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INTERIM REPORT

ENVIRONMENTAL SCIENCE AND ENGINEERING FOR THE 21ST CENTURY

The Role of the National Science Foundation

National Science Foundation

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National Science Board

NATIONAL SCIENCE BOARD

National Science Board
Committee on Programs and Plans

Task Force on the Environment

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The National Science Board (NSB) consists of 24 members plus the Director of the National Science Foundation (NSF). 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, 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 determining the best means of implementing activities related to this area. 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 the National Science Foundation at the policy level that will be used for designing an appropriate portfolio of activities, consistent with the overall National Science and Technology Council (NSTC) strategy, the goals of the NSF Strategic Plan, and activities of other agencies and organizations that support related programs.

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. This report is being released as an interim document to provide ample opportunity for discussion and consultation with the National Science and Technology Council, other agencies, the scientific community, public and private sectors, and other interested parties.

This interim report is based on extensive review of relevant policy documents and reports, a process of hearings and consultations with invested communities, invited commentary from a variety of organizations and individuals, and feedback from 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.

I want to commend Dr. Jane Lubchenco, the chair of the task force, and the other task force members, NSB members Drs. Mary K. Gaillard, Robert Solow, and Warren Washington; and 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 task force has also been assisted in its efforts by many members of the NSF staff, too numerous to mention individually. However, the contributions of Dr. Robert Webber, Office of Information and Resource Management, Ms. Anne Tenney, Office of the Director, and Ms. Jean Pomeroy, National Science Board Office, deserve special note, as well as Dr. Margaret

Cavanaugh, Program Director for Inorganic, Bioinorganic, and Organometallic Chemistry, and Dr. Robert Eisenstein, Assistant Director for Mathematical and Physical Sciences.

The Board is especially grateful for the strong support provided throughout by the Director of the National Science Foundation, Dr. Rita Colwell.

Eamon M. Kelly
Chairman

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Context and Framework for the Study

The promise and opportunities for our Nation in the decades ahead will depend on the role that science and technology can play in the generation of new wealth, in safeguarding the health of our planet, on opportunities for learning and individual development, and on the integration of our national interests into a global perspective. The environment, in this context, is a vigorous, essential, and central theme in both domestic and international affairs.

Investments by the National Science Foundation have played a key role in significantly increasing our understanding of the environment. Fundamental research has elucidated the physical, biological, chemical, geological, and societal interactions, dynamics, and functions of such issues as the health and vitality of ecosystems, the predictability of weather, the role that oceanic currents play in climate, projections on sea level changes, the evolution of animal and plant species, and changes in terrestrial and marine ecosystems. 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 primary mission, these funds primarily go to awards based on external, peer-reviewed national competition, and these investments provide advances in fundamental understanding of environmental systems. Therefore, the NSF, because of this mission and record of accomplishment, should provide a more vigorous intellectual and leadership role in advancing 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 National Science 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 of the emerging environmental issues in our Nation and around the world suggests a need to evaluate the challenges and opportunities that these critical issues raise for the NSF. Therefore, the National Science Board established a Task Force on the Environment, whose findings are detailed in this report, along with a set of recommendations to set the stage for a more vigorous role of the NSF in environmental research, education, and scientific assessments 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 from this spectrum of documents and from scholars in every scientific discipline. Comments were received from community groups, local and Federal agency officials, professional societies, non-governmental organizations, 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 environmental activities of the Foundation.

Principal Findings

A number of themes emerged from this diverse set of inputs. 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 develop its environmental portfolio. 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. It was clear throughout the public-input process that citizens, many governmental officials, other Federal agencies, professional scientific and engineering societies, and individual scientists look to the NSF for leadership in environmental research, education and scientific assessment. The strong message running throughout 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 requirement for significant new resources to accomplish these goals and an effective organizational structure to implement NSF's total environmental portfolio.

Recommendations

The 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 has developed twelve recommendations which are organized into (a) two overarching keystone recommendations that address critical funding resources and organizational issues, (b) five recommendations on research, education, and scientific assessment, (c) four crosscutting recommendations that address physical, technological and information infrastructure, and (d) one recommendation that addresses the importance of partnerships, collaborations, and coordination to NSF's programs and activities in research, education, and scientific assessments.

Keystone Recommendations

> **Resources and Funding (Recommendation 1)**: Environmental research, education and scientific assessment should be one of the highest priorities of the National Science Foundation. The current environmental portfolio, an investment of approximately $600 million, represents only about one-third of the resources necessary. In view of the overwhelming importance and exciting opportunities for progress in the environmental arena, and because existing resources are fully and appropriately utilized, new resources will be required. Therefore, we recommend that environmental research, education and

scientific assessment at NSF be increased by an additional $1 billion over the next 5 years.

Organizational Approach (Recommendation 2): 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 NSF. These criteria include:

1. 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;
   - A formal advisory process specifically for environmental activities.
2. Continuity of funding opportunities, in particular in interdisciplinary areas.
3. Integration, cooperation and collaboration with and across established programmatic areas, within NSF and between NSF and its sister Federal agencies.

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 may be required to facilitate successful interdisciplinary programs.

Disciplinary Research (Recommendation 3): 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.

Interdisciplinary Research (Recommendation 4): 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.

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

Education Recommendation

The role of the NSF is to create educational and training opportunities that enhance scientific and technological capacity associated with the environment, across both the formal and informal educational enterprise. 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.

> **Environmental Education (Recommendation 6):** The Foundation should enhance its formal educational efforts by encouraging submission of proposals that capitalize on the inherent student interest in environmental areas while supporting significantly more environmental educational 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, whether or not they have been part of the scientific and engineering traditions.

Scientific Assessment Recommendation

The Board defines scientific assessment, for the purposes of this report, as inquiry-based analysis 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 role of the NSF is to facilitate the development of methods and models of scientific assessment and foster the conduct of scientific analyses of environmental issues, both domestically and internationally. Research on how to do effective, credible and helpful scientific assessments is timely. 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. Such assessments, coordinated across the Federal sector and, where appropriate, internationally are needed for setting scientific priorities and for summarizing scientific information for decision-makers.

> **Scientific Assessments (Recommendation 7):** The Foundation should significantly increase its research on the methods and models that support the scientific assessment process. 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 that pull together interdisciplinary teams. The Board finds that an important role of the NSF is to facilitate the development of facilities, instrumentation, and other infrastructure that enables discovery, including the study of processes and interactions that occur over long-time scales.

> **Enabling Infrastructure (Recommendation 8):** High priority should be given to enhancing infrastructure for environmental observations and collections as well as new information networking capacity. A suite of environmental research and education hubs should be created, 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 role of NSF is to foster research that seeks to develop innovative technologies and approaches that assist the Nation in conserving its environmental assets and services. The NSF could 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.

> **Environmental Technology (Recommendation 9):** 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.

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

> **Enabling Technologies (Recommendation 10):** 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.

> **Environmental Information (Recommendation 11):** The Foundation should take the lead in enabling a coordinated, digital, environmental information network. In addition,

the NSF should catalyze a study to frame a central source that compiles comparable, quality-controlled time series of 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 and are most effective when they are based on intellectual needs. Partnerships, among federal agencies, with non-governmental bodies (e.g., private sector entities, NGO's, and others), and with international organizations can provide the intellectual and financial leveraging to address a) environmental questions at the local level, b) larger-scale regional issues, and c) problems for which the research and the policy dimensions are international. There are thus many opportunities to partner in bilateral/multilateral agreements or via National Science and Technology Council (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.

Implementation Partnerships (Recommendation 12): The 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. These 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 the NSTC, with advice from PCAST, 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 and education.

Conclusion

Scientific understanding of the environment, together with an informed, scientifically literate citizenry, is requisite to quality of life for generations to come. As the interdependencies of fundamental and applied environmental research become more evident, the 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.

I. Introduction

The Strategic Plan of the National Science Board highlights the promise and opportunity for science and engineering in the 21st century: "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 1998[1]).

Within the broad portfolio of science and engineering for the new century, the environment is emerging as a vigorous, essential, and central focus. New discoveries have revealed unappreciated linkages between the environment and human health, prosperity and well-being (Boxes 1 and 2). 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 is increasing (Box 3). Ongoing alterations to the biology, chemistry and in some cases physical structure of the land, air, and water of the planet will present formidable challenges in the years to come (Box 4).

Ecological services are essential, to humanity, but their dimensions and values are inadequately understood. *See Box 1, page 66.*

Meeting these challenges will require significant scientific and technological advances, rapid communication of new understanding to the private and public sectors, and an informed electorate demanding and capable of utilizing new knowledge. An improved understanding of the dynamics of complex systems, especially complex biological systems, will be essential (Box 5). New opportunities for environmentally benign technologies will expand rapidly due to multiple developments that have come to fruition as a result of past investment in very diverse areas of scientific research (Box 6). New advances in information sciences, biotechnology, materials science, mathematics, statistics, and social science will enable formerly impossible imaging, analyzing, modeling, engineering and decision-making opportunities (Boxes 7-11). Increased awareness of the importance of intact, functioning ecological and social systems will stimulate new requests by citizens and policy-makers for timely, credible information about environmental changes. In short, advances in environmental research, education and scientific assessment are key to realizing significant improvements in human health, prosperity and well being in the next century.

Environmental science and engineering are broadly interdisciplinary, drawing upon, integrating and invigorating virtually all fields of science and engineering. In addition to new disciplinary areas of investigation, new interdisciplinary interfaces will drive significant advances. These interdisciplinary perspectives will characterize not only the research enterprise, but educational and scientific assessment approaches as well. Moreover, large spatial and long temporal scales are required to understand adequately many environmental phenomena. This diverse and comprehensive nature of scientific environmental activities poses particular challenges to ensure quality, integration, and continuity across disciplines, over space and through time.

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[1] http://www.nsf.gov/cgi-bin/getpub?nsb98215

The National Science Foundation, other Federal agencies, and interagency coordinating bodies such as the Committee on Environment and National 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. However, the magnitude of the challenges and the timeliness of opportunities indicate that a whole new level of integrated activities and programs will be required in the near future (see, for example, PCAST 1998). Meeting this challenge will require (1) significant new scientific advances, (2) improved public understanding of environmental topics, (3) more effective communication of new knowledge, and (4) incorporation of new knowledge into policies and practices. NSF has significant responsibilities in the first three of these areas.

Because of its mission and track record, NSF is poised to provide a more vigorous and intellectual leadership role. NSF can provide the fundamental understanding of the complexity of the Earth's environmental envelope and its human interactions through discovery, focused education and training, information dissemination, and scientific assessments. This role is consistent with NSF's mission – "to promote the progress of science; to advance the national health, prosperity, and welfare; to secure national defense…" (NSF Act of 1950).

As part of its ongoing responsibilities for oversight of the National Science Foundation, the National Science Board posed the question: What should the environmental portfolio of the Foundation look like, within the context of the larger Federal agency suite of activities, in order to provide and communicate the knowledge required to respond to current and future environmental challenges? The Board focused on the overall level, the balance, and the organization of the environmental activities of the Foundation. Its findings are summarized in this report, beginning with a description of the goals to be accomplished, a summary of current and anticipated activities within the Foundation, a review of suggestions and information received by the Board during its review, and concluding with findings and recommendations.

Goals for NSF's Environmental Portfolio

Within the context of the family of federal agencies, the following goals should guide the design and implementation of the Foundation's environmental portfolio:

- Discovery across the fields of science and engineering to elucidate the processes and interactions among the atmosphere, biosphere, cryosphere, hydrosphere, lithosphere, and socio-economic systems, thereby providing an integrated understanding of the natural status and dynamics of, and the anthropogenic influences on, the Earth's environmental envelope.

- Education and training that enhance scientific and technological capacity associated with the environment, across both the formal and informal educational enterprise; and

- Effective integration and dissemination of research results 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 a combination of physical, technological, and information infrastructure, and partnerships:

- 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 assist the Nation in conserving and wisely utilizing its environmental assets and services;
- Mechanisms and infrastructure to synthesize and aggregate scientific environmental information and to provide open access to these informational materials; and
- Partnerships with other Federal agencies, state and local governments, the private sector and other nations to advance knowledge, understanding and solutions.

With these goals and enabling infrastructural needs in mind, the Board undertook an analysis of current and anticipated environmental activities within the Foundation.

II. The Larger Context for Environmental Research, Education, and Scientific Assessment

The national investment in science and engineering R&D produces a wide variety of benefits ranging from new knowledge and new technologies to new cures to more enlightened policies and practices. Multiple Federal agencies contribute to the national investment in environmental science and technology. Overall, the Federal Government currently supports an environmental R&D portfolio that is estimated to be in excess of $5 billion per year.

Collaboration and cooperation across agencies is enabled through multiple mechanisms. In addition to the bilateral and multi-lateral partnerships developed between individual agencies focusing on environmental research, many efforts have been coordinated through the White House. The Committee on Environment and Natural Resources (CENR) of the National Science and Technology Council (NSTC), operating through the President's Office of Science and Technology Policy (OSTP) coordinates environmental R&D activities. The President's Committee of Advisors on Science and Technology (PCAST) provides advice on the roles of science and technology in achieving national goals.

Established in 1993 and chaired by the President, the cabinet-level NSTC serves as an initiator and coordinator of interagency science and technology research and development. The CENR is one of five committees under the NSTC. With respect to the NSF, the NSTC/CENR informs and influences the process by which the Foundation establishes research priorities and responds to policy concerns. The NSF plays an active role in a variety of important multi-agency activities of the CENR, including the successful U.S. Global Change Research Program, the new Integrated Science for Ecosystem Challenges activity, and the National Biological Information

Infrastructure (NBII), 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. The CENR has sought, and continues to seek, advice from a wide range of stakeholders from academia, industry, other private-sector groups, Congress, and state and local governments. The 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 policymakers in understanding the basis and uncertainties of those projections.

A 10% savings in national environmental management costs is twice the current annual level of federal R&D expenditures for environmental research. When viewed in this context, the nation cannot afford not to invest in the insurance afforded by a sound .environmental research strategy and its implementation.

The term "assessment" is generally used to refer to two fundamentally different activities: resource assessment and scientific assessment. Resource assessment, evaluation of the quality and/or quantity of a particular natural resource, is best done by the relevant Federal management or regulatory agencies in cooperation with the cities, states, or regional entities that are naturally involved. Scientific assessment (also called knowledge assessment) is evaluation of the state of existing knowledge, and often serves to identify new research opportunities. Scientific assessments are particularly deserving of an interagency partnership approach, as the agencies involved must be prepared to act on the information resulting from the assessments and, thus, must be part of the development of the assessment protocols. The couplings of assessments to the needs of the mission agencies are clear, and go well beyond the purview of the NSF. The NSF does have a role, however, in enabling the synthesis, analysis, and clear communication of research findings---particularly basic research findings--- in a timely fashion. In addition, the NSF can provide a valuable service to other agencies and to the scientific and engineering community by supporting the development of explicit research agendas that articulate research needs for environmental issue areas.

Environmental changes often grab headlines and make sorting out fact from fiction problematic. Fortunately, credible information is available for some important phenomena. See Box 3, page 69.

The CENR has also encouraged increased extramural research and development in the overall mix of federal R&D. In addition, the 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 the CENR works to ensure that the capabilities and resources of each of these sectors are appropriately integrated, it looks to the 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.

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[2]. 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[3].

For many years, the dominant environmental paradigm has been learning too late. A new basic science and engineering research agenda can enable environmentally benign technology development. *See Box 6, page 74.*

Immense advances in science and engineering have been made possible by national policies assuring that discovery in science and engineering serves national goals to promote economic growth, improve the quality of life, and insure national security. As the interval between discovery and industrial innovation becomes shorter, university-industry partnerships must be strengthened to exploit new opportunities that will arise in environmental technologies and supporting fields. Overall industry sees strength in its ability to link inventions to markets and to commercialize new technologies. It relies on a rich science and technology base for future environmental technology innovations (Resetar et al. 1999[4]).

The environmental market is increasingly technology-driven, indicating that suppliers must make continuing large research and development expenditures. The large multinational environment companies are most R&D intensive, spending 8 to 10 percent of turnover on research, while smaller firms in lower-technology environmental sectors may spend less than 2 percent of turnover on research and development (OECD 1992[5]). 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[6]:

- 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.

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[2] National Science Board. 1998. National Science Board Strategic Plan. NSB 98-215.
[3] National Science Foundation. 1995. NSF in a Changing World: the National Science Foundation's Strategic Plan. NSF 95-24.
[4] Resetar, S., B. E. Lachman, R. Lempert, and M. M. Pinto. 1999. Technology Forces at Work. RAND Science and Technology Policy Institute. Available at http://www.rand.org/
[5] Organization for Economic Cooperation and Development. 1992. The OECD Environment Industry: Situation, Prospects, and Government Policies. OECD, Paris.
[6] National Science and Technology Council. 1994. Technology for a Sustainable Future: A Framework for Action. NSTC. Washington, D.C.

- 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.

III. Scope of Current NSF Environmental Activities

The NSF is a Federal funding agency, providing support that enables and facilitates the performance of scientific and engineering research and education. NSF 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. Appendix D provides information about the process and criteria used to develop NSF's programs.

Spending on environmental activities – defined broadly to recognize the full range of disciplines and fundamental research activities involved – currently represents roughly 20 percent of the total NSF budget. Expenditures totaled $542M in FY 1998 with $597M budgeted for environmental activities in the FY 1999 Current Plan and $671M requested in the FY 2000 budget. Consistent with NSF's primary mission, the majority of these funds go to integrated research and education projects: scientific assessment, as defined later in this report, receives modest support. By way of context, the larger Federal investment in environmental R&D totaled $5.3 billion in FY 1995 in the most recent budget crosscut published by the NSTC Committee on Environment and Natural Resources[7].

Research

NSF plays a key 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. Consistent with the mission of NSF, this research provides advances in 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. As in other scientific and engineering arenas, NSF's environmental research activities function as the fulcrum for advances by other Federal agencies, state and local governments, the private sector and citizens.

New research on climate and ecosystem change is shedding light on emerging human diseases. See Box 2, page 67.

A Diverse Portfolio across the Foundation

Investigation of fundamental environmental questions pervades the entire scientific and engineering research enterprise. From the rigors of the search for understanding microbial

[7] National Science and Technology Council. 1995. Preparing for the Future Through Science and Technology. An Agenda for Environmental and Natural Resource Research. Committee on Environment and Natural Resources. NSTC. Washington, D.C.

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 continue an age-old quest to understand Earth's lifeforms 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, more sensitive and versatile analytical instrumentation, and by increasing interest in interdisciplinary research. In addition, concerns about the effects of human activity have led to increased attention to development of environmentally benign advanced technologies and deeper understanding of the social dimensions of environmental systems.

The reach of environmental science and engineering is evident in NSF's multiple approaches to funding and its broad portfolio of interests. The new environmental challenges and opportunities increasingly require both disciplinary and interdisciplinary advances. Ongoing core programs 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. In addition, special competitions respond to new topical areas, are often interdisciplinary in nature, and provide opportunities for interagency cooperation. NSF's strategy is to enable these topical areas to mature, and to foster connections among participating investigators, and then to fold the area into ongoing programs, allowing new areas to emerge. Two recent examples of highly successful multidisciplinary special competitions include Environmental Geochemistry and Biogeochemistry, which supports research on the chemical processes that determine the behavior and distribution of inorganic and organic materials in environments near the Earth's surface, and Life in Extreme Environments, which addresses such fundamental questions as determining the evolutionary and physiological processes that led to the formation and adaptation of life on Earth. Center or large group activities provide a framework for long-term studies of complex, cutting-edge topics. NSF supports a number of centers that have environmental work as all or part of their portfolio (Appendix E).

After thousands of years of stability, the chemistry of the Earth's surface is changing rapidly. New information about the nitrogen cycle sheds light on some puzzling environmental trends. See Box 4, page 71.

Terrestrial, freshwater and marine ecosystems all around the world are probed, sometimes through interdisciplinary approaches. Much of this work is carried out in ongoing programs. At present, special initiatives are being supported in such areas as investigation of harmful algal blooms, life in extreme environments, and watershed scale research. Of note in this area are the opportunities for long-term studies that are essential to understanding ecosystem dynamics and the impact of stressors. Many of these studies are carried out in the Long Term Ecological Research (LTER) program, which is celebrating its 20^{th} anniversary.

Research on physical processes in the environment is a major effort currently underway. 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. 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

(NSF/NASA/NOAA/ONR/DOE). In addition, ongoing programs support studies of ocean, earth, and atmospheric systems.

Socioeconomic sciences add new understanding of interactions between humans and landscapes. See Box 9, page 77.

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. Some special initiatives in these areas take advantage of opportunities to collaborate with other agencies. For example, a joint NSF/EPA venture on environmental statistics is developing algorithms for use on environmental problems while 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 enable vigorous, healthy communities and sustainable growth.

A growing trend is the synthetic integration of data sets and the increasing use of modeling. Such integration takes place both at large centers such as the National Center for Atmospheric Research (NCAR) and the National Center for Ecological Analysis and Synthesis (NCEAS), and increasingly within individual investigator projects. These trends are facilitated by high-speed computers, 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.

Ecological systems are highly nonlinear, with abrupt threshold dynamics. Accurate predictions for these systems are difficult, even with the prodigious computing power now available. On the other hand, we can reasonably expect serviceable forecasts of the range of likely behaviors and the probabilities of various outcomes. See Box 5, page 72.

New Directions

A new intellectual construct for NSF's activities in environmental science and engineering is the theme Biocomplexity in the Environment[8] (BE). The title reflects the evolution of NSF thinking about how NSF activities in this area can take advantage of opportunities provided by recent advances in science and engineering and best contribute to the overall program of Federal activities related to the environment. BE incorporates and provides a broader context for the earlier suite of activities entitled Life and Earth's Environment (LEE).

BE activities include disciplinary studies of components of environmental systems as well as a variety of interdisciplinary efforts to look at aspects of interaction among these components. Scientific advances resulting from these lines of inquiry, combined with greatly enhanced technological capabilities, now enable more comprehensive study of phenomena at smaller scales, of relationships between scales, and of a wider range of simultaneous and interactive processes. In FY 2000, NSF will begin a focused initiative to study "biocomplexity", which

[8] http://www.nsf.gov/home/crssprgm/be/

describes the dynamic behavior between living organisms and their environments, in order to provide greater insight into the underlying processes of environmental systems.

Biocomplexity research will integrate expanding knowledge about living organisms, including humans, with an enhanced understanding of Earth's systems. This will require development of more sophisticated conceptual and computational models for use in understanding complex systems, which often span temporal and spatial scales and can exhibit unexpected behavior. Careful attention to the interplay among components as well as emergent system properties is critical to obtaining the level of credible predictive information on which management and regulatory decisions can be made. The study of biocomplexity will be a central element of the environmental portfolio, as it is critical to advancing multiple fields of research that focus on environmental challenges.

> *The recent finding that DNA can move between distantly related microbial groups shatters the long-held assumption of strict linear descent during evolution of species. Thus far, the genomic revolution has touched only the tip of microbial life, we have a great deal to learn from genomic analysis of higher organisms.* *See Box 8, page 76.*

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 NSF to make more effective use of partnerships is extraordinary. NSF presently cooperates with other Federal agencies, state and local governments, private sector firms, organizations and foundations, non-governmental organizations, and scholarly associations. Outside the United States, NSF works with counterpart agencies of foreign governments, intergovernmental organizations such as the United Nations, and non-governmental organizations such as the International Council of Scientific Unions (ICSU).

The NSTC Committee on Environment and Natural Resources (CENR) provides a mechanism to facilitate and foster interagency research (see Appendix D). The CENR has highlighted the importance of coordinating research that has relevance to national initiatives and priorities, environmental statutes, and regional and global agreements and conventions. Areas for improvement for such research have also been recognized by the CENR, including the need to strengthen extramural academic research programs, encourage external peer-review of all research and development programs and invest in future human-resource and technical research capabilities.

Building on the success of the U.S. Global Change Research Program (USGCRP) in developing a successful interagency program, the 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. In addition, the NSF has

> *The ocean beneath the sea floor is the deep biosphere. Conditions of high temperature and pressure, and absence of sunlight may have been the conditions at the dawn of life on this planet.* *See Box 10, page 79.*

developed a wide range of bi- and multi-lateral interagency environmental activities that are not specifically part of the larger NSTC efforts (see Appendix D). NSF has also assisted other agencies in developing NSF-style peer review systems for these competitions.

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

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 as well as 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.

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[9]. In addition, a growing number of primarily research activities are adding integrated education components. For example:

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

- The National Center for Ecological Analysis and Synthesis (NCEAS) has established a partnership with a locally-developed science curriculum called Los Marineros. The partnership forms the basis of the sciences curriculum for all 5th grade students in Santa Barbara, CA. Scientist volunteers from NCEAS adopt a 5th grade class and develop an ecology experiment that the class conducts during the school year.

- The Environmental Molecular Science Institutes were recently established through an NSF Division of Chemistry and U.S. DOE competition to provide for collaborative research on the molecular behavior of complex, dynamic environmental systems[10]. In addition to the other review criteria, proposals were evaluated based on the quality of the

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9 http://www.nsf.gov/home/crssprgm/reu/start.htm
10 http://www.nsf.gov/pubs/1997/nsf97135/nsf97135.htm

education and training components, especially plans to involve students and under-represented groups.

- All Water and Watersheds proposals now must include plans for meaningful integration of research with education and outreach. The Principal Investigator's (PIs) are encouraged to include involvement of local school groups in field sampling, lab analyses, or other project activities.

In addition to education accomplished through research project support, approximately $29 million was spent in FY 1998 on environment-related projects funded by the Directorate for Education and Human Resources (EHR). Consistent with a growing 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.

The Directorate for Education and Human Resources provides support for science and mathematics education across all levels of formal education as well as through informal mechanisms. 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 related to the environment include:

- Teacher preparation and professional development projects for teachers.
- 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.
- Informal education projects such as museum exhibits, video documentaries, radio programs; large-format films, and television series.

Acquiring data is no longer the major hurdle — managing, validating and understanding the data are the new challenges. *See Box 7, page 75.*

Joint funding of education projects across directorates has been increasing. For example, EHR also collaborates with the Directorate for Geosciences 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. GLOBE students make environmental observations at or near their schools and report their data through the Internet[11]. Scientists use GLOBE data in their research and provide feedback to the students to enrich their science education. GLOBE calls for proposals are released about every four years and NSF invests ~$2M per year on the awards.

[11] http://www.globe.gov/

Scientific Assessment

Scientific assessment is viewed by the Board as a critical element of the effective integration and communication of scientific research findings. Results of individual and team research efforts do not usually provide the synthesis and integration necessary to set research priorities or to provide guidance for environmental policy or management decisions. Scientific assessment is particularly desirable when there exist complex data sets and results from multiple research sites, disparate time intervals, or varying environmental conditions. Scientific analysis, synthesis and modeling provide rational mechanisms for integrating and evaluating results or for defining the most productive research avenues to pursue.

For the purposes of this report, scientific assessment is defined as inquiry-based analysis of relevant biological, socioeconomic, and physical environmental scientific information to provide an informed basis for 1) prioritizing scientific investments and 2) societal action.

Because the purpose of scientific assessment is the integration and communication of research results, the form of communication must be appropriate for and responsive to the intended audiences. The traditional audience for the vast majority of scientific research has been the scientific community, with publication in scientific journals the vehicle. Environmental topics can also employ alternate avenues of communication of peer-reviewed scientific findings to a broader array of audiences, both public and private sectors.

Advanced statistical approaches can improve understanding of fire in vulnerable regions. *See Box 11, page 80.*

NSF currently funds a small number of assessment activities. Some of these focus on the science of assessments, i.e., they provide grants to analyze the process of conducting effective assessments. Other activities involve grants to groups of recognized experts with the goal of synthesizing information and reporting it in a credible and useful fashion. NSF enables scientific assessments in the same way that it enables scientific and engineering research: by providing funding for the highest-quality work as judged by merit review. Three recent or current assessment activities funded by the Foundation are briefly described below.

1. The NSF is one of the interagency partners charged by the Global Change Research Act of 1990 to conduct a national assessment. The overall goal of the assessment is to analyze and evaluate what is known about the potential consequences of global change for the U.S. The current assessment focuses on the consequences of climate variability and change and is timed to provide input to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). NSF has contributed to the regional, sectoral, and national assessment activities coordinated by the US Global Change Research Program (USGCRP).

2. In 1997, the National Center for Ecological Analysis and Synthesis and the American Institute of Biological Sciences (AIBS) initiated a one-year project that organized a nation-wide graduate seminar, to examine the role of science in Habitat Conservation Plans[12] (HCPs). Private landowners are legally required to provide HCPs that outline

[12] http://www.nceas.ucsb.edu

how they intend to minimize the impact of planned activities on the destruction of endangered species and habitats. The seminar involved 106 graduate students and 13 faculty advisors at 8 universities. The 90,000-entry peer-reviewed HCP database was used by the U.S. Fish and Wildlife Service in revising their HCP Handbook.

3. NSF supports a competition entitled Methods and Models for Integrated Assessment (MMIA). The goal of the MMIA competition is to support fundamental and methodological research that advances the development of methodologies and models that will integrate or couple multiple component systems. MMIA is part of the USGCRP.

The majority 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 short- or long-term–become established as specific research areas (e.g., CO_2 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 recalcitrant to address. The NSF has just begun to tap opportunities for coupling its support of anticipatory research to scientific assessment activities in useful ways. The Foundation estimates that approximately $4M is spent annually on scientific assessment projects.

IV. Input Received from External Sources about Unmet Needs and Opportunities

The Board received and considered hundreds of recommendations from reports and policy documents; from scholars in every scientific discipline and a number of professional societies; from community groups, local and Federal agency officials; and from non-governmental organizations and concerned citizens (see Appendix C). 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 the findings and recommendations appearing later in the 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.

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

- The NSF's merit review approach is considered key to the credibility of its environment portfolio.

- The ability of core NSF programs to evolve over time as different fields of study change is widely supported.

- NSF gets positive marks for its support for education, and the integration of education with research.

- One of NSF's major strengths is its ability to activate the intellectual assets of the research and education communities and mobilize resources for addressing substantive scientific and engineering challenges.

- 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 to attract outstanding scientists to serve in the critical role of program officers.

These strengths place the Foundation in a unique position to enable a broad spectrum of advances in the research community and to bring other Federal agencies into productive partnerships in support of environmental research.

At the same time, the Board heard many ideas that framed ways in which NSF could and should develop its environmental portfolio. Repeated suggestions included:

- The need for significantly more cross-disciplinary/interdisciplinary 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. Expertise from multiple disciplines – including 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 emphasize, and a sizeable fraction of the ~200 reports on the Board web site discuss this issue. The Corson Report (NRC 1993) states that "the research establishment is poorly structured to deal with complex, interdisciplinary research on large spatial scales and long-term temporal scales." Many also emphasized the inherent difficulties in establishing interdisciplinary projects within the context of disciplinary programs. This is clearly an area where progress is needed.

- The necessity of recognizing the inherent complexity and non-linearity of most environmental systems.

  Numerous individuals suggested that NSF's new focus on biocomplexity is timely and urgently needed, but that a far greater effort is required. They emphasized 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) required to understand environmental systems. (Box 4)

- The importance of considering questions at the appropriate temporal and physical scale, namely long-term and large-scale research needs.

  The Board heard from a variety of sources that the needs for long-term research, monitoring, and assessment of environmental trends far exceed what is being currently delivered. A whole new level of effort is needed to complement the excellent examples of long-term, large-spatial-scale research that presently exist (e.g., certain Global Change Research endeavors; the Long-Term Ecological Research 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 1977-1987, Tilman (1989) found that 40% of those studies had time periods of less than one year and that more than 92% of experimental field studies had durations of five 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 of the whole cybernetic system.

- The need to include appropriate human components (i.e., economics and social sciences) in environmental research and education activities.

The Board noted that over the last decade or so an increasing number of environment-related reports highlight the fact that we are poised to make large advances in understanding as the paradigm expands to include human sciences in our understanding of environmental systems. The trajectory of scholarship in this area is simultaneously shifting focus and expanding rapidly. Needs include: 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.

Research on environmental valuing and decision making, in this country and elsewhere, indicates that human beings and communities use a complex calculus that weighs 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, evaluating, and implementing stable, sustainable environmental policies, frequently in the face of substantial scientific uncertainty.

- The need for more effective information infrastructure to enable significant advances in informatics, data management, modeling, synthesis and dissemination of information.

As information capabilities have grown, there is a greater realization of the potential for advancing our understanding of environmental questions. The Board heard and read many compelling examples of how these advancing capabilities have fundamentally changed research endeavors. The Board also was told that the information wave is far from cresting. For example, W. Franklin Harris (University of Tennessee) stated "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."

- The urgency of developing and exploiting 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. The capabilities that these new technologies enable are not far from the science fiction of past decades. The Board heard that previously inconceivable advances are being suggested. One scientist testified 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 fast as a supermarket scanner.

The other emerging new side of environmental technology is industrial ecology, a field that takes a systems view of the use and environmental implications of materials, energy, and products in industrial societies. It exploits the ecological analogy by placing industrial activity in its environmental context and by drawing on nature as a model. The Board heard and read that certain environmental problems are intimately linked to global population growth, material aspirations, and the organization and performance of the economy. The rich research agenda for industrial ecology has grown from more traditional research on particular materials and economic sectors and now includes needs for cross-sector and multi-scale approaches. For example, studies of dematerialization (materials intensity per unit of GDP) are needed to understand the roles of materials substitutions, new designs, shifts toward services in economies, and movement of materials-intensive production to the developing world. 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 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, dry cleaning, and paint application.

- The importance of inventory and monitoring programs to characterize animal and plant resources and 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 non-consumptive wildlife recreation. Protecting the basis of these endeavors calls for a more extensive understanding of the wild relatives of these species (rich sources of new genes) and of threats from invasive species including pests and pathogens. 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).

- The need for research to connect more effectively to decision making (policy, regulatory, management, institutional and individual).

Over the last decade, a great deal of interest has been expressed in improving the scientific basis for making decisions on environmental issues. Several recommendations the Board heard and read on this topic have relevance to this report: (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; and (3) public understanding of science and of complexity, in particular in the environmental area, needs to be improved.

The Board heard that there is a need for knowledge assessments to provide 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. This peer-reviewed publication reports, in lay language, the consensus of a panel of scientific experts on issues relevant to the environment.

The NRC Corson Report[13], the Committee for the National Institute for the Environment[14] (CNIE), the American Institute of Biological Sciences (AIBS), and the Ecological Society of America (ESA), among others, suggested specific ways to improve the use and usefulness of the knowledge resulting from the research enterprise. Suggestions include: improved coordination across the environmental research portfolio; setting of 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.

The Ehlers' Report of the U.S. House of Representatives Science Committee 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[15].

- The urgency of including educational elements in environmental programs and plans.

Many who communicated with the Board highlighted the need for environmental education and validated the NSF's current strategic plan, which calls for increased integration of education with research. The Board heard that education and training in the Nation's universities are strongly disciplinary, whereas solution of environmental problems also requires broadly trained people and multidisciplinary approaches. Opportunities for broadly

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[13] National Research Council. 1993. Research to Protect, Restore, and Manage the Environment. Committee on Environmental Research. National Academy Press. 242 pp.

[14] http://www.cnie.org

[15] http://www.house.gov/science/science_policy_report.htm

based interdisciplinary graduate degrees are few, and faculty are not rewarded as suitably for interdisciplinary activities as they are for disciplinary activities. The views expressed included the concern that environmental scientists are often not appropriately trained to address pressing needs and fill positions in career paths outside of academe.

- The importance of improved coordination among programs and agencies.

The need for good communication and coordination across agencies was highlighted as an ongoing challenge. The Committee on Environment and Natural Resources of the National Science and Technology Council provides a mechanism for this coordination.

- The need to improve predictive capabilities in a variety of environmental areas.

The Board heard testimony that the ability to predict the behavior of environmental systems has grown steadily with the increase in understanding of many of these complex systems. Most 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 conjoint 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. Comparison of model output with data from environmental experiments indicates how much confidence can be placed in the models. Models tested successfully in a variety of environments permit more robust predictions about the complex behavior of the environment. Modeling experiments can be conducted to help design research in unexplored areas or sets of environmental drivers can be used that represent management or impact scenarios of particular interest to scientists or society. In fact, simulation models have become tools of necessity for environmental research.

- The importance of obtaining input on priority setting from individuals and organizations familiar with research, education and assessment issues.

The Board heard and read that across science and engineering there are clear needs for priority setting. The Board examined several examples where research or education agendas were defined in an inclusive and integrated manner. It became clear that this is an area that needs much more attention, in particular where priorities are set in interdisciplinary areas.

It was clear throughout the public-input process that citizens, many governmental officials, other Federal agencies, professional scientific and engineering societies, and individual scientists look to the 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 (NRC) committees to advocacy groups. The strong message running throughout the hearings 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 requirement for significant new resources to accomplish these goals.

V. Findings and Recommendations

General 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. In order to be effective in this role, NSF activities must complement and enhance, not duplicate or replace, the extant portfolio of Federal activities in this area.

Environmental science and engineering has matured significantly over the last decade. New knowledge and new technologies have combined to bring the environmental sciences to an unprecedented threshold of discovery, understanding, and useful information. The NSF is supporting significantly more environmental research and education than is generally appreciated. Despite the current set of activities in the environmental arena, the Nation's need for fundamental environmental knowledge and understanding requires further attention. To expand and strengthen the Foundation's environmental portfolio, two key issues must be addressed. Environmental activities within NSF must 1) be organized more effectively and 2) 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. Suggestions for Federal organizational changes have included the creation of a new Federal agency, an environmental institute outside NSF, a strengthened interagency environmental committee that would involve NSF, an environmental institute within NSF, and a new directorate inside NSF. The Board finds that many of these suggestions have been productive in promoting dialogue and raising visibility of the issues.

The Board considered these multiple suggestions in light of its immediate focus on environmental research, education and scientific assessment within NSF. The suggestions of a new institute or directorate within NSF, for example, were deemed less desirable than a new mechanism which 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. The environmental portfolio of the NSF 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. These findings lead the Board to make two overarching recommendations.

Keystone Recommendations

Resources and Funding (Recommendation 1): Environmental research, education and scientific assessment should be one of the highest priorities of the National Science Foundation. The current environmental portfolio, an investment of approximately $600 million, represents only about one-third of the resources necessary. In view of the overwhelming importance and exciting opportunities for progress in the environmental arena, and because existing resources are fully and appropriately utilized, new resources will be required. Therefore, we recommend that environmental research, education and scientific assessment at NSF be increased by an additional $1 billion over the next 5 years.

Organizational Approach (Recommendation 2): 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 NSF. 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;
    - 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 its sister Federal agencies.

Specific Findings and Recommendations

The above two overarching recommendations are complemented by ten 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 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 the Earth's environmental envelope.

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 fields.

Information and understanding from certain disciplines are especially relevant to environmental problems, but are often lacking. The Board finds that lack of knowledge from 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 1). These specific areas were identified repeatedly in the Task Forces' inquiry, but 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.

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 interdisciplinary 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 data bases, observations, and experiments are necessary to provide understanding of many environmental problems, yet insufficient support exists for sustained research efforts.

> **Disciplinary Research (Recommendation 3)**: 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.
>
> **Interdisciplinary Research (Recommendation 4):** 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.
>
> **Long-Term Research (Recommendation 5):** The Foundation should significantly increase its investments in existing long-term programs and establish new support mechanisms for long-term research.

Education

The Board finds that the role of the NSF is to create educational and training opportunities that enhance scientific and technological capacity associated with the environment, across both the formal and informal educational enterprise.

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. There is a need to encourage changes 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.

While the Board recognizes that there are significant needs for schooling activities, there are also opportunities for enhancing the public's ability to deal with complex information in the environmental area. These include more informal educational 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. There is a need to 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.

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. The Board finds that environmental issues offer excellent vehicles for developing and exercising many of these skills using a systems approach.

> **Environmental Education (Recommendation 6):** The Foundation should enhance its formal educational efforts by encouraging submission of proposals that capitalize on the inherent student interest in environmental areas while supporting significantly more environmental educational 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, whether or not they have been part of the scientific and engineering traditions.

Table 1. Programmatic gaps or areas needing enhancement in the 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, area occupied by 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 (see Box 1).
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 disease. • 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 capabilities and other enabling technologies. • Industrial ecology: e.g. materials flow accounting; scale issues research including the scale of human perturbations to natural materials 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.

Scientific Assessment

The Board finds that the role of the NSF is to facilitate the development of methods and models of scientific assessment and foster the conduct of scientific analyses of environmental issues, both domestically and internationally.

The Board defines scientific assessment, for the purposes of this report, as inquiry-based analysis 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, 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. Such assessments are needed for setting scientific priorities and for summarizing scientific information for decision-makers.

> **Scientific Assessments (Recommendation 7):** The Foundation should significantly increase its research on the methods and models that support the scientific assessment process. 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

The Board finds that an important role of the NSF is to facilitate the development of facilities, instrumentation, and other infrastructure that enables discovery, including the study of processes and interactions that occur over long-time scales.

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 well suited as vehicles for pulling together interdisciplinary teams that can address problem-focused issues and complement the types of activities that individual investigators perform.

The Board finds that 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, but some require enhanced attention by NSF. 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) in order to ensure that researchers and educators can leverage past and future investments.

<u>Enabling Infrastructure (Recommendation 8):</u> High priority should be given to enhancing infrastructure for environmental observations and collections as well as new information networking capacity. A suite of environmental research and education hubs should be created, 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 role of role is to foster research that seeks to develop innovative technologies and approaches that assist the Nation in conserving 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 2 presents examples of technologies with promise for environmental research.

The 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 NSF could 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.

<u>Environmental Technology (Recommendation 9)</u>: 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.

<u>Enabling Technologies (Recommendation 10)</u>: The Foundation should enable and encourage the use of new and appropriate technologies in environmental research and education.

Table 2. 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 can be 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 can provide a better basis for comparison of patterns emerging from data at different levels of detail.

Information Infrastructure

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.

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. The Board finds that there is a clear need for a coordinated electronic network linking distributed information and databases at all levels, with attention to information access and transfer to the public.

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

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

Partnerships, Coordination and Collaborations

The Board finds that collaborations and partnerships are essential to important and high-priority environmental research, education, and scientific assessment efforts and 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 non-governmental bodies (e.g., private sector entities, NGO's, and others), and international organizations can provide the intellectual and financial leveraging to address a) environmental questions at the local level, b) larger-scale regional issues, and c) problems for which the research and the policy dimensions are international.

Many of NSF's international environmental research collaborations are essential to address the fundamental scientific questions central to many environmental issues (e.g., the role that equatorial ocean plays in controlling the timing and magnitude of the El Nino) and reflect the recognized urgency of developing 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 dialog within the U.S., 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 necessary for scientific consensus.

Within the Federal agency family, 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 (NSTC) 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 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.

> **Implementation Partnerships (Recommendation 12)**: The 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. These 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 the NSTC, with advice from PCAST, 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 and education.

VI. Conclusion

Scientific understanding of the environment, together with an informed, scientifically literate citizenry, are requisite to quality of life for generations to come. As the interdependencies of fundamental and applied environmental research become more evident, the 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 the NSF. The two overarching and ten 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 OSTP, and vigorous participation by the scientific community. The Board eagerly awaits the construction of this new portfolio.

Appendix A -
Charge: 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 Listing Compiled and Considered by the Task Force

The literature list is intended to highlight the broad sweep of environmental concerns considered by the Task Force. The number of references on a particular issue should not be interpreted as a measure of the priority for that issue.

	Title	Date	Initiators / Sponsors	Publication
1	Benefits of Biodiversity	1999	Council for Agricultural Science and Technology, Ames, Iowa	http://www.cast-science.org
2	Bioinformatics in the 21st Century	1999	A Report to the Research Resources and Infrastructure Working Group of the National Science and Technology Council, Committee on Science, Subcommittee on Biotechnology	Krasnow Institute for Advanced Study, George Mason University, Fairfax, VA
3	Evolution, Science, and Society: Evolutionary Biology and the National Research Agenda	1999	A.P. Sloan Foundation and the National Science Foundation	Thomas R. Meagher, Rutgers, The State University of New Jersey or contact http://www.amnat.org
4	Nature's Numbers	1999	National Research Council, 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.) National Academy Press, Washington, D.C.
5	Technology Forces at Work: Profiles of Environmental Research and Development at DuPont, Intel, Monsanto, and Xerox	1999	Sponsor: White House Office of Science and Technology Policy. Prepared by RAND, Science and Technology Policy Institute	Resetar, S., B. Lachman, R. Lempert & M. Pinto. RAND, Science and Technology Policy Institute. #MR-1068-OSTP http://www.rand.org/publications/MR/MR1068/
6	Towards a Sustainable America. Advancing Prosperity, Opportunity and a Healthy Environment for the 21st Century	1999	President's Council on Sustainable Development	PCSD, Washington, D.C.
7	Air Quality Research subcommittee Strategic Plan	1998	National Science & Technology Council; Committee on Environment and Natural Resources	NSTC, CENR, CENR Executive Secretariat 202-482-5916
8	Basic Research Needs to Achieve Sustainability: The Carbon Problem	1998	Sponsors: NSF & DOE. Conference organizers: Peter Eisenberger, Columbia Univ. & Michael Knotek, U.S. DOE	Conference & Workshops held October 22-24, 1998 in Tuscon, AZ
9	Endocrine Disruptors: Research Needs and Priorities	1998	National Science & Technology Council; Committee on Environment and Natural Resources	NSTC, CENR, CENR Executive Secretariat 202-482-5916

	Title	Date	Initiators / Sponsors	Publication
10	Entering the Century of the Environment: A New Social Contract for Science	1998		Lubchenco, J., 1998. Science 279:491
11	Federal Funds for Research and Development: FY 1996, 1997 and 1998	1998	National Science Foundation: Directorate for Social, Behavioral, and Economic Sciences; Division of Science Resource Studies	NSF 97-335; Susan T. Hill, Project Officer
12	Food Safety, Sufficiency, and Security	1998	Council for Agricultural Science and Technology, Ames, Iowa	http://www.cast-science.org
13	Foodborne Pathogens: Review of Recommendations	1998	Council for Agricultural Science and Technology, Ames, Iowa	http://www.cast-science.org
14	Future of Ocean Chemistry in the U.S. (FOCUS)	1998	NSF-sponsored workshop report	http://www.joss.ucar.edu/joss_psg/project/oce_workshop/focus/
15	Future of Physical Oceanography (APROPOS)	1998	NSF-sponsored workshop report	http://www.joss.ucar.edu/joss_psg/project/oce_workshop/apropos/
16	Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB)	1998	Report from a Joint IOC/SCOR Workshop held in Havreholm, Denmark	http://www.phys.ocean.dal.ca/~jhurst/SCOR/GEOHAB/GEOHAB.html
17	Global Environmental Change: Research Pathways for the Next Decade	1998	National Research Council, Policy Division, Board on Sustainable Development, Committee on Global Change Research	National Academy Press
18	Global Ocean Observing System (GOOS): Prospectus 1998	1998	UNESCO: Joint Scientific and Technical Committee for the Global Ocean Observing System	IOC 1998, Paris, 168 pp. Intergovernmental Oceanographic Commission. ISBN 0-904175-39-1
19	Hydrologic Sciences: Taking Stock and Looking Ahead	1998	National Research Council, Commission on Geosciences, Environment, and Resources, Water Science & Technology Board	National Academy Press, Washington, DC. 138 p.
20	Is Coastal Eutrophication out of Control?	1998	Environmental Science & Technology 3:462-466	Pelly, J. ES&T 3(10):462-466
21	Linking Industrial Ecology to Public Policy: Report of a Workshop	1998	NSF-sponsored workshop report	Andrews, C., D. Rejeski, R. Socolow & V. Thomas. RU/EJBS Working Paper 4. http://policy.rutgers.edu/projects/ie.htm
22	Major U.S. Oceanographic Research Programs: Impacts, Legacies and the Future	1998	Marine Technology Society, Wayne B. Ingram, president.	Marine Technology Society Journal 32(3)
23	Monitoring for Fine Particulate Matter	1998	Sponsor: OSTP. Prepared by RAND:CTI	Eiseman, Elisa. CTI:RAND, Santa Monica, CA
24	Ocean Ecology: Understanding and Vision for Research (OEUVRE)	1998	NSF-sponsored workshop report	http://www.joss.ucar.edu/joss_psg/project/oce_workshop/oeuvre/report/
25	Opportunities in Ocean Sciences: Challenges on the Horizon	1998	National Research Council: Ocean Studies Board; Kenneth Brink, chair	National Academy Press. 1998. Washington, D.C.

	Title	Date	Initiators / Sponsors	Publication
26	Our Changing Planet: The FY 1999 U.S. Global Change Research Program	1998	National Science and Technology Council, Committee on Environment and Natural Resources, Subcommittee on Global Change Research	OSTP, Washington, DC, 130 p.
27	Park Science: Integrating Research & Resource Management	1998	U.S. Dept of Interior, National Park Service	USDOI; NPS: C-1 November 1998; ISSN 0735-9462. http://www.nature.nps.gov/parksci/
28	Program Guide to Federally Funded Environment and Natural Resources R&D	1998	National Science and Technology Council, Committee on Environment and Natural Resources	NSTC, CENR. U.S. GPO. CENR Executive Secretariat 202-482-5916
29	Protecting Our Planet Securing Our Future: Linkages Among Global Environmental Issues and Human Needs	1998	Sponsors: United Nations Environment Programme; U.S. NASA; and The World Bank	Robert Watson, et al.
30	Report of U.S. Southern Ocean GLOBEC Planning Workshop	1998	U.S. Global Ocean Ecosystems Dynamics; Sponsored by NSF	http://www.ccpo.odu.edu/Research/globec/dcmeeting/dcrept.html
31	Research Frontiers in Environmental Engineering	1998	Sponsors: NSF & Assoc. of Envi. Engineering Professors	B.E. Logan, C.R. O'Melia, & B.E. Rittman (eds). Assoc. of Environmental Engineering Professors, Jan 1998, Monterey, CA
32	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
33	Successes, Limitations, and Frontiers in Ecosystem Science	1998	Pace, M.L. and P.M. Groffman, editors	Springer-Verlag, New York, 499 p.
34	Teaming with Life: Investing in Science to Understand and Use America's Living Capital	1998	PCAST Panel on Biodiversity and Ecosystems; Report prep. supported by: Gund Foundation, MacArthur Foundation, IBM, Lucent Tech., NSF, EPA & NASA	86-p. report available from PCAST Secretariat 202-456-6100 or: http://www.whitehouse.gov/WH/EOP/OSTP/html/OSTP_Home.html
35	The Atmospheric Sciences: Entering the Twenty-first Century	1998	National Research Council, Board on Atmospheric Sciences and Climate	John Dutton, Chair http://www.nap.edu/books/0309064155/html/R1.html
36	The National Report Card on Environmental Knowledge, Attitudes and Behaviors: The Seventh Annual Survey of Adult Americans	1998	National Environment Education & Training Foundation	www.neetf.org
37	The OECD Megascience Forum: Workshop on Global-scale Issues	1998	Organisation for Economic Co-operation and Development	Summary of workshop held on March 4-6, 1998 in Sweden. www.oecd.org
38	The Regional Impacts of Climate Change: An Assessment of Vulnerability	1998	WMO & UNEP: Intergovernmental Panel on Climate Change	R.T. Watson, M.C. Zinyowere, R.H. Moss (eds). Cambridge University Press for IPCC
39	The TOGA Decade: Reviewing the Progress of El Nino Research and Prediction	1998	American Geophysical Union; Journal of Geophysical Research	AGU, Washington, D.C. D.L.T. Anderson, E.S. Sarachik and P.J. Webster (eds).

	Title	**Date**	**Initiators / Sponsors**	**Publication**
40	Toward Prediction of the Arctic System: Predicting states of the arctic system on seasonal-to-century time scales by integration observations, process research, modeling, and assessment.	1998	Arctic Research Consortium of the U.S.	http://www.arcus.org/Publications/index.html
41	Unlocking Our Future: Toward a New National Science Policy	1998	A Report to Congress by the House Committee on Science	http://www.house.gov/science/science_policy_study.htm
42	Unlocking our Future: Toward a New National Science Policy	1998	U.S. House of Representatives Committee on Science: Report to Congress ("Ehlers Report")	http://www.house.gov/science/science_policy_report.htm
43	Visions for Natural Resource Education and Ecosystem Science for the 21st Century	1998	An Interim Report of the Northwest Center for Sustainable Resources; Chemeketa Community College, Salem, Oregon	Unpublished Report
44	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
45	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)
46	A Research Programme on Climate Variability and Predictability for the 21st Century (CLIVAR)	1997	ICSU: World Climate Research Programme; Hartmut Grassl, Director	World Climate Research Programme; WCRP No. 101, WMO/TD No. 853, ICPO No.10
47	Arctic Pollution Issues: A State of the Arctic Environment Report	1997	AMAP – Arctic Monitoring and Assessment Programme	http://www.grida.no/amap/
48	Atmospheric Nitrogen Deposition to Coastal Wetlands	1997	Ecological Society of America, Sustainable Biosphere Initiative: Workshop Report	http://esa.sdsc.edu/sbindep1.htm
49	Building a Foundation for Sound Environmental Decisions	1997	National Research Council	National Academy Press
50	Climate Change: State of Knowledge	1997	Office of Science and Technology Policy	OSTP:Executive Office of the President. Washington, D.C.
51	Climate, Ecology, and Human Health	1997	NOAA, NASA and NSF sponsorship; published in Consequences. Author: Paul R. Epstein	Consequences 3(2). 1997. http://www.gcrio.org/CONSEQUENCES/introCON.html
52	Contribution of Animal Products to Healthful Diets	1997	Council for Agricultural Science and Technology, Ames, Iowa	http://www.cast-science.org
53	Cooperative Ecosystem Studies Units: Concept Paper	1997	Cooperative Ecosystem Studies Units Implementation Working Group, Gary Machlis (chair)	Cooperative Ecosystem Studies Units Implementation Working Group, Gary Machlis (chair)

	Title	Date	Initiators / Sponsors	Publication
54	Critical Issues in K-12 Environmental Education	1997	Report from a workshop held July 11, 1997, hosted by Morgan State University/Environmental Protection Agency Teacher Institute	Unpublished Report
55	East Central Europe: An Environment in Transition	1997	Environmental Science & Technology 31:412-416	Schnoor, J.L., J.N. Galloway & B. Moldan. ES&T 31(9):412-416
56	Environmentally Significant Consumption - Research Directions	1997	National Research Council, Committee on the Human Dimensions of Global Change	Stern, P.C., T. Dietz, V.W. Ruttan, R.H. Socolow, and J.L. Sweeney (eds.) National Academy Press, Washington, D.C.
57	Federal Energy Research and Development for the Challenges of the 21st Century	1997	President's Committee of Advisors on Science and Technology	White House Office of Science and Technology Policy
58	Federal Environmental Research and Development: Status Report with Recommendations	1997	Carnegie Commission on Science, Technology, and Government, memorandum, Task Force chair David Z. Robinson, memorandum author: Dan Sarewitz	Carnegie Commission on Science, Technology & Government, 25 p.
59	From Classroom to Community and Beyond: Educating for a Sustainable Future	1997	Report of the Public Linkage, Dialogue, and Education Task Force of the President's Council on Sustainable Development	http://www.whitehouse.gov/PCSD
60	Fuels Decarbonization and Carbon Sequestration: Report of a Workshop	1997	sponsor: U.S. Dept. of Energy, report: Center for Energy & Environmental Studies, Princeton University; Robert Socolow (ed.)	PU/CEES Report No. 302. http://www.princeton.edu/~ceesdoe/
61	Global Ocean Ecosystem Dynamics (GLOBEC) Science Plan	1997	IGBP Report 40; GLOBEC Report 9. International Council of Scientific Unions; Scientific Committee on Oceanic Research. The International Geosphere-Biosphere Programme	IGBP; B.J. Rothschild, chair.
62	Human Alteration of the Global Nitrogen Cycle: Causes and Consequences	1997	Ecological Society of America	Issues in Ecology, Number 1, Spring 1997. http://www.sdsc.edu/~ESA/
63	Integrating the Nation's Environmental Monitoring and Research Networks and Programs: A Proposed Framework	1997	National Science & Technology Council, Committee on Environment & Natural Resources, Environmental Monitoring Team	NSTC: CENR. R. Watson & R. Huggett (chairs), M. Ruggiero & D. Scavia (team leaders)
64	Lessons from the Montreal Protocol	1997	Findings from Colloquium	http://www.ec.gc.ca/ozone/tenthann/coll_e.htm
65	Linking Sustainable Community Activities to Pollution Prevention: A Sourcebook	1997	Sponsor: OSTP. Prepared by RAND: CTI	RAND:CTI: Beth E. Lachman

	Title	Date	Initiators / Sponsors	Publication
66	Modeling the Arctic System	1997	Arctic Research Consortium of the U.S.	http://www.arcus.org/Publications/index.html
67	Organizing for Research and Development in the 21st Century	1997	sponsors: NSF & DOE; editors: P.M. Eisenberger, A.R. Faust & M. Knotek	Eisenberger, P.M., A.R. Faust & M. Knotek, eds. Princeton Materials Institute, Princeton University. http://pmi.princeton.edu/
68	Our Changing Climate	1997	NOAA Reports to the Nation; UCAR via NOAA Award no. NA57GP0576	NOAA Office of Global Programs and UCAR/OIES
69	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
70	Science & Engineering Degrees 1966-1995	1997	National Science Foundation: Directorate for Social, Behavioral, and Economic Sciences; Division of Science Resource Studies	NSF 98-332; Ronald L. Meeks, Project Officer
71	Science and Technology Shaping the Twenty-First Century	1997	Executive Office of the President, Office of Science and Technology Policy, report to the Congress	OSTP, Washington, DC. 141
72	The Global Ocean Observing System: Users, Benefits, and Priorities	1997	National Research Council, Ocean Studies Board	National Academy Press, Washington, D.C.
73	The Microbial World: Foundation of the Biosphere	1997	American Academy of Microbiology report sponsored by NSF, NOAA, DOE and Amer. Soc. for Microbiology.	Staley, JT, RW Castenholz, RR Colwell, JG Holt, MD Kane, NR Pace, AA Salyers, & JM Tiedje. Colloquium report. American Society of Microbiology. 32 p.
74	Valuing Ground Water - Economic Concepts and Approaches	1997	National Research Council, Commission on Geosciences, Environment, and Water (L.W. Canter, Chair)	National Academy Press, Washington, D.C.
75	A Geography of Hope: America's Private Land	1996	USDA Natural Resources Conservation Service	USDA Program Aid 1548. 1996. C. Cox and M. Schnepf, project managers.
76	A Plan for a Research Program on Aerosol Radiative Forcing and Climate Change	1996	National Research Council, Board on Atmospheric Sciences and Climate	National Academy Press, Washington DC
77	Common Future for Long-Term Ecological Research, Land Margin Ecosystem Research and Joint Global Ocean Flux Study	1996	NSF-sponsored workshop held Madison, WI, 1996.	http://atlantic.evsc.virginia.edu/~bph/LTER_LMER/NSFreport.html
78	DIVERSITAS: An International Programme of Biodiversity Science. Operational Plan	1996	Published by DIVERSITAS, Paris	http://www.icsu.org/DIVERSITAS/Plan/index.html
79	Ecological Resource Monitoring: Change and Trend Detection	1996	Ecological Society of America, Sustainable Biosphere Initiative: Workshop Report	http://esa.sdsc.edu/sbi_bull8.htm

	Title	Date	Initiators / Sponsors	Publication
80	Ecologically Based Pest Management, New Solutions for a New Century	1996	National Research Council, Board on Agriculture, Committee on Pest and Pathogen Control through Management of Biological Control Agents and Enhanced Cycles and Natural Processes	National Academy Press, Washington, DC, 144 p.
81	Freshwater Ecosystems: Revitalizing Educational Programs in Limnology "Brezonik Report"	1996	National Research Council, Commission on Geosciences, Environment, and Resources, Water Science & Technology Board, Committee on Inland Aquatic Ecosystems	National Academy Press, Washington, DC, 364 p.
82	Future of Marine Geology and Geophysics (FUMAGES)	1996	NSF-sponsored workshop report; Also sponsored by ONR Coastal Dynamics Program	Baker, P. and M. McNutt (compilers). http://www.joss.ucar.edu/joss_psg/project/oce_workshop/fumages/
83	Global Climate Change & Sustainability: Enhancing the Policy/Science Dialogue	1996	Dutch & U.S. Govts.	Klabbers, J.H.G., C. Bernabo, B. Moomaw, T. Carter, S.P. Hammond & M. Hisschemoller; Proceedings of the 27th Int. Conf. of the Int. Simulation & Gaming Association (Jurmala, Latvia, 7/96)
84	Grazing on Public Lands	1996	Council for Agricultural Science and Technology, Ames, Iowa	http://www.cast-science.org
85	Integrated Animal Waste Management	1996	Council for Agricultural Science and Technology, Ames, Iowa	http://www.cast-science.org
86	Linking Science & Technology to Society's Environmental Goals "Ahearne - Stever Report"	1996	National Research Council, Policy Division, Committee on the National Forum on S&T Goals: Environment	National Academy Press, Washington DC, 530 p.
87	National Acid Precipitation Assessment Program (NAPAP)	1996	NAPAP Report to Congress	U.S. Government Printing Office
88	Natural Disaster Reduction: A Plan for the Nation	1996	NSTC: CENR: Subcommittee on Natural Disaster Reduction	NSTC:CENR:SNDR; William Hooke, Chair
89	NSF/DOE Nuclear Science Advisory Committee Long Range Plan	1996	NSF	http://pubweb.bnl.gov/~nsac/
90	Oceans 2000: Bridging the Millenia: Partnerships for Stakeholders in the Oceans	1996	Consortium for Oceanographic Research and Education (CORE): A report on the Interagency Partnership Initiative. Sponsored: NSF, ORN, NASA, ARPA and DOE	Interagency Partnership Initiative, CORE, 1755 Massachusetts Ave., NW, Suite 800, Washington, DC 20036-2102, email: core@brook.edu
91	Sustainable America: A New Consensus for Prosperity, Opportunity, and a Healthy Environment for the Future	1996	President's Council on Sustainable Development	Buzzelli, D.T. and J. Lash (co-chairs). President's Council on Sustainable Development; U.S. GPO. ISBN 0-16-048529-0

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92	The MATE Forum: Critical Issues in Marine Advanced Technology Education	1996	Report on a forum held November 8-10, 1996 in Monterey, CA	MATE Center, Monterey Peninsula College, 980 Fremont Street, Monterey, CA 93940, Ph (831) 645-1393 email: info@marinetech.org
93	U.S. GLOBEC Northeast Pacific Implementation Plan	1996	U.S. Global Ocean Ecosystems Dynamics; Sponsored by NSF	http://cbl.umces.edu/fogarty/usglobec/reports/rep17/nepip.contents.html
94	Upstream: Salmon and Society in the Pacific Northwest	1996	National Research Council, Board on Environmental Science & Technology	National Academy Press, Washington D.C.
95	Wetland and Aquatic Ecosystem Research: Science Plan	1996	European Commission; Directorate General XII; Science, Research & Development	EUR 17452. H.J. Laanbroek, E. Maltby, P. Whitehead, B. Faafeng, H Barth (eds.); report of an international workshop
96	When We Don't Know the Costs or the Benefits: Adaptive Strategies for Abating Climate Change	1996	Climatic Change 33:235-274	Lempert, R.J., M.E. Schlesinger & S.C. Bankes
97	Allocating Federal Funds for Science and Technology	1995	National Academy of Sciences, NAE, IOM, NRC, Committee on Criteria for Federal Support of Research and Development	National Academy Press, 97 p.
98	Arctic Ocean Research and Supporting Facilities: National Needs and Goals	1995	National Research Council, Ocean Studies Board	National Academy Press, Washington D.C.
99	Basic Research Needs for Vehicles of the Future	1995	Sponsors: NSF, DOE, Chrysler, Ford, GM; editor: Peter Eisenberger	Eisenberger, P.M.,ed. Princeton Materials Institute, Princeton University. http://pmi.princeton.edu/
100	Beyond the Horizon: Using Foresight to Protect the Environmental Future	1995	U.S. EPA Science Advisory Board; Environmental Futures Committee: Raymond C. Loehr, Chair.	EPA-SAB-EC-95-007. U.S. EPA. 1995
101	Biotechnology for the 21st Century: New Horizons	1995	National Science and Technology Council, Committee on Fundamental Science, Biotechnology Research Subcommittee, Lura J. Powell, chair.	OSTP, Washington, DC. 89 p.
102	Bridge to a Sustainable Future	1995	National Science & Technology Council	U.S. GPO, Washington, DC, 87 p.
103	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
104	Ecology and Oceanography of Harmful Algal Blooms (ECOHAB): A National Research Agenda	1995	Woods Hole Oceanographic Institution with support from NSF and NOAA	Anderson, D.M. (workshop chair). Woods Hole Oceanographic Institution
105	Enhancing the effectiveness of research to assist international climate change policy development	1995	Dutch National Research Programme on Global Air Pollution and Climate Change	NRP Programme Office, Report no: 410 100 090 (C. Bernabo, M. Hisschemoller & J. Klabbers)
106	Managing Global Genetic Resources (4 Volumes)	1995	National Academy of Sciences	National Academy Press

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107	Molecular Biology in Marine Science: Scientific Questions, Technological Approaches, and Practical Implications	1995	National Research Council, Ocean Studies Board	National Academy Press, Washington D.C.
108	NSF in a Changing World: The National Science Foundation's Strategic Plan	1995	National Science Foundation	NSF 95-24. National Science Foundation. Arlington, VA.
109	Partnering to Build a Quality Workforce: Critical Issues in Environmental Technology Education at Two-Year Colleges	1995	Report from the National Forum on Critical Issues in Environmental Technology Education at Two Year Colleges, Held March 2-4, 1995, in Washington, DC	http://ateec.eiccd.cc.ia.us/ci1.html
110	Preparing for the Future Through Science and Technology: An Agenda for Environmental and Natural Resources Research	1995	National Science and Technology Council, Committee on Environment and Natural Resources	NSTC, CENR. U.S. GPO. CENR Executive Secretariat 202-482-5916
111	Priorities for Coastal Ecosystem Science	1995	National Research Council, Ocean Studies Board	National Academy Press, Washington D.C.
112	Research Restructuring and Assessment: Can We Apply the Corporate Experience to Government Agencies?	1995	National Research Council: Commission on Physical Sciences, Mathematics and Applications. Report of a workshop. W. Carl Lineberger and Charles A. Zraket, co-chairs	National Academy Press. 1995. Washington, D.C.
113	Science and the Endangered Species Act	1995	National Research Council, Board on Environmental Science & Technology	National Academy Press, Washington D.C.
114	Science, Policy, and the Coast: Improving Decisionmaking	1995	National Research Council, Ocean Studies Board	National Academy Press, Washington D.C.
115	Setting a New Course for U.S. Coastal Ocean Science	1995	NSTC:CENR: Subcommittee on U.S. Coastal Ocean Science	NSTC:CENR: SUSCOS; Don Scavia (NOAA) Chair
116	Sustainable Agriculture and the 1995 Farm Bill	1995	Council for Agricultural Science and Technology, Ames, Iowa	http://www.cast-science.org
117	The Conservation Reserve: A Survey of Research and Interest Groups	1995	Council for Agricultural Science and Technology, Ames, Iowa	http://www.cast-science.org
118	The Ecosystem Approach: Healthy Ecosystems and Sustainable Economies. Vol. 1 - Overview	1995	Interagency Ecosystem Management Task Force, Katie McGinty, Chair	NTIS, U.S. DOC, PB95-265583
119	The Ecosystem Approach: Healthy Ecosystems and Sustainable Economies. Vol. 2 - Implementation Issues	1995	Interagency Ecosystem Management Task Force, Katie McGinty, Chair	NTIS, U.S. DOC, PB95-265591

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120	The Freshwater Imperative Research Agenda	1995	Assoc. of Ecosystem Research Ctrs.; Ecological Soc. of Amer.; North Amer. Benthological Soc.; Internat. Assoc. for Great Lakes Research; North Amer. Lake Mgmt. Soc.; Soc. of Wetland Scientists; American Soc. of Limnology & Oceanography; funded by NSF	Naiman, R.J., J.J. Magnuson, D.M. McKnight & J.A. Stanford (eds.). Island Press, Washington, DC. 165 p.
121	The Population-Environment Connection: What does it mean for Environmental Policy?	1995	U.S. EPA, Office of Policy Planning and Evaluation	Carlyn E. Orians and Marina Skumanich, Battelle Seattle Research Center.
122	Understanding Marine Biodiversity: A Research Agenda for the Nation	1995	National Research Council: Ocean Studies Board, Board on Biology: Committee on Biological Diversity in Marine Systems	National Academy Press. 1995. Washington, D.C.
123	Waste Management and Utilization in Food Production and Processing	1995	Council for Agricultural Science and Technology, Ames, Iowa	http://www.cast-science.org
124	Assigning Economic value to Natural Resources	1994	National Research Council, Commission on Geosciences, Environment and Resources, Commission on Behavioral and Social Sciences and Education	National Academy Press, Washington, D.C.
125	Atomic, Molecular, and Optical Science - An Investment in the Future	1994	National Research Council	National Academy Press, Washington D.C.
126	Defining Soil Quality for a Sustainable Environment	1994	American Society of Agronomy, Crop Science Society of America, Soil Science Society of America	SSSA Special Publication # 35 http://www.asa-cssa-sssa.org/
127	El Nino and Climate Prediction	1994	NOAA Reports to the Nation; UCAR via NOAA Award no. NA27GP0232-01	NOAA Office of Global Programs and UCAR/OIES. Reports to the Nation on Our Changing Planet, Spring, 1994.
128	Environmental Science in the Coastal Zone	1994	National Research Council, Water Science and Technology Board	National Academy Press, Washington D.C.
129	Foodborne Pathogens: Risks and Consequences	1994	Council for Agricultural Science and Technology, Ames, Iowa	http://www.cast-science.org
130	How Much Land Can Ten Billion People Spare for Nature	1994	Council for Agricultural Science and Technology	Task Force Report. Paul Waggoner (chair). Council for Agricultural Science & Technology. No. 121 February 1994
131	Implications of the Convention on Biological Diversity: Management of Animal Genetic Resources and the Conservation of Domestic Animal Diversity	1994	U.N. Food and Agriculture Organization, Informal Working group; Animal Production and Health Division	Strauss, M.S. (ed.) 1994. American Association for the Advancement of Science. Washington, D.C.

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132	Life in the Soil: Soil Biodiversity: Its Importance to Ecosystem Processes	1994	Workshop sponsored by NSF and UK Natural Environment Research Council . Diana W. Freckman, Editor	Workshop report. Diana W. Freckman, ed. Colorado State Univ. 24 p.
133	Restoring and Protecting Marine Habitat: The Role of Engineering and Technology	1994	National Research Council, Marine Board	National Academy Press, Washington D.C.
134	Science and Judgment in Risk Assessment	1994	National Research Council, Board on Environmental Science & Technology	National Academy Press, Washington D.C.
135	Scientific Plan for a Regional Research Programme in the Arctic on Global Change	1994	National Research Council, Polar Research Board	National Academy Press, Washington D.C.
136	Strategies and Mechanisms for Field Research in Environmental Bioremediation	1994	American Academy of Microbiology colloquium report. Colloquium supported by Oak Ridge National Laboratory	Miller, R.V. & J.S. Poindexter. 1994. American Academy of Microbiology
137	Systematics Agenda 2000	1994	American Society of Plant Taxonomists; Society of Systematic Biologists; Will Hennig Society; Association of Systematics Collections; funded by NSF	co-chairs: J. Cracraft, M. Denton, H. Eshbaugh, M. Novacek, N. Platnick. 34 p.
138	Technology for a Sustainable Future	1994	National Science & Technology Council	U.S. GPO, Washington, DC, 154 p.
139	Ten-Year Review of the NSF Long-Term Ecological Research (LTER) Program	1994	Report commissioned by the NSF Biological Sciences Directorate. Paul G. Risser and Jane Lubchenco, Co-chairs of review committee	NSF 94-26. National Science Foundation. Arlington, VA.
140	The Long View	1994	National Science Foundation, Directorate for Engineering	NSF 93-154
141	The National Biodiversity Information Center	1994	The National Biodiversity Information Center Advisory Planning Board; Thomas Lovejoy (chair)	The National Biodiversity Information Center Advisory Planning Board; Thomas Lovejoy (chair)
142	The Role of Terrestrial Ecosystems in Global Change: A Plan for Action	1994	National Research Council, Board on Sustainable Development	National Academy Press, Washington D.C.
143	Valuing the Environment	1994	Proceedings of the First Annual International Conference on Environmentally Sustainable Development. The World Bank.	Environmentally Sustainable Development Proceedings Series No. 2. The World Bank, Washington, D.C.
144	A Biological Survey for the Nation "Raven Report"	1993	National Research Council, Commission on the Formation of The National Biological Survey, Committee on the Formation of The National Biological Survey	National Academy Press, Washington DC, 205 p.

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145	A Proposal for a National Institute for the Environment: Need, Rationale, Structure	1993	Committee for the National Institute for the Environment (CNIE)	Committee for the NIE, Washington, D.C.
146	Agricultural Ecosystem Effects on Trace Gases and Global Climiate Change	1993	American Society of Agronomy, Crop Science Society of America, Soil Science Society of America	ASA Special Publication #55 http://www.asa-cssa-sssa.org/
147	Assessment of the U.S. Outer Continental Shelf Environmental Studies Program. IV. Lessons and Opportunities	1993	NRC: Board on Environmental Science & Technology	National Academy Press, Washington D.C.
148	Biodiversity in Marine Systems: A Proposed National Research Initiative	1993	NSF-sponsored workshop report	Butman, C.A. & J.T. Carlton (organizers). 1993. Workshop held Denver, CO
149	Biodiversity on Private Lands	1993	President's Commission on Environmental Quality; Michael Deland (Chair); Biodiversity Steering Committee; Sharon Haines (chair)	President's Commission on Environmental Quality, Executive Office of the President. 1993.
150	Biotechnology for the 21st Century: Realizing the Promise	1993	Federal Coordinating Council for Science, Engineering and Technology, Committee on Life Sciences and Health, Biotechnology Research Subcommittee, David Galas chair.	OSTP, Washington, DC. 90 p.
151	Choosing a Sustainable Future	1993	National Commission on the Environment; private-sector initiative convened by World Wildlife Fund	Island Press, Washington, DC
152	Global Marine Biological Diversity: A Strategy for Building Conservation into Decision Making	1993	Center for Marine Conservation, World Conservation Union, World Wildlife Fund, UNEP, World Bank. Elliott A. Norse, ed.	Norse, E.A. (ed.) Island Press, Washington, DC, 383 p.
153	Incorporating Biodiversity Considerations into Environmental Impact Analysis Under the National Environmental Policy Act	1993	Council on Environmental Quality with the U.S. EPA, DOD, DOI and DOT	O'Malley, R., L. Langstaff, and M. Southerland. 1993.
154	National Center for Ecological Synthesis: Scientific Objectives, Structure, and Implementation	1993	Joint committee report: Ecological Society of America and the Association of Ecosystem Research Centers	Carpenter, S.R. (chair of Report Preparation Committee). ESA & AERC
155	National Center for Synthesis in Ecology: A Design Study	1993	NSF-sponsored workshop report	Unpublished report
156	New Perspectives on Environmental Education and Research: A Report on the University Colloquium on Environmental Research and Education	1993	Sigma Xi	Sigma Xi: Research Triangle Park, NC

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157	Norway/UNEP Expert Conference on Biodiversity: Proceedings	1993	Hosted by: Norwegian Ministry of Environment & U.N. Environment Programme.	Sandlund, O.T. & P.J. Schei (eds). 1993. Conference held Trondheim, Norway
158	Report of the NSB/CPP Task Force on the Environment	1993	National Science Board, Committee on Programs and Plans, Task Force on the Environment	NSB/ENV-93-9, National Science Foundation
159	Report of the Technology and Sustainable Development Workshop	1993	NSF BCS-92-07174; David H. Marks, organizer	Program for Environemtnal Engineering Education and Research Publication No. 94-1: MIT. 1993
160	Research Opportunities in Oceanic Biology	1993	National Research Council, Ocean Studies Board	National Academy Press, Washington D.C.
161	Research Opportunities in Remote Sensing	1993	National Research Council, Ocean Studies Board	National Academy Press, Washington D.C.
162	Research to Protect, Restore, and Manage the Environment "Corson Report"	1993	National Research Council, Commission on Life Sciences, Committee on Environmental Research	National Academy Press, Washington DC, 242 p.
163	Risk and the Environment: Improving Regulatory Decision Making	1993	Carnegie Commission on Science, Technology and Government	http://www.carnegie.org/science_tech/reg.txt
164	Science and Stewardship in the Antarctic	1993	National Research Council, Polar Research Board	National Academy Press, Washington D.C.
165	Science, Technology, and the Federal Government: National Goals for a New Era "Griffiths Report"	1993	NAS, NAE, IOM, Committee on Science, Engineering, and Public Policy	National Academy Press, Washington DC, 54 p.
166	Statistics and Physical Oceanography	1993	National Research Council: Committee on Applied and Theoretical Statistics: Panel on Statistics and Oceanography; Dudley B. Chelton and William F. Eddy (co-chairs)	National Academy Press, Washington, D.C.
167	Understanding and Predicting Atmospheric Chemical Change	1993	National Research Council, Board on Atmospheric Sciences and Climate	National Academy Press, Washington D.C.
168	A Science and Technology Agenda for the Nation: Recommendations for the President and Congress	1992	Carnegie Commission on Science, Technology, and Government	Carnegie Commission on Science, Technology, and Government, New York, 37 p.
169	Assessment of the U.S. Outer Continental Shelf Environmental Studies Program. II. Ecology	1992	NRC: Board on Environmental Science & Technology	National Academy Press
170	Biotechnology and Genetic Resources	1992	U.S. - E.C. Task Force on Biotechnology Research.	U.S. - Commission of the European Communities Workshop: Airlie, VA 10/92

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171	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. Guyford Stever, Chair	Carnegie Commission on Science, Technology, and Government, New York, 72 p.
172	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, Robert W. Fri and H. Guyford Stever, Co-Chairs	Carnegie Commission on Science, Technology, and Government, New York, 143 p.
173	EPA's Research Agenda: Strengthening Science for Environmental Decisions	1992	U.S. EPA	U.S. EPA, Washington, DC
174	Federal Funding of Environmental R&D	1992	American Association for the Advancement of Science, Directorate for Science and Policy Programs, by Kathleen M. Gramp, Albert H. Teich, & Stephen D. Nelson	AAAS Pub. No. 92-48S, Washington, DC, 72 p.
175	Federal Ground-Water Science and Technology Programs	1992	FCCSET: CEES: Subcommittee on Water Resources	FCCSET: CEES: SWR; Steve Ragone (USGS) Chair
176	Federal Research on Environmental Biology	1992	Federal Coordinating Council for Science, Engineering and Technology, Committee on Life Sciences and Health, Subcommittee on Environmental Biology, Mary E. Clutter, chair	FCCSET. 72 p.
177	Global Environmental Change: Understanding the Human Dimensions	1992	National Research Council, Commission on the Behavioral and Social Sciences & Education; Committee on the Human Dimensions of Global Change	Stern, P.C., O.R. Young & D. Druckman (eds.) National Academy Press; 308 p.
178	Oceanography in the Next Decade: Building New Partnerships	1992	National Research Council: Ocean Studies Board; Carl Wunsch, chair	National Academy Press. 1992. Washington, D.C.
179	Our Living Oceans: Report on the Status of U.S. Living Marine Resources	1992	U.S. Dept. of Commerce: National Oceanic & Atmospheric Administration & National Marine Fisheries Service	U.S. Dept. of Commerce: NOAA Tech. Memo. NMFS-F/SPO-2. Washington, D.C.
180	Our Ozone Shield	1992	NOAA/UCAR	Reports to the Nation, Fall 1992, No.2
181	Predicting our Weather: A Strategic Plan for the U.S. Weather Research Program	1992	Federal Coordinating Council on Science, Engineering and Technology, Committee on Earth and Environmental Sciences, Subcommittee on Atmospheric Research	OSTP, Washington, DC, 36 p.

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182	Preparing U.S. Agriculture for Global Climate Change	1992	Council for Agricultural Science and Technology	Task Force Report. Paul Waggoner (chair). Council for Agricultural Science & Technology. No. 119. June 1992. http://www.cast-science.org
183	Report of a Workshop for a National Park Service Ecological Research Program	1992	U.S. Department of Interior, National Parks Service	Unpublished report
184	Restoration of Aquatic Ecosystems: Science, Technology, & Public Policy "Cairns Report"	1992	National Research Council, Commission on Geoscience, Environment, & Resouces, Water Science & Technology Board, Committee on Restoration of Aquatic Ecosystems	National Academy Press, Washington, DC, 552 p.
185	Safeguarding the Future: Credible Science, Credible Decisions	1992	U.S. EPA report of the expert panel on the role of science at EPA: Raymond C. Loehr, Chair.	EPA/600/9-91/050. U.S. EPA. 1992
186	Science and the National Parks	1992	National Research Council, Board on Environmental Science & Technology	National Academy Press
187	Science, Technology, and the States in America's Third Century	1992	Carnegie Commission on Science, Technology and Government	Firth, P. and S. Fiske, eds. Carnegie Commission on Science, Technology and Government, Washington, DC
188	Soil and Water Quality: An Agenda for Agriculture	1992	NRC: Board on Agriculture	National Academy Press
189	The Atmospheric Sciences in the 1990s: Accomplishments, Challenges, and Imperatives	1992	Bulletin American Meteorological Society 73(10):1549-1562	Dutton, J.A. 1992.
190	The Atmospheric Sciences: Entering the Twenty-first Century	1992	NRC Board on Atmospheric Sciences & Climate	John Dutton, Chair. National Academy Press
191	Water Quality: Agriculture's Role	1992	Council for Agricultural Science and Technology, Ames, Iowa	http://www.cast-science.org
192	A Sustainable Biosphere: The Global Imperative "ISBI"	1991	Workshop funded by MacArthur Foundation & Universidad Autonoma de Mexico	Huntley, B.J. + 18. Ecology International 20: 1-14.
193	Environmental Engineering Education in the Year 2000	1991	supported by NSF; sponsors: American Academy of Environmental Engineers, Assoc. of Envi. Eng. Professors & Western Region Hazardous Substance Research Center	Conf. chairs: K.J. Williamson & H.G. Schwartz; editors: K.J. Williamson & M.R. Miller; NSF 91-00098
194	Federally Funded Research: Decisions for a Decade	1991	Office of Technology Assessment	U.S. GPO, Washington, DC
195	From Genes to Ecosystems: A Research Agenda for Biodiversity	1991	IUBS-SCOPE-UNESCO Workshop report. Otto T. Solbrig, Editor. Supported by NSF and U.S. Committee for the MAB Program	International Union of Biological Sciences, Paris, France. 124 p.

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196	Implementation: Science and Technology	1991	in Global Change and the Human Prospect: Issues in Population, Science, Technology and Equity, Sigma Xi Forum Proceedings	Gibbons, J.H. pp. 183-201. Sigma Xi, The Scientific Research Scoeity, Inc: Research Triangle Park, NC
197	Justification and Criteria for the Monitoring of Ultraviolet Radiation	1991	National Research Initiative Competitive Grants Program/Cooperative State Research Service (USDA) & Colorado State University	Gibson, J.H. (coordinator). 1991. Natural Resource Ecology Laboratory, CSU, Ft. Collins, CO.
198	Opportunities and Priorities in Arctic Geoscience	1991	National Research Council, Commission on Geosciences, Committee on ARctic Solid-Earth Geosciences	National Academy Press, 67 p.
199	Opportunities in the Hydrologic Sciences; "Eagleson Report"	1991	National Research Council, Commission on Geosciences, Environment, and Resources, Water Science and Technology Board, Committee on Opportunities in the Hydrologic Sciences	National Academy Press; Peter Eagleson, Chair
200	Technology Development in the LTER Network: Status Report on GIS, Remote Sensing, Internet Connectivity, Archival Storage & Global Positioning Systems	1991	Sponsor: NSF BSR-91-00342; Report prepared in response to NSF request.	LTER Publication No. 12. 1991. D. Foster & E. Boose. LTER Network Office, Seattle, WA.
201	The Sustainable Biosphere Initiative "SBI"	1991	Ecological Society of America	Lubchenco, J. et.al.. Ecology 72(2):371-412.
202	Transforming Technology: An Agenda for Environmentally Sustainable Growth in the 21st Century	1991	World Resources Institute	Heaton, G., R. Repetto & R. Sobin, World Resources Institute, Washington, DC
203	1990's Global Change Action Plan: Utilizing a Network of Ecological Research Sites	1990	Report from a LTER Workshop held Nov. 1989 in Denver, CO. Support: NSF BSR-8996172	Long Term Ecological Research Network Office, University of Washington, Seattle.
204	Climate Change: The IPCC Scientific Assessment	1990	Intergovernmental Panel on Climate Change	Cambridge University Press: Great Britain
205	Climate Variability and Ecosystem Response	1990	Proceedingsof a Long-Term Ecological Research (LTER) Workshop; LTER Network Office (NSF-sponsored) and USDA Forest Service	Greenland, D. and L.W. Swift, Jr. (eds).
206	Conserving the World's Biological Diversity	1990	IUCN, WRI, CI, WWF-US, and the World Bank	McNeely, J.A., K.R. Miller, W.V. Reid, et al., Washington, DC
207	Ecological Impacts of Federal Conservation and Cropland Reduction Programs	1990	Council for Agricultural Science and Technology, Ames, Iowa	http://www.cast-science.org
208	Forestry Research: A Mandate for Change	1990	National Research Council	National Academy Press

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209	Global Stewardship: A Review of the Context and Challenges Facing Science and Economics Research Related to Global Change	1990	National Research Council (?); Proceedings of a White House conference	National Academy Press
210	Reducing Risk: Setting Priorities and Strategies for Environmental Protection	1990	U.S. EPA Science Advisory Board	SAB-EC-90-021, Washington, DC
211	Arctic Social Science: An Agenda for Action	1989	National Research Council, Commission on Physical Sciences, Mathematics, and Resources, Polar Research Board, Committee on Arctic Social Sciences	National Academy Press, 75 p.
212	Environmental Accounting for Sustainable Development	1989	The World Bank	Ahmad, Y.J., S.E. Serafy & E. Lutz (eds). The World Bank, Washington, DC
213	Global Change and Our Common Future: Papers from a Forum	1989	National Research Council: Committee on Global Change	DeFries, R.S. & T.F. Malone (eds). 1989. National Academy Press, Washington, D.C.
214	Intellectual Property Rights Associated with Plants	1989	American Society of Agronomy, Crop Science Society of America, Soil Science Society of America	ASA Special Publication #52 http://www.asa-cssa-sssa.org/
215	Investing in Research: A Proposal to Strengthen the Agricultural, Food, and Environmental System	1989	National Research Council, Board on Agriculture	National Academy Press, 155 p.
216	Loss of Biological Diversity: A Global Crisis Requiring International Solutions	1989	National Science Board, Committee on International Science, Task Force on Global Biodiversity, Craig C. Black, chair	NSB-89-171, National Science Foundation, 19 p
217	Opportunities in Biology	1989	National Research Council, Commission on Life Sciences, Board on Biology, Committee on Research Opportunities in Biology	National Academy Press, 448 p.
218	Research Priorities for Conservation Biology	1989	The Society for Conservation Biology: Supported by NSF and the University of Michigan	Soule, M.E. & K.A.Kohm (eds). 1989.
219	Chemistry and the Environment	1988	Sponsor: NSF Chemistry Division	J.W. Frost & D.M. Golden (eds.). NSF
220	Cross-disciplinary Research in the Statistical Sciences	1988	Institute of Mathematical Statistics; panel sponsored by NSF (DMS-85-08383).	Olkin, I. And J. Sacks (co-chairs). 1988.
221	Future Risk: Research Strategies for the 1990s	1988	U.S. EPA Science Advisory Board	SAB-EC-88-040, Washington, DC
222	Research Priorities for Single Species Conservation Biology	1988	National Science Foundation and the National Zoological Park	Wildt, D.E. and U.S. Seal (eds.). 1988. NSF Project DCB 8821694. Workshop 13-16 Nov 1988.
223	Water 2020: Sustainable Use for Water in the 21st Century	1988	Science Council of Canada. Geraldine A. Kenney-Wallace (chair)	Science Council of Canada Report 40. 1988. ISBN 0-662-16220-X.

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224	Directions in Engineering Research: An Assessment of Opportunities and Needs	1987	National Research Council, Commission on Engineering and Technical Systems, Engineering Research Board	National Academy Press, 331 p.
225	Environmental Impacts on Human Health: The Agenda for Long-Term Research and Development	1987	President's Council on Environmental Quality	Praeger Publishers, ISBN 0-275-92338-X
226	Environmental Impacts on Human Health: The Agenda for Long-Term Research and Development	1987	Council on Environmental Quality, Interagency Subcabinet Committee on Long-term Environmental Research, supported by NSF	Draggan, S., J.J. Cohrssen & R.E. Morrison (eds.) 228 p.
227	Environmental Monitoring, Assessment and Management: The Agenda for Long-term Research and Development	1987	President's Council on Environmental Quality	Praeger Publishers, ISBN 0-275-92336-3
228	Environmental Monitoring, Assessment, and Management: The Agenda for Long-Term Research and Development	1987	Council on Environmental Quality, Interagency Subcabinet Committee on Long-term Environmental Research	Draggan, S., J.J. Cohrssen & R.E. Morrison (eds.) 128 p.
229	Geochemical and Hydrologic Processes and Their Protection: The Agenda for Long-term Research and Development	1987	President's Council on Environmental Quality	Praeger Publishers, ISBN 0-275-92339-8
230	Geochemical and Hydrologic Processes and their Protection: The Agenda for Long-Term Research and Development	1987	Council on Environmental Quality, Interagency Subcabinet Committee on Long-term Environmental Research	Draggan, S., J.J. Cohrssen & R.E. Morrison (eds.) 210 p.
231	Infrastructure for the 21st Century: Framework for a Research Agenda	1987	National Research Council, Commission on Behavioral and Social Sciences and Education, Commission on Engineering and TEchnical Systems, Transportation Research Board, Committee on Infrastructure Innovation	National Academy Press, 100 p.
232	Preserving Ecological Systems: The Agenda for Long-Term Research and Development	1987	President's Council on Environmental Quality	Praeger Publishers, ISBN 0-275-92337-1
233	Preserving Ecological Systems: The Agenda for Long-Term Research and Development	1987	Council on Environmental Quality, Interagency Subcabinet Committee on Long-term Environmental Research	Draggan, S., J.J. Cohrssen & R.E. Morrison (eds.) 191 p.
234	Status and Future of Ecosystem Science	1987	Institute of Ecosystem Studies	Occasional Publication of The Institute of Ecosystem Studies, the New York Botanical Garden, Millbrook, NY. No. 3. 1987
235	Technologies to Maintain Biological Diversity	1987	Office of Technology Assessment	U.S. GPO, Washington, DC

	Title	Date	Initiators / Sponsors	Publication
236	Global Change in the Geosphere-Biosphere: Initial Priorities for an IGBP "Eddy Report"	1986	National Research Council, Commission on Physical Sciences, Mathematics, and Resources, U.S. Committee for an International Geosphere-Biosphere Program, John A. Eddy, chair	National Academy Press, Washington, DC, 91 p.
237	Organic Farming: Current Technology and Its Role in a Sustainable Agriculture	1984	American Society of Agronomy, Crop Science Society of America, Soil Science Society of America	ASA Special Publication #46 http://www.asa-cssa-sssa.org/
238	A Patron for Pure Science: The National Science Foundation's Formative Years, 1945-57	1982	National Science Foundation	J. Merton England, NSF Publication Number NSF 82-24.
239	Planning Future Land Uses	1981	American Society of Agronomy, Crop Science Society of America, Soil Science Society of America	ASA Special Publication #42 http://www.asa-cssa-sssa.org/
240	Planning the Uses and Management of Land	1979	American Society of Agronomy, Crop Science Society of America, Soil Science Society of America	Agronomy Monograph #21 http://www.asa-cssa-sssa.org/
241	Impact of Climatic Fluctuation on Major North American Food Crops	1976	Sponsor: C.F. Kettering Foundation, Dayton, OH. The Institute of Ecology. A. Dexter Hinckley, Project Manager	The Institute of Ecology (a non-profit corporation)
242	Environmental Science: Challenge for the Seventies	1971	National Science Board, H.E. Carter, Chair	NSB 71-1, National Science Foundation, U.S. GPO, 50 p.
243	The Universities and Environmental Quality – Commitment to Problem Focused Education	1969	Executive Office of the President, Office of Science & Technology, Report to the President's Environmental Quality Council by John S. Steinhart and Stacie Cherniack	J. S. Steinhart & S. Cherniack; U.S. GPO, Washington, DC., 22 p.
244	Science – The Endless Frontier	1945	National Science Foundation	Vannevar Bush report to President Franklin D. Roosevelt. Reprints available from NSF, Publication Number NSF 90-8.

Appendix C -
Individuals and Organizations that Provided Comments to the Task Force

Comments submitted by individuals did not necessarily represent organizational positions.
*"**" indicates that the organization's position was presented by the individual.*
Some individuals listed multiple affiliations. They are indented following the individual's name.

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Appendix D -
Context for NSF’s Approach to Support in the Environmental Area

In environmental science and engineering, the Foundation works closely with the external community, through advisory committees and other groups, to identify the most important environmental research needs. As a result of this consultative process, environmental research directions are proposed for allocation of resources. Although budget constraints have made it impossible to accomodate all suggestions received by the Foundation, many of the directions taken by new initiatives are strongly influenced by external community recommendations. Budget decisions are made by the Director in consultation with senior Foundation staff, subject to review and approval by the National Science Board and the Office of Management and Budget. These allocations are subject to further review and approval by the President and Congress. Criteria used include the Foundation's mission to support a broad and balanced portfolio of research, Administration priorities as expressed through the National Science and Technology Council, and other priorities developed through the Foundation's long-range planning process. NSF’s Government Performance and Results Act (GPRA) strategic plan outlines key investment strategies and an action plan for achievement of each of the outcome goals. There are common themes running through these investment strategies, and the performance plan reflects the importance of emphasizing activities that influence achievement of multiple objectives.

The research agendas that influence the Foundation's environmental programs have historically emerged from the academic community–either individually, or, increasingly, in a coordinated and prioritized framework. The significance of the research in advancing specific fields of study has been a prime criterion for inclusion in these agendas. The relevance of such research to societal issues is also vitally important. A cogent argument for maintaining a vigorous fundamental research effort in environmental science and engineering is for the Nation to have information available that can be used to address as yet unknown environmental problems likely to arise in the future. The NSF recognizes these dual goals, and has recently promulgated revised review criteria that address both the intellectual merit as well as the broader impacts of work supported by NSF:

> *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 well qualified is the proposer (individual or team) to conduct the project? (If appropriate, the reviewer will comment on the quality of prior work.) 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?
>
> *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 (e.g., gender, ethnicity, disability, geographic, 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 may be the benefits of the proposed activity to society?

Coordination of planning, setting priorities, management, and evaluation of NSF's environmental research and development activities in areas of mutual interest with other agencies traditionally has been undertaken through bilateral cooperation, but NSF has also played an active role in the increasingly important multi-agency activities of groups established under the auspices of the National Science and Technology Council (NSTC) such as the Integrated Science for Ecosystem Challenges activity of the CENR. The NSTC/CENR informs and influences the process by which the Foundation establishes research priorities and responds to policy concerns.

A number of bi- and multi-lateral environmental activities complement the NSTC/CENR initiatives. These include the NSF-EPA environmental partnership, the NSF-NIH-USDA International Cooperative Biodiversity Groups, the NSF-EPA-DOE-ONR Joint Program on Bioremediation, the NSF-USGS-FEMA-NIST National Earthquake Hazard Reduction Program, and the NSF-NOAA-NASA-DOD U.S. Weather Research Program. NSF's unique relationship with the university-based science and engineering community allows it to bring to the Federal planning table a valuable outside perspective from the researchers themselves.

Appendix E -
Selected Centers Supported by NSF in Fiscal Year 1998

NSF supports a variety of individual centers and centers programs to advance science and engineering, particularly in the areas of interdisciplinary research and the integration of research and education. Centers are expected to share a commitment 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.

The term "Centers," in the context of this appendix, includes consortia, collaboratories and similar arrangements intended to facilitate research or educational activities. The Centers listed below are either primarily involved in research related to the environment, or conduct a subset of activities with relevance to environmental research and education.

Examples of individual centers supported under broader center program initiatives are listed in *italics.* Descriptions of center programs and some individual centers may be found by searching the NSF web site http://www.nsf.gov/home/search.htm.

Centers
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*

Centers
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* *IUCRC for Biosurfaces* *Surfactants*
Land Margin Ecological Research (LMER)
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 (NCAR)
National Center for Ecological Analysis and Synthesis
National Center for Geographic Information and Analysis
National Optical Astronomy Observatories

Centers
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 Coop. Research Centers
Capsule Pipeline for Coal
Intelligent Information Retrieval
Rock Mechanics
University NAVSTAR Consortium (UNAVCO)

Appendix F -
Selected Acronyms

AIBS	American Institute of Biological Science
BE	Biocomplexity in the Environment – NSF theme area
CENR	Committee on Environment and Natural Resources (of the NSTC)
CNIE	Committee for the National Institute for the Environment
DGE	EHR Division of Graduate Education
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOI	U.S. Department of Interior
DUE	EHR Division of Undergraduate Education
EHR	Directorate for Education and Human Resources
EPA	U.S. Environmental Protection Agency
EPS	Experimental Program to Stimulate Competitive Research
ESIE	EHR Division of Elementary, Secondary and Informal Education
FEMA	Federal Emergency Management Administration
FGDC	Federal Geographic Data Committee
FY	Fiscal Year (October 1 for Federal government)
GLOBE	Global Learning and Observations to Benefit the Environment
GPRA	Government Performance and Results Act
HCP	Habitat Conservation Plan
HRD	EHR Division of Human Resource Development
ICSU	International Council of Science
IPCC	Intergovernmental Panel on Climate Change
ISEC	Integrated Sciences for Ecosystem Challenges – a multi-agency CENR activity
LEE	Life and Earth's Environment – superceded by BE – NSF theme area
LTER	Long-Term Ecological Research
MMIA	Methods and Models for Integrated Assessment – an NSF competition, part of USGCRP
NASA	National Aeronautic and Space Administration
NBII	National Biological Information Infrastructure
NCAR	National Center for Atmospheric Research
NCEAS	National Center for Ecological Analysis and Synthesis
NIH	U.S. National Institutes of Health
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration – in U.S. Dept. of Commerce
NRC	National Research Council
NSB	National Science Board

NSF	National Science Foundation
NSTC	National Science and Technology Council
ONR	Office of Naval Research
PCAST	President's Committee of Advisors on Science and Technology
PI	Principal Investigator
R&D	Research and Development
R&RA	Research and Related Activities – an NSF budget line
REC	EHR Division of Research, Evaluation and Communication
USDA	U.S. Department of Agriculture
USGCRP	U.S. Global Change Research Program – a multi-agency CENR activity

Box 1. Nature's Services: What Ecosystems Provide to People, What is at Risk and Why New Interdisciplinary Knowledge is Required

The ecological systems of the planet – including forests, grasslands, wetlands, riparian zones, estuaries, kelp forests, mangroves, coral reefs and open oceans – provide goods and services to people. The goods are more familiar to most of us: food, fiber, medicines, and more recently, genes. Only recently have we begun to understand and appreciate the essential services provided by ecological systems. 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. Some services are local, others regional and still others global. Ecosystems also provide yet another type of service: places for recreation, enjoyment, inspiration and learning. Together, these goods and services constitute the life support systems for Earth (Daily 1997, Daily et al. 1997).

These services are a byproduct of the functioning of intact ecological systems. Over the last century, a broad spectrum of human activities has inadvertently resulted in substantial changes to many of these ecosystems (see Box 3) and consequent disruption of the services provided. As land is transformed, as ecosystems are fragmented, reduced in size or lost, or as species are lost or transplanted, the functioning of the system is disrupted or lost, and the provision of services is often impaired (UNEP 1995). In most cases, we are beginning to appreciate and understand these services because they are being disrupted.

A recent example highlights the potential threats to vital services, the economic consequences to disruption, and the potential for restoration efforts to conserve essential services (Chichilnisky and Heal 1998). Historically, the watershed of the Catskill Mountains provided the ecosystem service of 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 sewage, industrial and agricultural runoff to the point that the water quality in the city fell below EPA drinking water standards. An economic analysis provided 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 to be $1 billion. The cost of building and maintaining a water purification and filtration plant was $6-8 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.

Natural and socioeconomic scientists have been collaborating on environmental questions for well over a decade in a limited fashion. There is presently not a common understanding among scholars as to the most important unanswered questions or most fruitful directions for future research. Such a research agenda will be necessary to fully realize the benefits of information on nature's services.

REFERENCES

Chichilnisky, G. and G. Heal. 1998. Economic returns from the biosphere – Commentary. Nature 391:629-630.

Daily, G.C. (ed.). 1997. Nature's Services. Island Press. Washington, D.C.

Daily, G.C., S. Alexander, P. R. Ehrlich, L. Goulder, J. Luchenco, P. A. Matson, H. A. Mooney, S. Postel, S. H. Schneider, D. Tilman, and G. M. Woodwell. 1997. Ecosystem services: Benefits supplied to human societies by natural ecosystems. *Issues in Ecology 2*: 1-16; available at http://www.sdsc.edu/~ESA/

United Nations Environment Programme. 1995. Global Biodiversity Assessment. Cambridge University Press, Cambridge, UK, 1140 pp.

Box 2. New Insight into Infectious Diseases: An Emerging Interface Between Health and the Environment

In the early 1960s, a disease outbreak occurred in the small northeastern Bolivian village of San Joaquin that killed hundreds and ultimately infected over one third of the population. The disease was found to be caused by a new pathogen, Machupo virus, that was transmitted directly from rodents to humans, causing a condition known as Bolivian Hemorrhagic Fever. Reaction to the outbreak was largely mounted by the public health community and quickly subsided once the disease burnt itself out. Machupo virus and other similar pathogens have been considered to be disease problems restricted to developing countries, until 1993, when an outbreak of Hantavirus Cardio-Pulmonary syndrome (HCPS) caused by a previously unknown Hantavirus, Sin Nombre virus (SNV) 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). The new virus was found to use the Deer Mouse, *Peromyscus maniculatus*, as its primary reservoir, and to be fatal in almost 50% 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. Data from NSF-supported long-term ecological and biodiversity research have played a significant role in solving the mystery of this and other emerging viruses.

In the case of Hantavirus, it is becoming clear that a cascade of climatic and biological events combine to cause increased risk to humans (Ernest et al., in press). This new understanding, improved remote sensing capabilities and modeling of complex systems is enabling improved prediction and prevention of hantavirus outbreaks in the Western United States. El Nino events are now known to trigger population explosions of the host rodent populations and eventually an increased incidence of infection in the mice and increased risk of infection in humans.

This realization has led to a fundamental change in how we approach the study of zoonotic diseases and is leading to the emergence of a field of study in the ecology of infectious diseases. 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 hantavirus, but for many other zoonotic diseases. A clear understanding of the ecology and evolution of these pathogens will be needed if we are to properly respond to emerging biological threats, both naturally occurring and man-made.

REFERENCES

Ernest, S. K. M., J. H. Brown, and R. R. Parmenter. In Press. Rodents, plants, and precipitation: Spatial and temporal dynamics of consumers and resources. OIKOS.

Hjelle, B. , B. Anderson, N. Torrez-Martinez, W. Song, W. L. Gannon, and T. L. Yates. 1995. Prevalence and geographic genetic variation of Hantaviruses of New World harvest mice (Reithrodontomys): Identification of a divergent genotype from a Costa Rican Reithrodontomys mexicanus. Virology. 207:452-459.

Keller D, P. Ettestad, C.M. Sewell, R. Rains, S. Englender, T. Woods, J. Pape, D. Tanda, J. Reynolds, R. Hoffman, G. Mertz, G. Scully, D. Mapel, F. Koster, J. DeLury, C. Hansbarger, B. Hjelle, T. Yates, J. Iralu, C. Freeman, B. Hroch, A. Nunes, D. Loretto, D. Peter, R. Fulgham, L. Courtois, M. Mattson, R. Charleston, and J. Cheek. 1998. Hantavirus pulmonary syndrome - Colorado and New Mexico. *Journal of the American Medical Association* 280: (6) 504-505

Parmenter, R.R., J. W. Brunt, D. I. Moore, and S. Ernest. 1993. The Hantavirus epidemic in the Southwest: Rodent population dynamics and the implications for transmission of Hantavirus-associated Adult Respiratory Distress Syndrome (HARDS) in the Four Corners Region. Report to the Federal Centers for Disease Control and Prevention, Atlanta, GA. Sevilleta LTER Publication No. 41, 45 pp.

Parmenter, C. A., T. L. Yates, R. R. Parmenter, and J. L. Dunnum. 1999. Statistical sensitivity for detection of spatial and temporal patterns in rodent population densities. Emerging Infectious Diseases. 5(1):118-125.

Box 3.
Unprecedented Environmental Changes:
New Challenges for Humanity

Assertions about a wide variety of environmental changes often 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. 1997 and references therein). These global-scale indicators of change provide a credible platform for discussing environmental challenges.

1. **Between 40 and 50% 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 (see Box 1).

2. **The concentration of carbon dioxide in the atmosphere has increased by 30% 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% of that amount is used in agriculture. Diversions and impoundments have altered river systems substantially, with only 2% 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 nitrogen fixed annually since the beginning of the century.** This additional fixed N – 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 non-native species are increasing globally, with often more than half of the plant species on islands and 20% or more on continental areas 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 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 1000 times those before humanity's dominance of Earth.
7. **Two-thirds of the major marine fisheries are now fully exploited, over exploited or depleted. Just over 40 years ago, this figure stood at less than 5%.** Currently, 22% are overexploited or already depleted and 44% are at their limit of exploitation. In addition to the reported biomass of landed catches, an additional 27 million tons of bycatch is discarded annually, nearly one-third as large as total landings.

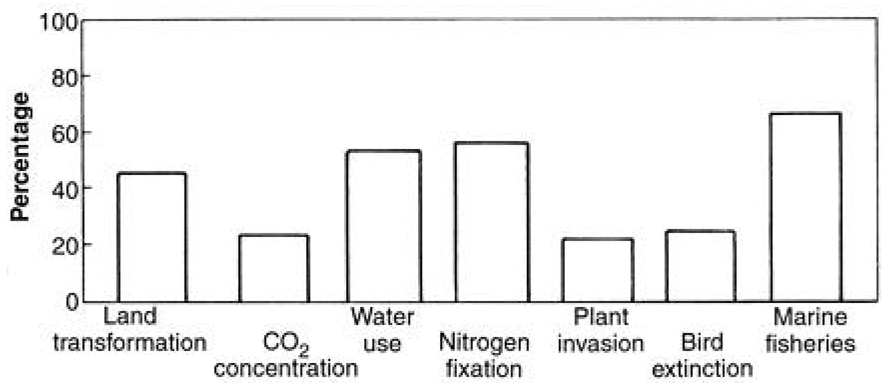

Figure 1. Human dominance or alteration of several major components of the Earth system. Data are expressed as (from left to right) percentage of the land surface transformed; percentage of the current atmospheric CO2 concentration that results from human action; percentage of accessible surface fresh water 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 two 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. 1997, Science 277:494-499.

It is clear from these seven global-scale indicators of change that human activities are transforming the planet in new ways, at faster rates, over broader scales and in new combinations 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.

REFERENCE

Vitousek, P. M., H. A. Mooney, J. Lubchenco, and J. M. Melillo. 1997. Human domination of Earth's ecosystems. Science 277:494-499.

Box 4.
Nitrogen: 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). Research is beginning to reveal some of the causes and consequences of changes in many biogeochemical cycles. New information about one of the most basic and important of these cycles, that of nitrogen, sheds light on some puzzling environmental trends. Changes to the nitrogen biogeochemical cycle are substantial and link together a wide variety of human activities and concerns (Vitousek et al., 1997a,b). New knowledge is needed to help guide decisions about future activities that could either exacerbate or ameliorate emerging problems.

The abundant nitrogen in the atmosphere cannot be used directly by most plants until it has been fixed (combined with carbon, hydrogen, or oxygen). Until the beginning of this century, microbes and lightning were the primary sources of nitrogen fixation, accounting for approximately 90 to 130 million metric tons of N (Tg N) per year across all terrestrial ecosystems. Humans contribute to nitrogen fixation by making fertilizers, burning fossil fuels and planting legumes over broader areas than they occur naturally. As the scale and rate of these activities have increased, so too has the anthropogenic contribution to the global nitrogen budget. At the beginning of this century, the anthropogenic contribution to the nitrogen cycle was negligible. Now, human activities dominate. More than 140 TG N is now fixed annually, more than double the non-anthropogenic sources of terrestrial nitrogen fixation.

When nitrogen was only scantily available to the biological world, it served as one of the major limiting factors that controlled the dynamics, biodiversity, and functioning of many ecosystems. Ecosystems now flush with excess fixed nitrogen are changing rapidly. Nitrogen unused by crops, lawns and garden plants, nitrogenous wastes from livestock and human sewage, and airborne nitrogen resulting from the burning of fossil fuels are disrupting a wide range of downstream and downwind systems. Excess nitrogen stimulates the growth of algae and can lead to eutrophication, toxic 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 biodiversity including species important to commercial and sport fisheries and shellfish industries. In short, excess nitrogen “seriously degrades our marine and freshwater resources and impairs their use for industry, agriculture, recreation, drinking water and other purposes.” (Carpenter et al. 1998.) Human-driven alterations in the nitrogen cycle are also causing regional and global change in the chemistry of the atmosphere, 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 1999).

Harmful algal blooms, some of which are triggered by increases in nitrogen (and oftentimes phosphorus as well) can wreak havoc with fisheries, aquaculture and tourism. They can also threaten human health directly. Toxins produced by the algae may be concentrated in filter-feeding bivalves such as clams, mussels and oysters or transported through the water or possibly the air. The frequency, intensity and duration of harmful algal blooms are increasing globally and may be correlated with documented increases in nitrogen in coastal waters.

Major scientific uncertainties concerning the nitrogen cycle include the controls on nitrogen fixation and denitrification processes in coastal and open ocean waters; causes of harmful algal blooms; transport of nitrogen across the landscape and from air to soil and water; evolutionary consequences of long-term nitrogen enrichment; variance in and controls of nitrogen-retention processes among ecosystems; and the specifics of nitrogen movement from large river basins back to the atmosphere.

Now that the existence of the biogeochemical links across agriculture, tourism, health, fisheries and industry are becoming better known and knowledge is emerging about the extent to which human activities are altering basic biogeochemical process, fundamental research to guide understanding and decisions is urgently needed.

REFERENCES

Carpenter, S. R., N..F. Caraco, D. L. Correll, R. W. Howarth, A. N. Sharpley, and V. H. Smith. 1998a. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Issues in Ecology* 3: 1-12; available at http://www.sdsc.edu/~ESA/

Carpenter, S. R., N.F. Caraco, D.L. Correll, R.W. Howarth, A.N. Sharpley, and V. H. Smith. 1998 b. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications* 8: 559-568.

Schlesinger, W. H. 1997. Biogeochemistry: An Analysis of Global Change. Second Edition. 588 pp. Academic Press.

U.S. Geological Survey. 1999. The Quality of Our Nation's Waters–Nutrients and Pesticides. U.S. Geological Survey Circular 1225, 82 pp.

Vitousek, P. M., et al. 1997b. Human alteration of the global nitrogen cycle: Causes and consequences. *Ecological Applications* 7: 737-750.

Vitousek, P. M., J. Aber, R.W. Howarth, G.E. Likens, P. A. Matson, D. W. Schindler, W. H. Schlesinger, and G. D. Tilman. 1997a. Human Alteration of the Global Nitrogen Cycle: Causes and Consequences. *Issues in Ecology* 1: 1-15, available at http://www.sdsc.edu/~ESA/

Box 5.
Complexity Theory and Ecosystems

The eminent 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 honestly face the awesome complexity of ecosystems and incorporate that complexity into our scientific endeavors. As scientists have departed from the historically reductionist approach to studying natural systems, they have begun to develop an important new range of capabilities that applies knowledge about forecasted behavior. Ecological systems are highly nonlinear, characterized by abrupt thresholds in dynamics and possibly chaotic behavior. It is unreasonable always to expect 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. Viewing systems as complex and not as the simple sum of their parts is the key to progress.

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 generatikon and maintenance of biological complexity across multiple spatio-temporal levels of resolution.

Stated simply, driving variables influence rates of processes that determine flows of matter and energy among components of the ecosystem, and thereby determine the structure and properties of the ecosystem (Elliott et al. 1994). System properties at a higher level of resolution become driving variables at the next lower level (Allen and Starr 1982). The causal relationships showing how driving variables determine properties of the ecosystem are studied through experimentation, and this information is expressed in mathematical simulation models that capture the quantitative relationships at each level, thereby producing a nested set of predictive capabilities. Moving back up through the levels becomes a statistical exercise where taking many individual samples at one spatial scale provides knowledge of the structure at the next spatial scale (Allen et al. 1984). This scaling allows extrapolation of information; for example, of microbial processes within soil pores to much larger spatial scales.

Perhaps the greatest significance of this approach is that information on driving variables derived at larger scales (for example, from satellite imagery) can be used to drive linked simulation models down to levels of microbial communities and make predictions of properties that could never be adequately sampled. These modeled properties can be scaled back up to the regional level as forecasts that may be used by decision makers. Such an approach is an example of the tremendous power becoming available to us as we begin linking complexity theory (holarchy and systems theory) with disciplinary knowledge (ecosystem science, microbial ecology) and experimental approaches. Information derived in this way must be carefully evaluated by comparing with observations before it is applied to real-world situations.

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 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). 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. While significantly more research will clearly advance our ability to apply knowledge of ecosystem and other system behavior, we must be wary of delivering what might appear to be firm predictions about issues of concern to the public. Ecosystems are not simple and much better understanding must be obtained about the dynamics and management of complex biological systems before we understand just how well ecological forecasts can be made.

REFERENCES

Allen, T.F. and T.B. Starr. 1982. Hierarchy: Perspectives for Ecological Complexity. University of Chicago Press, Chicago. 310 pp.

Allen, T.F., R.V. O'Neill, and T.W. Hoekstra. 1984. Interlevel relations in ecological research and management: Some working principles from hierarchy theory. USDA Forest Service General Technical Report RM-110. Fort Collins, CO. 11 pp.

Elliott, E.T., H.H. Janzen, C.A. Campbell, C.V. Cole, and R.J.K. Myers. 1994. Principles of ecosystem analysis and their application to integrated nutrient management and assessment of sustainability. In: R.C. Wood and J. Dumanski (eds.), Sustainable Land Management for the 21st Century. Volume 2: Plenary Papers. Proceedings of the International Workshop on Sustainable Land Management for the 21st Century. University of Lethbridge, Lethbridge.

Levin, S. A. 1999. Fragile Dominion – Complexity and the Commons. Perseus Books, Reading, MA. 250 pp.

Muller, F. 1997. Hierarchical approaches to ecosystem theory. *Ecological Modeling* 63:215-242.

Muller, F. 1997. State-of-the-art in ecosystem theory. *Ecological Modeling* 100:135-161.

Pace, M.L. and P.M. Groffman. 1998. Successes, limitations, and frontiers in ecosystem science: Reflections on the Seventh Cary Conference. *Ecosystems* 1:137-142.

Box 6.
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 been discovered to cause unintended problems, necessitating after-the-fact treatment and remediation, often at immense cost and effort. Ozone-destroying chlorofluorocarbons, brain-damaging heavy 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. The new goal for environmental technology is to "learn more before doing."

For example, the development of microarray technology for analyzing simultaneously the total component of genome-encoded messenger RNA holds promise for 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 eventually it can be used to help understand the likely responses of microorganisms to environmental perturbations. Understanding how compounds travel through ecosystems as well as how species interact will enable more comprehensive understanding of likely consequences of different compounds or technologies.

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 do rapid prototyping and learning about potential environmental impacts as a part of production. Can we use the capacity we have in 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 the potential for 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.

Box 7.
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 not longer the major hurdle – managing, validating and understanding the data are the new challenges. The Web and Internet connectivity have fueled the expectations by citizens, policy-makers, scientists and mangers 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 in 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 data bases 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 (NBII) 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 from data to useful information is currently employed in the private sector. The potential benefit arising from public-private partnerships which would bring together software and hardware designers with environmental scientists and engineers is immense.

REFERENCES

President's Committee of Advisers on Science and Technology (PCAST). 1998. Teaming with Life: Investing in Science to Understand and Use America's Living Capital. PCAST Panel on Biodiversity and Ecosystems.

Frondorf, A. and G. Waggoner. 1996. Systematics information as a central component in the National Biological Information Infrastructure. Annals of the Missouri Botanical Garden 83:546-550.

Box 8.
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 and many more are in progress. With the exception of one nematode worm, all of the published sequences have been from microbes. Although genomic sequencing of more complex organisms is in progress, what scientists are learning from the analysis of microbes alone is fueling a scientific revolution.

Some of the unanticipated findings were that in the genomes sequenced thus far, about 40 – 60% of the putative genes encode proteins that had not been seen or studied before and approximately 25% 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% 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 evolution of species. 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. The recognition that DNA can be transferred between even distantly related microbes has increased scientists' interest in understanding the extent and rate of interspecies communication.

Thus far, the genomic revolution has touched only the tip of microbial life. We have at least as much to learn from genomic analysis of more complex organisms, the 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.

REFERENCES

Nelson, K. E., R. A. Clayton, S. R. Gill, M. L. Gwinn, R. J. Dodson, D. H. Haft, E. K. Hickey, J. D. Peterson, W. C. Nelson, K. A. Ketchum, L. McDonald, T. R. Utterback, J. A. Malek, K. D. Linher, M. M. Garrett, A.M. Stewart, M. D. Cotton, M. S. Pratt, C. A. Phillips, D. Richardson, J. Heidelberg, G. G. Sutton, R. D. Fleischmann, J. A. Eisen, O. White, S. L. Salzberg, H. O. Smith, J. C. Venter, and C. M. Fraser. 1999. Evidence for lateral gene transfer between Archaea and Bacteria from genome sequence of *Thermotoga maritima*. Nature 399:323-329.

Pennisi, E. 1999. Is it time to uproot the tree of life? Science 284:1305-1307.

Box 9.
Human Dimensions of Environmental Questions

The demographic prospect for individual nations is widely variable. In some countries, populations are projected to decline somewhat over the next half-century, while other nations will experience a tripling of population. Humans have always played a large role in forming and modifying the environment. Environmental degradation, in turn, usually carries a high human cost.

Historical ecology is emerging as a field of study capable of providing lessons applicable to current problems. Researchers in this area trace sequences of mutual causation between human acts and acts of nature (e,g, DieffenbacherKrall 1996, Crumley 1993, Hammett 1992). Studies in Europe have drawn from 10,000 years of human occupation to illuminate human and environmental causes for increased erosion and desertification of the northern Mediterranean region. As social, physical and natural scientists develop a common language and shared concepts, they can more effectively address the distinct historical and geographical distributions of particular conditions, and their periodicity, duration, and severity. Historical evidence records past human choice and response 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.

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 understand better 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 a delimited range of forest biomes with three major types of forest ownership, the researchers can identify the differential impact of social processes on sites. Preliminary findings range from the identification of key biophysical and behavioral variables associated with differences in rates of forest regrowth to further understanding of the relationship between forest conditions and property rights systems. Expanding support for global and regional studies of land use and land cover change, employing remote-sensing and geographic information systems technologies with anthropological, ecological, and survey research, can advance our understanding and forecasting of socio-environmental interactions.

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, attention is needed to developing a strong theoretical framework for this research.

REFERENCES

Crumley, C. L. 1993. Analyzing historic ecotonal shifts. Ecological Applications. 3:377-384.

DieffenbacherKrall, A. C. 1996. Paleo- and historical ecology of the Cutler grasslands, Cutler, Maine (USA): Implications for future management. Natural Areas Journal 16:3-13.

Hammett, J. E. 1992. The shapes of adaptation – historical ecology of anthropogenic landscapes in the Southeastern United States. Landscape Ecology 7:121-135.

Box 10.
The Ocean Beneath the Sea Floor

The ocean sciences may be on the threshold of a major scientific revolution linking the origins and sustainability of life on this planet to the potential for life elsewhere in the solar system and beyond. Utilizing rapidly emerging technology in fiber optics information transmission, robotic and manned submersible sampling systems, molecular biology, genomic sequencing and more, NSF, in cooperation with other agencies in the National Ocean Partnership Program and internationally in the Ocean Drilling Program, has embarked on the design of seafloor observatories and new deep drilling technologies. The purpose is to explore the ocean beneath the sea floor – the deep biosphere - organisms living in extreme conditions of temperature, pressure and absence of sunlight - known to populate regions around sea floor vents spewing hot water and chemical energy and the potentially huge ecosystem of microorganisms deep within the Earth's crust (Figure 2). For primordial life forms, these may well have been the normal conditions for them at the dawn of evolution.

Figure 2. This vigorously venting hydrothermal deposit stands 45 meters above the seafloor and is forming on the Juan de Fuca Ridge, 2100 meters below sea level. The manned submersible ALVIN is shown for scale. Drawing by Veronique Robigou, courtesy of University of Washington.

Box 11.
Statistical Prevention Models for Wildfire Suppression

Some of the most devastating natural disasters in the history of the US 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 predications. 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.