raubenheimer, B.	Woods Hole Oceanographic Institution
Reichman, O. James	National Center for Ecological Analysis and Synthesis
Reinhart, Debra	Affiliation Unknown
Rejeski, David	White House Council on Environmental Quality
Resetar, Susan	RAND, Environmental Science and Policy Center
Rickson, Fred	Oregon State University, Department of Botany
Ritter, Don	National Environmental Policy Institute
Rittman, Bruce	Northwestern University
Rupp, Lawrence D.	Affiliation Unknown
Satterfield, Theresa	Decision Research, Inc.
Saundry, Peter	Committee for the National Institute for the Environment
Scalet, Charles G.	*National Association of University Fisheries and Wildlife Programs
Schimel, David	National Center for Atmospheric Research, Climate and Global Dynamics Division
Seaman, Nelson L.	Pennsylvania State University, Department of Meteorology
Sedell, James	U.S. Forest Service
Sherman, Lou	*American Society of Plant Physiologists
Shmagin, Boris	University of Minnesota, Department of Geology
Skiles, Jim	Affiliation Unknown
Somerville, Christopher	The Carnegie Institution of Washington
Soule, Michael	University of California The Society for Conservation Biology The Wildlands Project
Soulen, Richard	T&MS, Inc.
Stevenson, William B.	Boston College, Organization Studies Department

Stone, John V.	Affiliation Unknown
Strauss, Steven H.	Oregon State University, Department of Forest Science
Sullivan, Kathryn	*Center of Science and Industry, Columbus, OH
Taylor, Dorceta E.	University of Michigan
Tenney, J.L.	Arizona Resource Advisory Council
Thompson, Marilyn	Smithsonian Institution
Thornton, E.	Naval Postgraduate School
Tian, Lei	University of Illinois, Agricultural Engineering Department
Todd, Barbara Sheen	Pinellas, FL, County Board of Supervisors
Turner, Bill	Clark University
Unsworth, Mike	Oregon State University, Center for Analysis of Environmental Change
Weinman, James	NASA, Goddard Space Flight Center
Wilson, Thomas	Affiliation Unknown
Wright, Beverly	Xavier University, Deep South Center for Environmental Justice
Yates, Terry	University of New Mexico, Department of Biology
Zimmer, Judy	Environmental News Network
Zoback, Mary Lou	U.S. Geological Survey

APPENDIX D

SOURCES OF PUBLIC COMMENT: AFTER RELEASE OF INTERIM REPORT

On July 29, 1999, the National Science Board unanimously approved and released an Interim Report (NSB 99-133) that contained its findings and recommendations. The Interim Report was placed on the NSB web site, and the public was encouraged to comment through a variety of outreach efforts, including invitations to organizations with environmental interests and to NSF advisory committees. Between release of the Interim Report and November 30, 1999, the report on the web site received nearly 7,000 hits from people outside the Foundation. Over 40 written comments were received by e-mail, fax, and regular mail; some individuals submitted more than one set of comments. The name and affiliation of individual authors are listed below, followed by the names of people submitting comments as multiple signatories from an organization. Comments submitted by individuals did not necessarily represent organizational positions. However, if an organization's position was presented in an individual's comments, this is indicated by an asterisk (*) next to the organization's name.

Name	*Organizational Affiliation*
Single Signatories:	
Adams, Michael S.	University of Wisconsin, Botany and Environmental Studies
Blockstein, David E.	Committee for the National Institute for the Environment
Crow, Michael M.	Columbia University
Dame, Richard	Coastal Carolina University, Marine Science Department
Englehardt, James D.	University of Miami
Fenstermaker, Lynn K.	Nevada Desert Research Center
Fox, Marye Anne	North Carolina State University
Fulkerson, William	Joint Institute for Energy and Environment
Groat, Charles G.	*U.S. Geological Survey
Hall, Philip G.	*Water Environment Research Foundation
Hoagland, Elaine	*Council on Undergraduate Research
Kaman, Jeffrey S.	University of Notre Dame
Kroening, Nancy	Affiliation Unknown
Lepage, Francoise O.	Dominican College
Malone, Thomas	Connecticut Academy of Science and Engineering
Naiman, Robert J.	University of Washington, School of Fisheries
Noonan, Norine E.	*U.S. Environmental Protection Agency, Office of Research & Development
Norse, Elliott A.	*Marine Conservation Biology Institute
Noss, Reed F.	*Society for Conservation Biology
Orme, Thomas	*Council for Agricultural Science and Technology
Pettit, Lawrence K.	Indiana University of Pennsylvania

Rahni, David N.	Pace University
Rittmann, Bruce E.	Northwestern University
Robertson, Thomas A.	Affiliation Unknown
Soulen, Richard	T&MS, Inc.
Steinman, Alan	South Florida Water Management District
Trenberth, Kevin E.	NCAR, Climate Analysis Section
Vanderhoef, Larry N.	University of California–Davis
Wall, Diana H.	*The Ecological Society of America
Wasserman, Ed	*American Chemical Society
Weinberg, Howard	University of North Carolina, Department of Environmental Sciences and Engineering
Wright, Joseph B.	Affiliation Unknown
Yuill, Thomas M.	University of Wisconsin–Madison, Institute for Environmental Studies
Zemankova, Maria	National Science Foundation

Multiple Signatories:

Luthy, Richard G.	
Gray, Kimberly A.	
Autenrieth, Robin L.	
Logan, Bruce E.	
Conway, Richard A.	
Ford, Davis L.	
Harleman, Donald R.F.	
Kavanaugh, Michael C.	*Association of Environmental Engineering and Science Professors
McCarty, Perry L.	
O'Melia, Charles R.	
Okun, Daniel A.	
Pohland, Frederick G.	
Schnoor, Jerald L.	
Singer, Philip C.	
Snoeyink, Vernon L.	
Symons, James M.	
Hubbell, Stephen P.	
Benedick, Hon. Richard E.	
Howe, Henry F.	
Ahmed, A. Karim	
Bartlett, Richard C.	
Bringer, Robert	
Dayton, Charles K.	
Gillis, Malcolm	
Greenfield, Stanley	*Committee for the National Institute for the Environment
Height, Dorothy I.	
Johnson, Hon. Randy	
Langenberg, Donald N.	
Leonard, H. Jeffrey	
McNamara, Hon. Robert S.	
Peterson, Hon. Craig A.	
Pulliam, Ronald	
Saundry, Peter D.	
Todd, Hon. Barbara Sheen	
Knauft, David A.	*Council for Agricultural Science and Technology
Stuckey, Richard E.	

Arntzen, Charles J. Avise, John Cairns, John Jr. Davis, Margaret B. Diamond, Jared M. Eisner, Thomas Leopold, Estella Likens, Gene E. Margulis, Lynn Paine, Robert T. Terborgh, John Wilson, Edward O.	Members of the National Academy of Sciences
Norse, Elliott A. Auster, Peter J. Cukor, Benjamin E. Alcala, Angel Pauly, Daniel Andrade, Roberto Enriquez Riser, Alison Mee, Lawrence Boersma, P. Dee Idechong, Noah Maida, Mauro Orbach, Michael Trivelpiece, Wayne Stone, Gregory Tegner, Mia Bean, Michael Heneman, Burr Steneck, Robert Estes, James A. Suzuki, David Cohen, Andrew Estrada, Marta Repetto, Robert Watling, Les Burkholder, JoAnn Teal, John Marsh, Helene Palumbi, Steven Allen, Richard Muir, Derek C.G.	Pew Fellows in Marine Conservation and Pew Fellows Program Advisory Committee Members

Raven, Peter H.
John P. Holdren
Neal Lane
John A. Young
Norman R. Augustine
Francisco J. Ayala
John M. Deutch
Murray Gell-Mann
David A. Hamburg
Diana MacArthur
Shirley M. Malcom
Mario J. Molina
Sally K. Ride
Judith Rodin
Charles A. Sanders
David E. Shaw
Charles M. Vest
Virginia V. Weldon
Lilian Shiao-Yen Wu

*President's Committee of Advisors on Science and Technology

APPENDIX E

LETTER FROM THE PRESIDENT'S COMMITTEE OF ADVISORS ON SCIENCE AND TECHNOLOGY

At the request of Neal Lane, the President's Science Advisor, the President's Committee of Advisors on Science and Technology (PCAST) reviewed the Interim Report *Environmental Science and Engineering for the 21st Century* (NSB 99-133). Peter Raven and John Holdren, as chairs of two relevant PCAST committees, led the review. Their report, approved by PCAST on December 10, 1999, is reprinted on the following pages.

The following letter was approved by PCAST, December 10, 1999

Chairs

Neal Lane
Assistant to the President for Science and Technology
Director, Office of Science and Technology Policy

John A. Young
Former President and CEO
Hewlett-Packard Co.

Members

Norman R. Augustine
Former Chairman and CEO
Lockheed Martin Corporation

Francisco J. Ayala
Donald Bren Professor of Biological Sciences
Professor of Philosophy
University of California, Irvine

John M. Deutch
Institute Professor, Department of Chemistry
Massachusetts Institute of Technology

Murray Gell-Mann
Professor, Santa Fe Institute
R.A. Millikan Professor Emeritus of Theoretical Physics
California Institute of Technology

David A. Hamburg
President Emeritus
Carnegie Corporation of New York

John P. Holdren
Teresa and John Heinz Professor of Environmental Policy
Director, Program on Science, Technology and Public Policy
John F. Kennedy School of Government
Harvard University

Diana MacArthur
Chair and CEO
Dynamac Corporation

Shirley M. Malcom
Head
Directorate for Education and Human Resources Programs
American Association for the Advancement of Science

Mario J. Molina
Institute Professor, Lee and Geraldine Martin
Professor of Environmental Science
Massachusetts Institute of Technology

Peter H. Raven
Director, Missouri Botanical Garden
Engelmann Professor of Botany
Washington University in St. Louis

Sally K. Ride
Professor of Physics
University of California, San Diego

Judith Rodin
President
University of Pennsylvania

Charles A. Sanders
Former Chairman
Glaxo-Wellcome Inc.

David E. Shaw
Chairman and CEO
D.E. Shaw and Co.

Charles M. Vest
President
Massachusetts Institute of Technology

Virginia V. Weldon
Directer, Center for the Study of American Business
Washington University in St. Louis

Lilian Shiao-Yen Wu
Research Scientist and Consultant, Corporate
Technical Strategy Development, IBM

EXECUTIVE OFFICE OF THE PRESIDENT
PRESIDENT'S COMMITTEE OF ADVISORS ON SCIENCE AND TECHNOLOGY
WASHINGTON, D.C. 20502

December 3, 1999

Neal Lane
Assistant to the President for Science and Technology

Dear Neal,

As you requested, we have taken a close look at the interim report of the National Science Board, "Environmental Science and Engineering for the 21st Century." Specifically, you asked our advice on how the NSTC should address the report's recommendation on reevaluating the government's environmental R&D portfolio and on what implications there might be for the overall Federal effort.

With regard to your specific question, doing an adequate job of providing the science we need to respond to the environmental challenges facing the Nation will unquestionably require the involvement of all federal agencies that support such research. We believe that NSF must weigh its responses to the report in the context of the entire federal environmental research portfolio. The resources and processes of the CENR should be used to help NSF optimize coordination, build on existing agency strengths, and minimize conflict. The Board's suggestion that the NSTC reevaluate the portfolio to identify research gaps and set priorities is very appropriate. In fact, this process is already well underway with the development of the "Integrated Science for Ecosystem Challenges" (ISEC) initiative developed for the FY 2000 and 2001 budget requests. As you know, this effort involved dozens of representatives of the CENR agencies in an effort to begin an expansion of ecosystem research to improve the information available to decision makers. The PCAST Environment and Natural Resources Panel has been carefully tracking the development of ISEC and believes that much of the thinking that has gone into the initiative could form a starting point for the development of future priorities.

It is perhaps also an appropriate time to enlist the assistance of OMB to do an evaluation of the status of environmental R&D funding across all agencies to update the budget information that was prepared for the 1995 CENR strategy document, "Preparing for the Future Through Science and Technology." We are well aware that it is no simple task to develop an accurate picture of the environmental portfolio. On the other hand, we do not see how the identification of research gaps and the setting of priorities for expanding the portfolio can be adequately done without accurately determining where we are at the moment, both inside NSF and across the environmental R&D agencies. We would be happy to work with OMB and the CENR leadership to develop an appropriate taxonomy for such an exercise.

With regard to the NSB report overall, we applaud the Board's recommendation that environmental research be made one of NSF's highest priorities and agree that funding should be substantially augmented, particularly in five specific areas emphasized in the report: interdisciplinary research; environmental education; economic valuation of ecological goods and services; long-term, large-scale research; and improving environmental assessment capabilities. As you know, PCAST has recommended increasing the priority and funding of environmental science in several of our own recent reports. Those of us in the environmental field know that such funding increases are justified; many in policy positions may need to be convinced. Perhaps the Board adding its voice on this issue will tip the balance and gain the attention of Congressional decision-makers in a position to help implement this recommendation.

The funding increase recommended (ultimately an additional $1 billion per year at the end of a five year period) is very large, equal to about 20 percent of the entire current federal environmental R&D portfolio. We do not disagree that an increase of this magnitude is needed. But we believe, as noted above, that if NSF were to carefully address the integration of its efforts with other ongoing Federal research to ensure minimal duplication of effort, cooperation, not competition for resources, and sharing of expertise and research infrastructure as part of its planning to make effective use of new funding, it would greatly help to justify such an increase.

We strongly agree with the Board's call for increased support for interdisciplinary research. It is clear that, despite many earlier calls for increased interdisciplinary research by numerous prestigious groups, this is a very difficult thing to accomplish in practice. While we do not mean to advocate additional bureaucracy, we do think the "focal point" recommendation must be taken seriously and should be addressed using some creative thinking.

We do not believe that the increased emphasis on interdisciplinary activities called for in the report will materialize without the establishment of some mechanism designed to foster such activities.

We also note with satisfaction that the Board has reiterated the need for enhanced attention to work that addresses the interface between ecology and economics, including ecological goods and services and the social, cultural, and economic aspects of the environment. We believe this is an area of study that only NSF can promote at the moment, because there is no other logical focal point in the federal government for such work. As we did in *Teaming With Life,* we urge the Foundation to find a way to make this possible and we appreciate the Board's seconding one of our key recommendations.

We are also pleased to see an added emphasis on issues of larger spatial and longer temporal scales, which is crucial to being able to address emerging problems, such as climate change and loss of biological diversity, and agree that an increased emphasis on "assessment" is appropriate. With respect to the latter, however, we think it is essential for the report to be much more specific about what kinds of "assessment" are included in the recommendation for increased attention by NSF. We agree that appropriate kinds of assessment include not just synthesis, but also "evaluation and communication of scientific understanding." The addition of some specific examples of what the Board views as appropriate and inappropriate types of assessment activities for NSF would clarify the recommendation. It would also be helpful in providing reassurance to other CENR agencies about where NSF is likely to be headed as it implements the NSB's guidance.

In closing, we would like to make one additional comment on NSF's "Biocomplexity" initiative and its relationship to the recommendations in the report. The NSB indicated to us that "Biocomplexity in the Environment" has now become the descriptor of the full portfolio of environmental science and engineering at NSF. Furthermore, the Board has stated that the funding increases obtained for an FY2000 "Biocomplexity" initiative ($50 million) represent the beginnings of the increased investment in environmental science called for in the Board's report. We urge NSF to clarify which of the Board's recommendations will benefit from the increase this year, as well as those proposed for 2001. Such information will be very important to the CENR for further development of ISEC across all of the agencies.

We very much appreciate having had the opportunity to comment on this important report. We would be happy to discuss our views with you further.

Sincerely,

Peter Raven
Chair
PCAST Environment Panel

John Holdren
Chair
PCAST Energy Panel

Appendix F

Selected Centers Supported by NSF

NSF supports a variety of individual centers and center programs to advance science and engineering, particularly in the areas of interdisciplinary research and the integration of research and education. In general, these centers and programs are committed to addressing scientific and engineering questions with a long-term, coordinated research effort; ensuring a strong educational component; and developing partnerships with industry to help ensure that research is relevant to national needs. Note that as used here, “centers” include consortia, collaboratories, and similar arrangements intended to facilitate research or educational activities.

This appendix lists centers and center programs that were supported by NSF in FY 1998 and were either primarily involved in research related to the environment or conducted a subset of activities with relevance to environmental research and education. Individual centers having an environmental dimension within these programs are shown in *italics*. For descriptions of center programs and of some individual centers, search the NSF web site (http://www.nsf.gov/home/search.htm).

Centers of Research Excellence in Science and Technology
- *Advanced Materials and Smart Structures*
- *Environmental Science*
- *Innovative Manufacturing of Advanced Materials*
- *Systems Science Research*

Collaboratory for Lower Atmospheric Research

Digital Library & Spatial Information for Ecological & Environmental Studies

Earthquake Engineering Research Centers
- *Center for Advanced Technologies in Earthquake Loss Reduction*
- *Mid-America Earthquake Center*
- *Pacific Earthquake Engineering Center*

Electronic Library for Environmental Impact Evaluation

Engineering Research Centers
- *Biofilm Engineering*
- *Biotechnology Process Engineering*
- *Engineered Biomaterials*
- *Environmentally Benign Semiconductor Manufacturing*
- *Interfacial Engineering*
- *Marine Bioproducts Engineering*
- *Offshore Technology*

Environmental Molecular Science Institutes
- *Chemical Sources and Sinks at Liquid/Solid Interfaces*
- *Institute for Environmental Bioinorganic Chemistry*
- *Institute for Environmental Catalysis*

Global Change Institutes

Incorporated Research Institutions for Seismology

Industry/University Cooperative Research Centers
- *Berkeley Sensor & Actuator Center*
- *Biodegradation*
- *Building Environment*
- *Center for Advanced Control of Energy and Power Systems*
- *Cooperative Research Center in Coatings*
- *Corrosion*
- *Hazardous Substance Management*
- *Integrated Pest Management*
- *Biosurfaces*
- *Surfactants*

Land Margin Ecological Research

Long Term Ecological Research Sites
- *Arctic Tundra*
- *Bonanza Creek Experimental Forest*
- *Cedar Creek Natural History Area*
- *Central Arizona-Phoenix Urban LTER*
- *Central Plains Experimental Range*
- *Coweeta Hydrologic Laboratory*
- *H.J. Andrews Experimental Forest*
- *Harvard Forest*
- *Hubbard Brook Experimental Forest*
- *Jornada Experimental Range*
- *Kellogg Biological Station*
- *Konza Prairie Research Natural Area*
- *Luquillo Experimental Forest*
- *McMurdo Dry Valleys, Antarctica*
- *Metropolitan Baltimore Urban LTER*
- *Niwot Ridge-Green Lakes Valley*
- *North Temperate Lakes*
- *Palmer Station, Antarctica*
- *Plum Island Sound*
- *Sevilleta National Wildlife Refuge*
- *Virginia Coast Reserve*

Mathematical Sciences Research Institutes
- *Institute for Mathematics and Its Applications*

National Center for Atmospheric Research

National Center for Ecological Analysis and Synthesis

National Center for Geographic Information and Analysis

National Optical Astronomy Observatories

Plant Genome Centers
- *Functional Analysis of Arabidopsis Genome*
- *Genomics of Plant Stress Tolerance*
- *Soybean Functional Genomics*

Regional Research Institutes

Research Centers on the Human Dimensions of Global Change

Science and Technology Centers
- *Advanced Concrete Based Materials*
- *Analysis and Prediction of Storms*
- *Astrophysical Research in Antarctica*
- *Biological Timing*
- *Clouds, Chemistry, and Climate*
- *Computer Graphics and Scientific Visualization*
- *Engineering Plants for Resistance Against Pathogens*
- *Light Microscope Imaging and Biotechnology*
- *Microbial Ecology*
- *Molecular Biotechnology*
- *Southern California Earthquake Center*

Science and Technology Policy Institute

State/Industry/University Cooperative Research Centers
- *Capsule Pipeline for Coal*
- *Intelligent Information Retrieval*
- *Rock Mechanics*

University NAVSTAR Consortium

Appendix G

Acronyms and Abbreviations

BE	Biocomplexity in the Environment
CENR	Committee on Environment and Natural Resources
CI	Conservation International
CNIE	Committee for the National Institute for the Environment
CSREES	Cooperative State Research, Education, and Extension Service
DIVERSITAS	Umbrella program to coordinate the global research effort in the biodiversity sciences
DOC	Department of Commerce
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DOT	U.S. Department of Transportation
EHR	NSF Directorate for Education and Human Resources
EPA	U.S. Environmental Protection Agency
ESA	Ecological Society of America
FEMA	Federal Emergency Management Agency
FCCSET	Federal Coordinating Council for Science, Engineering and Technology
FY	fiscal year
GIS	Geographic Information System
GLOBE	Global Learning and Observations to Benefit the Environment
GLOBEC	Global Ocean Ecosystems Dynamics
GPO	Government Printing Office
HCP	habitat conservation plan
HHS	(Department of) Health and Human Services
ICSU	International Council for Science (formerly International Council of Scientific Unions)
IGBP	International Geosphere-Biosphere Programme
IOM	Institute of Medicine
IPCC	Intergovernmental Panel on Climate Change
ISEC	Integrated Science for Ecosystem Challenge
IUCN	World Conservation Union (formerly International Union for the Conservation of Nature)
LTER	Long Term Ecological Research
MAB	Man and Biosphere
NAE	National Academy of Engineering
NASA	National Aeronautic and Space Administration

NCAR	National Center for Atmospheric Research
NCEAS	National Center for Ecological Analysis and Synthesis
NGO	nongovernmental organization
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSB	National Science Board
NSF	National Science Foundation
NSTC	National Science and Technology Council
OECD	Organisation for Economic Co-operation and Development
OMB	Office of Management and Budget
ONR	Office of Naval Research
OSTP	Office of Science and Technology Policy
PCAST	President's Committee of Advisors on Science and Technology
R&D	research and development
SAES	State Agricultural Experiment Stations
SCOPE	Scientific Committee on Problems of the Environment
SI	Smithsonian Institution
UCAR	University Corporation for Atmospheric Research
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
USGCRP	U.S. Global Change Research Program
WHO	World Health Organization
WMO	World Meterological Organization
WRI	World Resources Institute
WWF	World Wildlife Fund

Environmental Science and Engineering for the 21st Century/The Role of the National Science Foundation (NSB 00-22) is available electronically at:
http://www.nsf.gov/cgi-bin/getpub?nsb0022

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