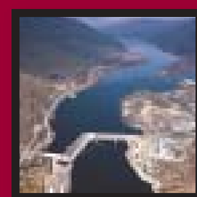
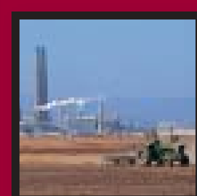
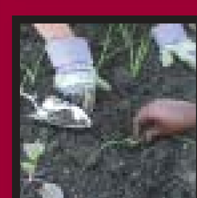
Complex Environmental Systems

Synthesis for Earth, Life, and Society in the 21st Century



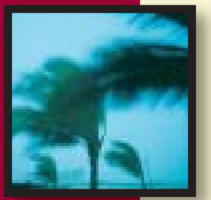


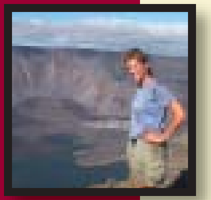


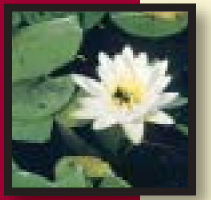
A 10-Year Outlook for the National Science Foundation

NSF Advisory Committee for
Environmental Research and Education

About the Advisory Committee for Environmental Research and Education



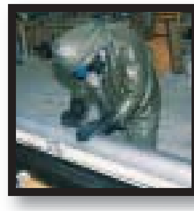
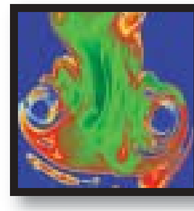
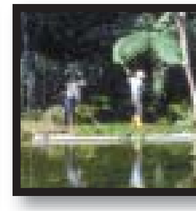




In 2000, the National Science Foundation (NSF) established the Advisory Committee for Environmental Research and Education (AC-ERE) under the Federal Advisory Committee Act (FACA) to:

- Provide advice, recommendations, and oversight concerning support for NSF's environmental research and education portfolio.
- Be a base of contact with the scientific community to inform NSF of the impact of its research support and NSF-wide policies on the scientific community.
- Serve as a forum for consideration of interdisciplinary environmental topics as well as environmental activities in a wide range of disciplines.
- Provide broad input into long-range plans and partnership opportunities.
- Perform oversight of program management, overall program balance, and other aspects of program performance for environmental research and education activities.

The AC-ERE has a particular interest in those aspects of environmental science, engineering, and education that affect multiple disciplines. Each of the directorates and major offices of NSF has an advisory committee that provides guidance on the disciplinary activities within that directorate. The AC-ERE includes scientists from many disciplines, including a member from each of the other NSF advisory committees, and focuses on coordination, integration, and management of environmental programs across the Foundation. AC-ERE interests include environmental education, digital libraries, and cyberinfrastructure, as well as interdisciplinary programs, centers, and major instrumentation.

Complex Environmental Systems

Synthesis for Earth, Life, and Society in the 21st Century

A 10-Year Outlook for the National Science Foundation

NSF Advisory Committee for
Environmental Research and Education

January 2003

Development of this Document

To develop the Outlook, AC-ERE members familiarized themselves with NSF's current portfolio of environmental activities, consulted broadly with NSF staff and the staff of other federal agencies, took into account the many community reports in environmental research areas that have been issued in the last five years, and engaged in dialogue with the scientific, engineering, and science education communities. An early draft of the Outlook was posted on the Web for public comment; the Committee received comments from 133 individuals, professional societies, advocacy groups, and local, state, and federal agencies (see Sources of Public Comment on page 65). These comments were very thoughtful and offered many insightful suggestions that have been incorporated into the Outlook. As a result, this document represents the views of a wide range of the science and engineering community.

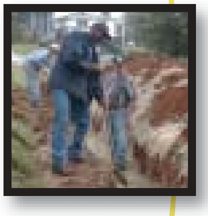
For purposes of citation, please use: Pfirman, S., and the AC-ERE, 2003, *Complex Environmental Systems: Synthesis for Earth, Life, and Society in the 21st Century*, A report summarizing a 10-year outlook in environmental research and education for the National Science Foundation, 68 pp.

Foreword

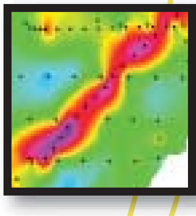
In early 2000, the National Science Board (NSB) issued the report, *Environmental Science and Engineering for the 21st Century*. The report recommended that the National Science Foundation (NSF) expand its efforts in environmental research and education, create an organizational focus, and establish an external advisory committee. These organizational changes were necessary to carry out the Board's ambitious recommendations to identify and support critical needs in disciplinary and interdisciplinary environmental areas, advance the current scope of environmental research using new tools and technologies, form partnerships with other agencies, and enhance environmental education and critical infrastructure.

While the NSB report cited some possible topics, it did not assess research challenges and opportunities. In 2001, the National Research Council's report on *Grand Challenges in Environmental Sciences* identified priority areas for study but did not specify which were appropriate for NSF.

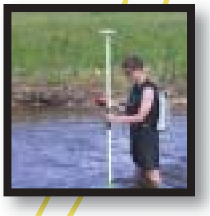
The Advisory Committee for Environmental Research and Education (AC-ERE), the external advisory board established in 2000 in response to the NSB report, took on the task of bridging those two reports to provide overall strategic guidance about environmental research and education areas specifically aligned with NSF's mission. NSF is authorized to support basic scientific research, to support research fundamental to engineering processes, and to strengthen science and engineering education at all levels. The outcomes are knowledge, methods, and new technologies that can enable solutions to critical environmental problems.



In preparing this Outlook, the AC-ERE assumed a 10-year horizon and focused on those environmental activities that cross NSF's organizational boundaries or that undergird NSF's entire environmental portfolio. The Committee gave priority to those opportunities that were intellectually compelling, timely, and feasible, and important to the progress of knowledge and of society. The result is this Outlook, which contains the AC-ERE's recommendations to NSF regarding the direction of cross-Foundation environmental research and education at NSF during 2003-2012.



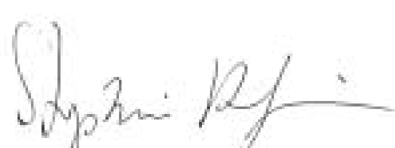
Ultimately, the success of environmental research and education depends on advances in all science and engineering disciplines, ready communication across fields of new knowledge and methodologies, and effective collaborations. In captions and boxes throughout this Outlook, NSF's disciplinary and interdisciplinary environmental activities are highlighted both to show the scope of activities and to stress the importance of contributions and collaborations involving many fields.



Contrails, Cloud Cover, and Temperature, David J. Travis, University of Wisconsin-Whitewater. The grounding of all commercial aircraft for three days following the September 11, 2001 terrorist attacks provided a unique opportunity to measure the effects of jet condensation trails (see figures), or contrails, on surface temperature. Our previous research suggests that jet contrails are capable of reducing the diurnal temperature range (DTR- difference between daytime maxima and nighttime minima) by efficiently blocking sunlight during the daytime and reducing outgoing infrared radiation at night. Our results show a statistically significant increase in DTR during the three-day grounding period when no new contrails were being formed compared to the two adjacent three-day periods (September 8 to 10 and September 15 to 17) and considered against the previous 30-year period. We also determined that this increase in DTR was the largest such increase during any comparable period in the past 30 years. Finally, we determined that the regions of the United States that had the greatest increases were those areas that normally received the greatest amount of contrail coverage during mid-September (Pacific Northwest, Midwest, and Northeast). This suggests that the primary cause for the DTR increase was the lack of contrails and significantly clearer skies that occurred across the United States during those 3 days. NSF grant BCS-0099011.

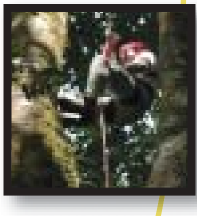
We know that implementation of this Outlook will not be easy for NSF. The challenges are enormous, and current resources pale in comparison. NSF will need to develop a plan that encompasses new as well as existing programs, and fosters individual investigator as well as multidisciplinary team research. Environmental cyberinfrastructure and observing systems are extensive and expensive endeavors. Interdisciplinary pursuits will be successful only if credible review processes and mechanisms for collaboration are in place. Integrating research and education remains a challenge, as does developing creative approaches to interdisciplinary education. Attracting a diverse workforce will require that we include paths to environmental careers of all types.

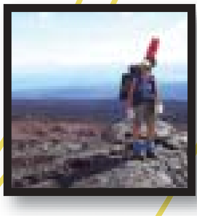
Means of supporting long-term research and establishing long-term partnerships among federal agencies are also needed. One of the main features of the Outlook is outreach to communities, groups, and institutions, some of which have not previously been major partners for NSF. Building these connections will require time and patience, however, the AC-ERE is committed to pursuing this path. We hope that you will support us in this effort and will continue to send us your best ideas about how to implement this ambitious Outlook, which has been greatly enriched by the involvement of so many who are dedicated, as is the AC-ERE, to "growing knowledge and know-how" for the environment.



Stephanie Pfirman, Chair
Advisory Committee for Environmental Research and Education

Contents





Acknowledgements

The Advisory Committee is grateful to numerous NSF staff members who assisted us in the preparation of this report. Of particular note are the contributions of Margaret Leinen, Assistant Director of Geosciences and NSF Coordinator for Environmental Research and Education; Margaret Cavanaugh, chair, and members of the NSF Working Group for Environmental Research and Education, especially Melissa Lane. Frederick Meyerson, AAAS/NSF Science and Technology Policy Fellow, had a lead role in researching, preparing, and editing multiple drafts of this report and assisted the Committee in the review of public comments. Ellen Kappel of Geosciences Professional Services also edited the report, and aided in gathering and editing text and graphics for the scientific vignettes. Johanna Adams of Geosciences Professional Services provided graphic design services. Cheryl Thorpe, Suzanne Marshalonis, and Jiang Yu of Booz-Allen-Hamilton developed the new web site and the tool allowing users to submit comments over the Internet. Also, Patricia McBride, Booz-Allen-Hamilton, developed the graphic designs for the NSF Environmental Research and Education logo as well as the web site. Special thanks are due to all those who provided information to the Committee and took time to attend the public briefings and submit comments. Finally, the AC-ERE is indebted to its sister NSF Advisory Committees for their help in developing this Outlook and looks forward to continuing to work with them to advance environmental research and education in disciplinary as well as interdisciplinary areas.

Advisory Committee for Environmental Research and Education (2000-2002)

James Allen, Department of Computer Science, University of Rochester
Joan Brennecke, Department of Chemical Engineering, University of Notre Dame
Ronald Brisbois, Department of Chemistry, Macalester College
James P. Collins, Department of Biology, Arizona State University
Jack Dangermond, Environmental Systems Research Institute
Costel D. Denson, Department of Chemical Engineering, University of Delaware
David Ellis, Boston Museum of Science
Jean H. Futrell, Pacific Northwest National Laboratory
Thomas E. Graedel, School of Forestry and Environmental Studies, Yale University
Bruce A. Jackson, Biotechnology Programs, Massachusetts Bay Company Community College
James J. Kay, Environment and Resources Studies, University of Waterloo (Canada)
Elizabeth Kelly, Statistical Sciences, Los Alamos National Laboratory
Charles E. Leonard, Solucient, LLC, New York City, New York City
Simon A. Levin, Department of Ecology and Evolutionary Biology, Princeton University
Richard G. Luthy, Department of Civil and Environmental Engineering, Stanford University
Rosalyn McKeown, Center for Geography and Environmental Education, University of Tennessee
Mary Jane Perry, School of Marine Science, University of Maine
James Peterson, Science Museum of Minnesota, St. Paul, Minnesota
Stephanie Pfirman, AC-ERE Chair, Department of Environmental Science, Barnard College
John Priscu, Department of Land Resources and Environmental Sciences, Montana State University
Eloy Rodriguez, Department of Biology, Cornell University
David Skole, Center for Global Change and Earth Observations, Michigan State University
Diana H. Wall, Natural Resource Ecology Laboratory, Colorado State University

NSF Coordinator for Environmental Research and Education (2000-)

Margaret Leinen, NSF Assistant Director for Geosciences

NSF Working Group for Environmental Research and Education (2001-2002)

W. Richard Adrion, Directorate for Computer and Information Science and Engineering
Thomas J. Baerwald, Directorate for Social, Behavioral, and Economic Sciences
Donald M. Burland, Directorate for Mathematical and Physical Sciences
David B. Campbell, Directorate for Education and Human Resources
Margaret A. Cavanaugh, WG-ERE Chair, Office of the Director
H. Lawrence Clark, Directorate for Geosciences
Cheryl L. Dybas, Office of Legislative and Public Affairs
Penelope Firth, Directorate for Biological Sciences
Pamela B. Green, Office of Budget, Finance and Award Management
Bruce K. Hamilton, Directorate for Engineering
Melissa J. Lane, Directorate for Geosciences
Herbert Levitan, Directorate for Education and Human Resources
Frances C. Li, Office of International Science and Engineering
Stephen R. Mahaney, Directorate for Computer and Information Science and Engineering
Polly A. Penhale, Office of Polar Programs
Lurrie V. Pope, Office of Budget, Finance and Award Management
Joann P. Roskoski, Directorate for Biological Sciences
Herman B. Zimmerman, Directorate for Geosciences

NSF Environmental Research and Education Staff

Javier Bobonis, Hispanic Association of Colleges and Universities (HACU) Intern
Kathy Jo Carstarphen, Directorate for Geosciences
Susan Henson, Office of the Director
Frederick A.B. Meyerson, AAAS/NSF Science and Technology Policy Fellow
Mary J. Mosley, Directorate for Geosciences

New instrumentation, data-handling, and methodological capabilities have expanded the horizons of what we can study and understand about the environment. These advances create the demand for collaborative teams of engineers and natural and social scientists that go beyond current disciplinary research and educational frameworks.

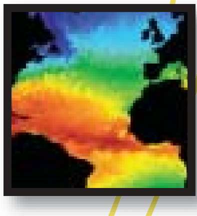
Executive Summary

As the global footprint of human activity continues to expand, environmental science and engineering problems will provide great challenges and opportunities in the next decade. Because of the complex relationships among people, ecosystems, and the biosphere, human health and well-being are closely linked to the integrity of local, regional, and global ecosystems. Therefore, environmental research and education are central elements of local, national, and global security, health, and prosperity.

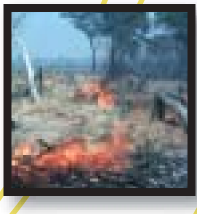
New instrumentation, data-handling, and methodological capabilities have expanded the horizons of what we can study and understand about the environment. These advances create the demand for collaborative teams of engineers and natural and social scientists that go beyond current disciplinary research and educational frameworks. Imagination, diversity, and the capacity to adapt quickly have become essential qualities for both institutions and individuals, not only to facilitate research, but also to ensure the immediate and broad-based application of research results related to the environment.

To meet these complex challenges as well as urgent human needs, we need to develop *environmental synthesis* to frame integrated interdisciplinary research questions and activities and to merge data, approaches, and ideas across spatial, temporal, and societal scales. An essential part of this process is the effective communication of scientific information, models, and conclusions to and among researchers, educators, students, resource and industrial managers, policy makers, and the public.

To advance the fundamental knowledge necessary to address critical environmental challenges, the Advisory Committee for Environmental Research and Education recommends increased focus on three interrelated areas: (A) coupled human and natural systems, (B) coupled biological and physical systems, and (C) people and technology. Research in these areas is important, timely, feasible, and likely to lead to significant scientific and practical outcomes in the next decade.



Coupled human and natural systems research explores the complex web of environmental relationships and feedbacks at diverse temporal and spatial scales. Research challenges include: (1) land, resources, and the built environment, (2) human health and the environment, (3) freshwater resources, estuaries, and coastal environments, and (4) environmental services and valuation.



Coupled biological and physical systems research focuses on understanding the systems, processes and dynamics that shape the physical, chemical, and biological environment from the molecular to the planetary scale. Research areas include: (1) biogeochemical cycles, (2) climate variability and change, and (3) biodiversity and ecosystem dynamics.

People and technology research seeks to discover new technologies that protect and improve the environment and also to understand how individuals and institutions interact with the environment, and how they use resources and respond to change. Research areas include: (1) materials and process development, (2) decision making and uncertainty, and (3) institutions and environmental systems.

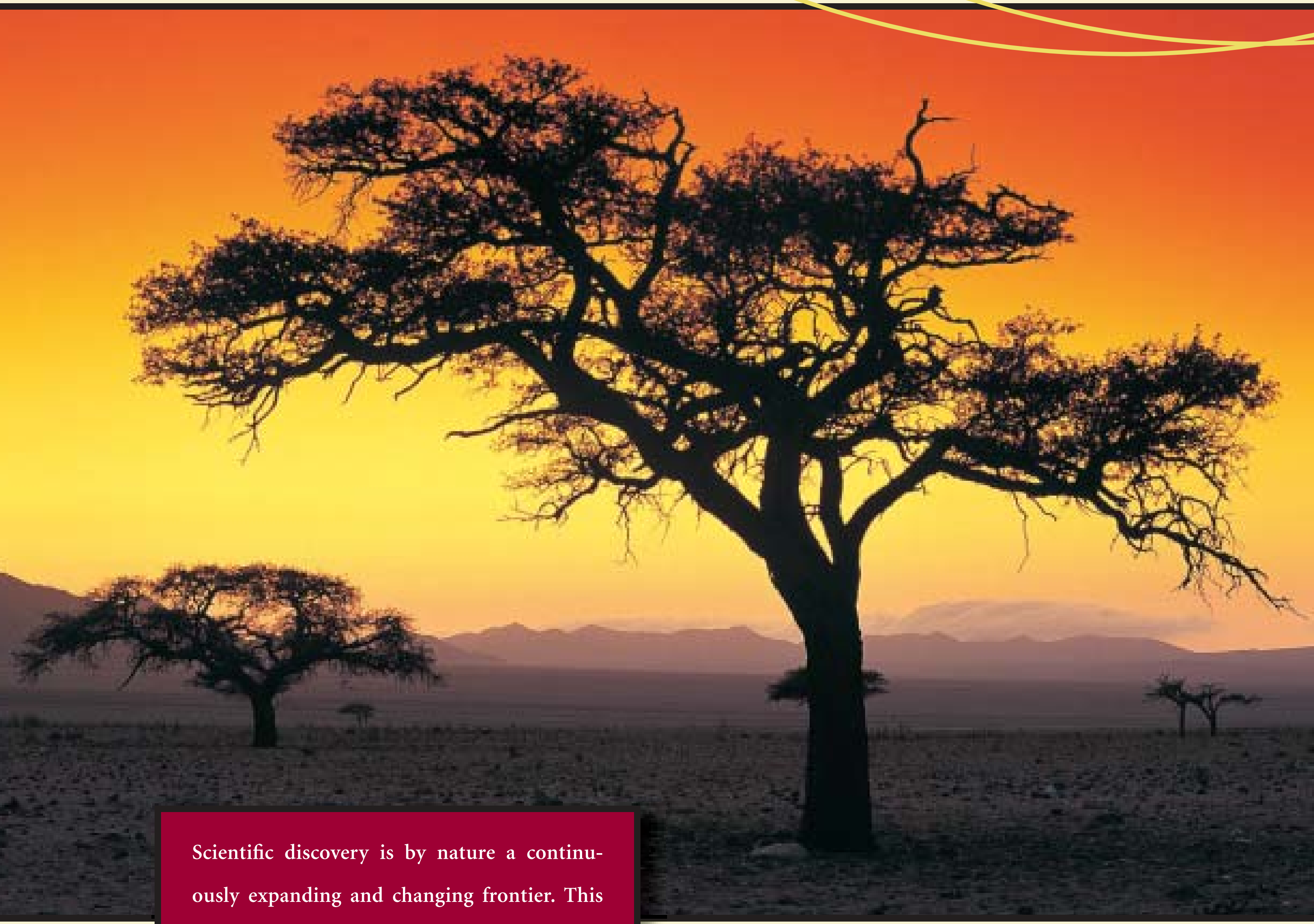
To fulfill this research Outlook and to support a new generation of environmental professionals, the Advisory Committee recommends major investments in environmental education, training, infrastructure, and technical capacity. Scientists, engineers, technicians, resource managers, and educators must be prepared to cross disciplines, integrate diverse information, and collaborate to solve environmental problems. Long-term, dynamic partnerships that cross national and regional jurisdictions and international boundaries can be the most effective means of addressing multi-scale challenges.

Environmental education should be used as an integrating concept in pre-school, elementary, and secondary education, particularly when enhanced with teacher education and professional training programs. At two and four year colleges and research institutions, academic institutional structures and incentives should facilitate interdisciplinary environmental research, increased diversity in the environmental workforce, and productive interactions with policy makers and the community. Informal education about the environment through parks, museums, zoos, media, and citizen-scientist partnerships is also a critical component of enhancing public understanding of complex environmental information and decisions.

Infrastructure and technical capacity must also be expanded and strengthened to address the environmental challenges of the coming decade. As sensors, instruments, and observing systems continue to improve, and the quantity and quality of environmental data grow rapidly, cyberinfrastructure must evolve quickly in order to archive, integrate, interpret, and communicate environmental information. Interdisciplinary research also necessarily relies on experiments, models, and their interactions to understand environmental systems at multiple scales and to develop scenarios and projections that are relevant to policy and practice.

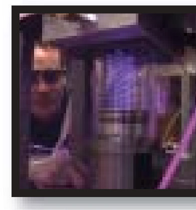
As our technological and research capacity increases, we face both the promise of understanding the environment and our relationship to it, and the responsibility of making wise decisions about managing the complex relationships among people, ecosystems and planetary processes.

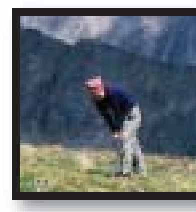
Garden Mosaics, Marianne Krasny, Cornell University. The Garden Mosaics program promotes science learning, as well as intergenerational and multicultural understanding, through youth-conducted research in urban community gardens. Youth engaged in Garden Mosaics first collect data for a national database, focused on answering three questions: What horticultural, social, environmental, and educational amenities do community gardens provide for their neighborhoods? Are there any other sites in these urban communities where residents can access these amenities? What horticultural practices are implemented by community gardeners, many of whom are recent immigrants from developing countries and African-Americans with roots in the rural South? Youth use a number of methods to answer these questions, including interviews with gardeners and air photo and map interpretation. The results of the youths' research are posted to the Garden Mosaics web site (gardenmosaics@cornell.edu), and are available to greening organizations, agricultural and social scientists, gardeners, and others interested in community gardens and ethnic horticultural practices. In addition to contributing to a national database, the youth use their results to define a local research or action project. Rural and other youth who do not have access to a community garden will be able to participate in Garden Mosaics through working with home gardeners in their community. NSF grant ESI-0125582.



Scientific discovery is by nature a continuously expanding and changing frontier. This is certainly true of environmental research, where the challenges evolve rapidly not only in response to scientific discovery and tech nological breakthroughs, but also in response to current and projected human and ecological needs. The development of solutions for known environmental problems is a critical component of this process.

Introduction





We face significant new scientific and engineering challenges at the beginning of the 21^{st} century, including rapid climate and ecological change, the degradation of freshwater resources, the globalization of disease, the threat of biological and chemical warfare and terrorism, and the more complicated question of long-term environmental security. The footprint of human activity continues to expand to the point that it is having a significant impact on nearly all of Earth's environmental systems. We are participating in and increasingly becoming designers and managers of the complex relationships among people, ecosystems, and the biosphere. Human and environmental health are highly intertwined, and human well-being is inextricably linked to the integrity of local, regional, and global ecosystems. Environmental research and education are therefore key elements of local, national, and global security, health, and prosperity.

Advances in technology, such as smart sensors used in combination with high-resolution satellite images, are rapidly and continuously improving environmental data quantity and quality. Spatially explicit information in increasingly compatible formats and scales is now becoming available to researchers from the natural and social sciences. This is creating new opportunities for collaboration among scientists and engineers, the potential to move across disciplinary boundaries, and even the prospect of developing entirely new methodologies and fields of knowledge. These new instrumentation, data-handling, and methodological capabilities have expanded the horizons of what we can study and understand about the terrestrial, freshwater, marine, and sedimentary environments, the atmosphere, and near-Earth environments in space. These tools are helping us address long-standing scientific questions as well as issues of immediate societal concern.

Fundamental research on the environment includes, integrates, and builds on the physical, chemical, biological, and social sciences, mathematics, and engineering. This important disciplinary work must continue to be strengthened. The present and future challenges include connecting across disciplines and scales, supporting synthesis studies and activities, more tightly linking science, technology, and decision making, and achieving predictive capability where possible. Many of these issues go beyond current disciplinary research and educational frameworks and will require new funding and institutional approaches.

Scientists Use Seals as "Eyes" Under Antarctic Ice, Lee Fuiman, University of Texas at Austin, Randall Davis, Texas A&M University, Galveston, and Terrie Williams, University of California, Santa Cruz. By equipping 15 Weddell seals with a video camera, infrared LEDs, and data recorders, we have gained new insights into the habits of two very important Southern Ocean fish species, the Antarctic silverfish and the Antarctic toothfish. The seals—marine predators—served as guided, high-speed, midwater sampling devices for fish that have been especially difficult to study. New information about the behavior and distribution of these species indicates that some existing theories may need to be revised. Although the "seal cam" has its limitations, it is a promising technique and could be used to study other pelagic and deep-water fishes and invertebrates that are otherwise impossible to observe in their natural environment. NSF grant OPP-9909863.

In this new era, imagination, diversity, and the capacity to adapt quickly are essential qualities for both institutions and individuals. This places a premium on the quality and evolutionary capacity of environmental research and education. In turn, the richness and complexity of interdisciplinary environmental research is creating the opportunity for more immediate and broad-based application of the results to human systems and problems.

Education about the environment, and the research needed to support and enhance this education, are the foundation for a creative, diverse, knowledgeable, and adaptable environmental workforce, including scientists, engineers, teachers, technicians, and resource managers. Environmental education should prepare the public as well as researchers and workers for interdisciplinary environments in which results often have immediate application to human systems and problems. Physical infrastructure and cyberinfrastructure are needed to support local and global research and to disseminate information to a diverse set of users, including environmental professionals, the public, and decision makers at all levels.

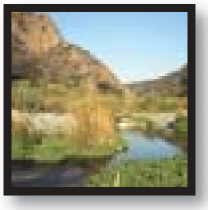
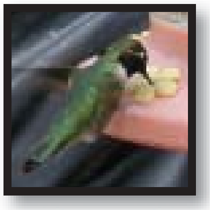
Long-term Research and Education Outcomes

Scientific discovery is by nature a continuously expanding and changing frontier. This is certainly true of environmental research and education, where the challenges evolve rapidly not only in response to scientific discovery and technological breakthroughs, but also in response to current and projected human and ecological needs. The development of solutions for known environmental problems is a critical component of this process.

From a long-term perspective, the desired outcome of environmental research and education is to understand, maintain, and improve the *robustness*, *health*, and *well-being* of environmental systems. These qualities are related and interdependent, but they each convey somewhat different concepts. Environmental *robustness* refers to the functional soundness of environmental systems, from local to planetary scales. Important aspects of robustness include a system's ability to resist outside stress and its capacity to adapt, develop, regenerate, and evolve.

Environmental *health* focuses on the inter-relation among human health, the health of other species, and more broadly, ecosystem health. Infectious diseases, contaminated water and air, environmental disrupters, invasive species, and biological warfare pose important research challenges in a world in which human systems have become agents of evolution, designers of urban, rural and natural landscapes, and vectors for movement of organisms and abiotic materials in air, water, and below ground.

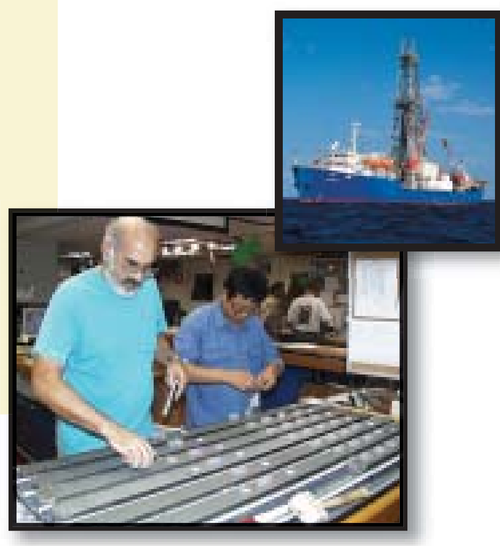
Environmental *well-being* refers to the ability of the environment to support all life, including human economic and social systems. The efficiency and sustainability of environmental services, the design of the built environment, the cycling of materials, the flow of energy, and the role of organisms are all important research priorities that advance scientific and engineering understanding and strengthen institutions that enable society to maintain and enhance the environment.

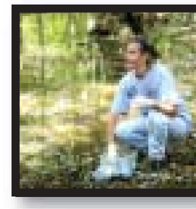

One of the keys to understanding, maintaining, and improving environmental *robustness*, *health*, and *well-being* is to strengthen the links and interaction among scientific knowledge, engineering know-how, and societal benefits. The co-evolution of humans, biotic, and abiotic systems has woven a complex fabric of relationships that support life by providing environmental services, harboring biodiversity, and maintaining stability and functions for humans and other species.

Critical scientific and engineering challenges include how to measure and understand these interrelated components, systems, and relationships; how to assess their vulnerability and resilience; and how to predict or project their reactions to ongoing and future processes and events, such as climate change and continued human transformation of the environment. Other sets of challenges include designing processes and systems that are as sustainable and environmentally benign as possible, and developing technological and policy solutions for the prevention or mitigation of adverse human-related impacts.

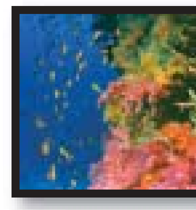
A Tale of Two Hemispheres, Alan Mix, Oregon State University. Ice cores from Antarctica and Greenland reveal rapid climate changes in both hemispheres, but the patterns are subtly different. Why? Competing theories invoke different climatic trigger points: North Atlantic control of deep-water formation, interactions of Southern Ocean currents with strong westerly winds, or tropical air-sea interactions analogous to well-known El Niño events. To help choose among these options, an international team of scientists and students on board the Ocean Drilling Program's (ODP) drillship *JOIDES Resolution* (see photo) probed the sea floor of the southeast Pacific, one of the least studied regions on Earth. This program targeted sites ranging from stormy southern Chile to steamy Costa Rica that record global and regional climate information at high resolution. Work continues with sampling and detailed analyses of more than 7 km of sediment cores recovered by drilling. Already, shipboard results from sites off Chile provide evidence that the westerly winds, and the torrential rains they bring to the southern Andes, oscillated in both their strength and positioning in concert with rapid climate oscillations of the global ice age. Photos courtesy ODP. NSF award numbers OCE-9308410 and OCE-9320477. (More on ice cores on p. 27.)



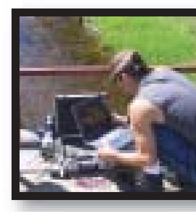
Synthesis: Environmental Science and Engineering at the Frontier



The inherently interwoven character of environmental processes, advances in knowledge and technical capabilities, and urgent human needs, has created an opportunity and demand for *environmental synthesis*. While synthesis of data and ideas has historically occurred within disciplines, integrated synthesis across disciplines is a relatively new and evolving frontier. An integral part of this approach is the collection of environmental information across spatial, temporal, and organizational scales and the effective communication of this knowledge to and among researchers, educators, students, resource and industrial managers, policy makers, and the public.



The synthesis of environmental knowledge and know-how depends on the development of a robust theoretical and empirical understanding of complex systems, including their capacity for self-organization, resilience, and adaptation. Integrated models of environmental systems require the integration of measurements, initial assumptions, uncertainty of events, and model performance.



Environmental synthesis involves four distinct processes, all of which are critical to the frontier of environmental research and education.

Framing questions or problems for investigation requires *synthesis* of scientific and engineering literature across many disciplines, development of the theory, methods and research framework to work across scales, sectors, and disciplines, and often involves two-way communication between scientists and non-scientists.

Integrated research activity involves the *synthesis* of teams of scientists and engineers working across varied disciplines, scales, and sectors to explore broad and challenging research and education activities. These teams create an integrated, systemic understanding of the environmental problem or place under study, and they produce and disseminate related research, education, and outreach materials that inform engineering, management, and policy solutions.

Meta-analysis to define the state of knowledge requires the *synthesis* of existing data sets from diverse fields and sources, and the development of new methods of knowledge assessment to extract relevant science and engineering results. In this non-traditional area of research, new ideas and conclusions emerge from the meta-analysis itself rather than directly from new experimental results.

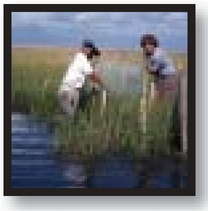
Finally, publicly accessible scientific data, models, and conclusions depend on the *synthesis* of information in powerful digital libraries, data networks, and web-based materials that serve as essential resources for scientists, engineers, policy makers, educators, students, and the general public.

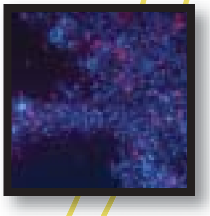
Significant challenges must be met to achieve the objectives of environmental research and education: to discover and understand natural phenomena and processes, to develop new practices for the preservation and use of environmental resources and services, and to understand human behavior and decisions with respect to the environment and resources.

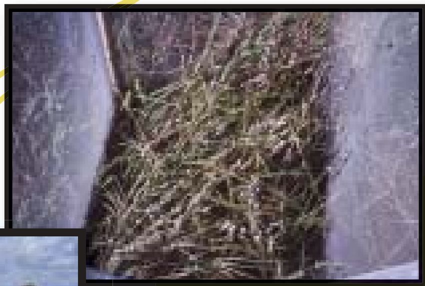
Environmental Research Frontiers 2003-2012

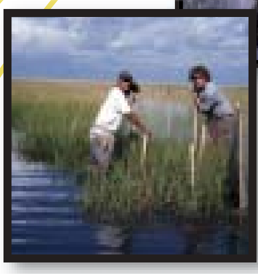
Because human and natural systems are complex, dynamic, and interdependent, research that addresses them needs to be imaginative and sophisticated. It must integrate spatial, temporal, and organizational scales, draw from many disciplines, and facilitate the synergy that results from partnerships among governmental, academic, and private organizations. This research must use diverse tools, datasets, and approaches. These significant challenges must be met to achieve the objectives of environmental research and education: to discover and understand natural phenomena and processes, to develop new practices and technologies for the preservation and use of environmental resources and services, and to understand human behavior and decisions with respect to the environment and resources.

To advance the fundamental scientific knowledge necessary to address these critical environmental challenges, the Advisory Committee recommends increased attention in three interrelated areas: (A) coupled human and natural systems, (B) coupled biological and physical systems, and (C) people and technology. These areas share two vital characteristics: they are interdisciplinary, and they are synthetic. This path-breaking research is important, timely, feasible, and likely to lead to significant scientific and technological outcomes in the next decade.









A Trophic Cascade Regulates Salt Marsh Primary Production

Brian Silliman and Mark Bertness, Brown University

Salt marshes are among the most productive systems in the world and play a critical role in the ecology and economy of North American shorelines. In addition to reducing erosion, marshes temper coastal flooding, filter terrestrial run-off, act as expansive sinks for greenhouse gases, and are nursery grounds for many commercially important species (e.g., sea trout, blue crabs, shrimp). For ecologists and marine scientists, salt marshes have long been viewed as the model example of an ecosystem controlled by bottom up forces (i.e., nutrients and physical factors). Our experimental manipulation of crab and snail densities in Georgia salt marshes, however, strongly challenges this theory and demonstrates that marsh plant biomass and growth are ultimately controlled by grazers and their predators (top-down forces). In a process termed a "trophic cascade," our caging experiments (photos) showed that marine predators such as blue crabs, by controlling densities of plant-grazing snails, indirectly facilitate the persistence of salt marsh communities. In the absence of marine predators, snail numbers increase and moderately high densities of periwinkles, which "farm" fungi on marsh grass leaves, convert one of the most productive grassland systems in the world into barren mudflats in eight months.

These findings challenge conventional wisdom of nearly a half-century of coastal ecologists and have enormous implications for the conservation and management of coastal systems. Specifically, they suggest that the over-exploitation of a major predator such as the blue crab could lead to the collapse of southeastern salt marshes. Before our study, marsh ecologists and marine conservation managers assumed that there was no link between marsh health and animals higher in the marine food chain. However, our study shows marsh grass health is intricately intertwined to the marine food web, in which we are the top predator. Our data do not suggest that we completely stop the harvest of blue crabs, rather we likely need to be more cautious in the numbers we harvest in relation to the status of the crab population. We now know the potential consequences of over-harvesting and should proceed with reserve before another fishery becomes commercially and ecologically extinct.

Can findings from caging experiments be scaled up? In both Georgia and Louisiana salt marshes where blue crab densities are in significant decline, we have found fronts of snails over 50 m long and 2 m wide with densities greater than 2000 individuals per m^2 mowing down marsh grass at 6 m per year. In areas of massive marsh die back (>10 km) in Louisiana, we have seen this interaction occurring, although observational evidence does not suggest that snails initiated the die off. Given that blue crab densities have recently declined precipitously along the Gulf Coast and in these states, it is possible that the cascading effects of crab consumption shown in our experiment may be a contributing factor to marsh die off in the southeastern United States. NSF grant DEB-0082467.

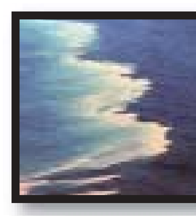
Coupled Human and Natural Systems

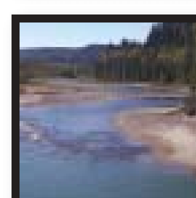
Coupled human and natural systems research seeks to understand the complex web of environmental feedbacks at diverse temporal and spatial scales. The principal questions are how the environment functions, how people use the environment, how this use changes the environment, sometimes irreversibly, and how the resultant environmental changes affect people. It involves consideration of the natural and human dimensions of environmental change, including different configurations of human social systems, political and institutional structures, and class, race, and gender relationships.

The topic builds on, supports, and integrates many existing disciplines and tools, including geography, demography, civil and environmental engineering, sociology, population ecology, geology, economics, anthropology, ecosystem ecology, genomics, hydrology, limnology, and oceanic and atmospheric systems science. The integration of these and other tools and disciplines leads to new research questions that go beyond discipline-based inquiry.

Four interrelated major research challenges in coupled human and natural systems follow:

- Land, Resources, and the Built Environment
- Human Health and the Environment
- Freshwater Resources, Estuaries, and Coastal Environments
- Environmental Services and Valuation





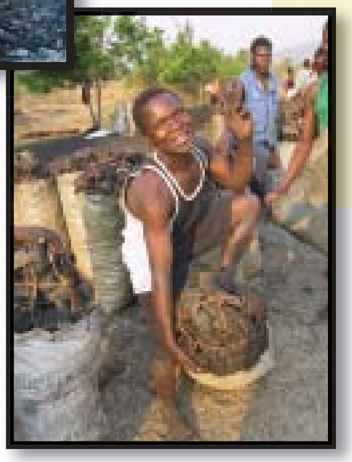
Land, Resources, and the Built Environment

Humans are major forces shaping Earth's surface and are conscious architects of urban, rural, natural, and protected ecosystems—both terrestrial and aquatic. The natural environment is modified by physical processes and natural hazards (e.g., precipitation, hurricanes, earthquakes), by activities of plants, animals, and people (e.g., shading, grazing, agriculture, mining, forestry, damming), and by chemical processes (e.g., oxidation, reduction, acidification). The forces influencing the dynamics of human resource use and development come not only from individuals, households, and communities, but also from natural and social processes at local, regional, national, and global levels.

The intelligent use, extraction, and re-use of resources, and the design of long-term strategies, require not only comprehensive understanding of the systems and their problems, but also new and appropriate technologies and solutions. Projected human population growth, migration, and development will increase the extent and complexity of the co-evolution among humans, other species, and ecosystems. Understanding the complex past and present relationships between human and natural systems as they relate to land and resource use will require the further development of spatially explicit, integrative, dynamic models that incorporate behavior and structural theory and methods.

Examples of research and education areas include:

- Integrating population, ecosystem, and socioeconomic models to improve understanding of landscape fragmentation, including assessing how coupled human and natural landscapes function.
- Determining how development processes and urbanization patterns affect water and resource use, nutrient distribution, biodiversity, and ecosystems, and understanding the feedbacks associated with different engineering and policy options.
- Developing and testing new engineering and architectural principles and designs to minimize impacts of cars, roads, industries, and other human activities on ecosystems and species.
- Understanding how human and natural systems respond to climate variability and change, and developing dynamic spatial simulation techniques to model the response of these systems and to aid design of mitigation methods.



Land Use and Land Cover Change Research in Africa: Coal-Making, Paul V. Desanker, University of Virginia. The Miombo Woodlands are a major biome in southern Africa and a key source of timber, firewood, non-wood products, wildlife, and watershed protection. NSF has facilitated development of a science agenda on ecology and land use here, as well as development of collaborations between the United States and southern African countries. At a workshop held in the summer of 2001, participants focused on an interdisciplinary study of processes, interactions, and impacts of environmental changes on livelihoods, especially for the greater Zambezi and Limpopo River Basins within the southern African region. Left: Miombo woodlands are routinely cut and burned to enrich soils before planting crops, resulting in extensive fire use in the region (photo courtesy of Peter Frost). Right: Charcoal made from Miombo species is sold along roads such as here in Manica, Mozambique (photo courtesy of Paul Desanker). NSF grant INT-0218022.

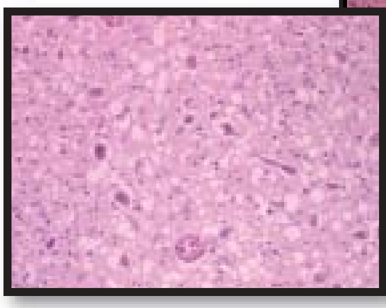
Human Health and the Environment

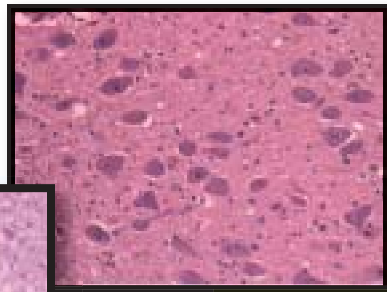
Human health is affected by nutrition, contact with allergens and pathogens, and exposure to contaminants in air, water, and foods. Population density, age distribution, mobility, and other demographic variables, as well as the genetic composition and cultural and behavioral attributes of individuals, interact with these environmental factors. Thus, understanding the relationships between human health and the environment is critical, particularly given the potential for alteration of ecosystems by socio-economic activity, rapid global change, and climate variability.

Among the most important environmental issues of the century are emerging and resurgent infectious diseases, agents that alter ecosystem processes, invasive species, the spread of regional and global contaminants, and biological warfare. Introduction of organisms and abiotic substances into new environments can be accidental, intentional with unintended effects, or intentional with the purpose of causing harm (e.g., bioterrorism). Pathogens, toxins, and contaminants are spread by regional and global transportation systems, as well as other human and natural vectors.

Subtle changes in the environment that affect vital resources such as air quality, the quantity or quality of freshwater, and the distribution and assemblages of native and introduced species may have profound impacts on human, animal, and plant health. There have been many examples of the disastrous, unintended effects of human actions. The study of the feedbacks between human health and the environment must therefore be comprehensive, including research on the long-term shifts in ecological and human health, as well as the effects of extreme events.

Microbial Threat to Ecosystem and Human Health, Donald M. Anderson, Woods Hole Oceanographic Institution. Microscopic, single-celled plants called dinoflagellates exhibit periodic population explosions or "blooms" along coastlines worldwide. The photo (courtesy of P.J.S. Franks) is of a red tide off southern California caused by a bloom of the dinoflagellate *Noctiluca*. Several genera are toxic, so shellfish feeding on the dinoflagellates can accumulate toxins and pose a threat to human health. In addition, some of these "harmful algal blooms" or "red tides" are associated the death of marine mammals, fish, and seabirds and with the formation of hypoxia (low oxygen) and "dead zones," where the productivity of coastal marine ecosystems collapses. We are using genomic methods to study the biosynthesis of saxitoxins, the neurotoxins produced by some toxigenic dinoflagellates, and the factors that cause variation in toxicity under different growth conditions. The results may lead to a probe that can distinguish toxic from non-toxic cells in a natural assemblage of plankton. NSF grant OCE-0136861.





Chronic Wasting Disease in Wildlife: Responses to Changing Land Use, N. Thompson Hobbs, Michael W. Miller, and Elizabeth Williams, Colorado State University. Chronic wasting disease (CWD) of the deer family is a transmissible spongiform encephalopathy, a member of a group of infectious diseases affecting animals and people known as prion diseases. Similar diseases include scrapie in sheep and goats, bovine spongiform encephalopathy in cattle (i.e., "mad cow disease") and Creutzfeldt-Jacob disease in humans. These diseases are associated with proteinase-resistant prion protein that accumulates in the brain of affected individuals, causing neural degeneration and eventually death. New techniques we developed to sample tissue from live animals have allowed us to examine effects of human population density on disease prevalence. Early findings suggest that concentrations of the disease in deer are associated with high densities of people. Although current evidence suggests that the transmission of CWD to people is unlikely, this possibility cannot be ruled out. Left photo: Brain from mule deer with chronic wasting disease showing spongiform change. Right photo shows brain tissue from a healthy mule deer. NSF grant DEB-0091961.

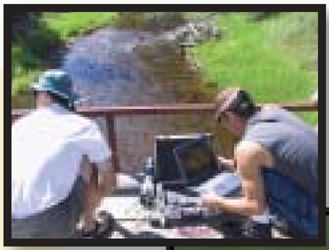
Examples of research and education areas include:

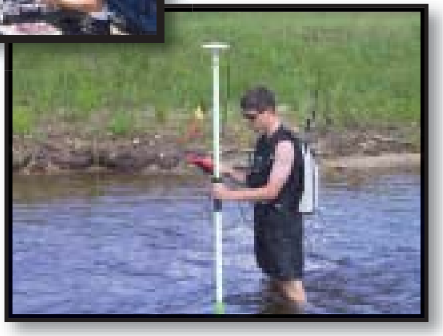
- Identifying the patterns of regional and global transport and transformation of contaminants/pathogens as they move through the dynamic environment (atmospheric, aquatic, biologic, constructed).
- Developing microbial ecosystem knowledge and tools to analyze the spread of invasive species and pathogens and developing technological solutions to mitigate their unintended effects.
- Developing technologies to analyze air, drinking water, and foods for presence of existing and emerging harmful chemical and microbiological contaminants and protect humans from their detrimental effects.
- Developing genomic methods for identifying organisms and understanding their mutations, life cycles, and functions.

Freshwater Resources, Estuaries, and Coastal Environments

Research is necessary to improve understanding of the natural and human processes that govern the quantity, quality, and availability of freshwater in natural and human-dominated ecosystems. The distribution, abundance, quality, and biodiversity of freshwater resources are vital for the sustenance of life on Earth. Freshwater structures the physical landscape, is a central feature of climate, and greatly influences patterns of human population, economic growth, behavior, and conflict. Scientists and engineers are increasingly called upon to provide predictions of water stocks and flows, particularly in areas with current or projected water shortages, and those affected by climate change or natural hazards.

The integration of the terrestrial, aquatic, atmospheric, and subsurface systems and processes within watersheds requires new, multidisciplinary approaches if we are to maintain a viable freshwater supply for human needs and ecosystem functions. Likewise, because more than half of all humans live close to coastlines, understanding the complex functions, processes, and limitations of estuaries and coastal systems is of great importance, particularly in the context of global change. It is also critical to study and understand the feedbacks among human perception and behavior and water resources.





Tracking and Evaluating River Ecosystem Restoration, Peter Goodwin, University of Idaho. Our research tracks a variety of streams from highly urban to wilderness watersheds with restorative actions ranging from natural recovery to the construction and reconnection of historic channels. Using a hierarchical framework comprised of external processes, physical forcing variables, physical response variables, and biological response variables (with feedback among the variables), we structure our monitoring and analysis program for each river studied. The restoration's performance is evaluated by integrating observations, simulation models of the physical processes such as streamflow, temperature, sediment transport, and substrate characteristics with links to ecological indicators. For example, for the Red River study site in northern Idaho, we conclude that about 20 years of data will be required to statistically demonstrate salmon recovery due to site-specific restoration actions in terms of numbers of returning fish or other ecologic metrics. While not diminishing the critical importance of adequate biological monitoring, our model can show that trends in a range of physical characteristics (e.g., temperature) can be statistically verified by only two to five years of data, and give early indications that the site is evolving toward the desired future conditions. NSF Grant BES-9874754.

There is still limited understanding and predictive ability with respect to hydrological forecasting, and substantial opportunity for advancement of theory, methods, and models for watersheds, rivers, lakes, wetlands, estuaries, and coastal systems. However, recent developments in remote sensing of precipitation, soil moisture, suspended sediments, vegetative cover, surface topography, and other parameters are beginning to yield data and analyses that are driving a revolution in hydrologic science and water resource engineering.

Examples of research and education areas include:

- Understanding and predicting the flux of organisms, invasive species, sediments, organic matter, and nutrients through inland waters, estuaries, and coastal systems.
- Modeling and tracking the processes, mechanisms, cycles, and ecology of watersheds and the human activities that affect them.
- Developing novel engineering and social methods for protecting water resources, managing their use, and evaluating and rehabilitating damaged or degraded watersheds, estuaries, and coastal systems in urban and rural areas.
- Enhancing research in polar regions, where more than 70% of Earth's freshwater is in a sensitive balance between liquid and solid phases, to understand climate-driven hydrological and biological responses.

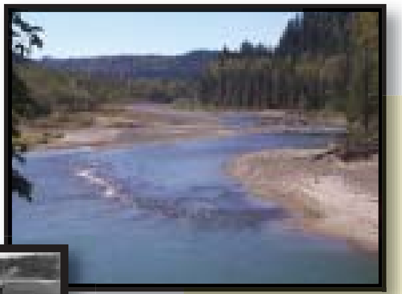
Environmental Services and Valuation

A fundamental scientific challenge is to understand human dependence on natural systems and determine the economic and social value of this dependence. Of particular importance is ascertaining how the interaction of human and natural processes affects the capacity of natural systems to meet human needs and support the quality of life. Natural systems provide many tangible and intangible items that people use for food, fiber, fuel, recreation, and many other purposes. Some of these services are irreplaceable. Natural systems also provide humans with a habitable environment and climate. Wetlands filter contaminants; the hydrologic cycle supplies and maintains freshwater; the climate system regulates temperature, precipitation, and sea level; and estuaries and oceanic upwelling sustain fisheries. All these elements are critical to present-day functioning of society, and yet they are undergoing significant changes.

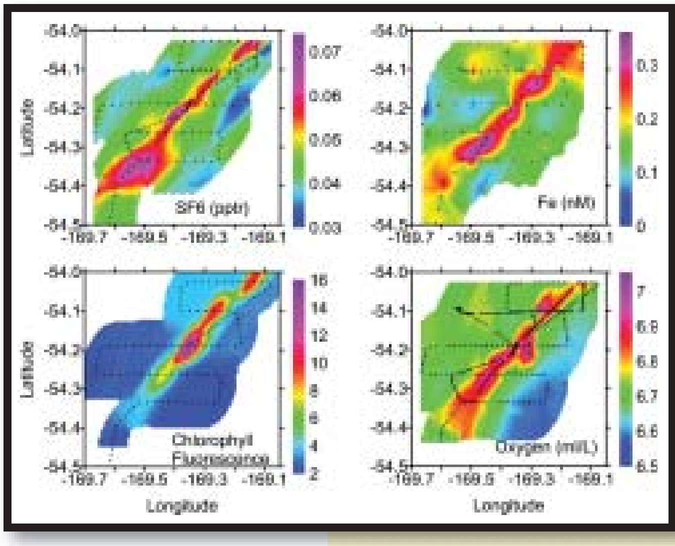
Scientists from a range of fields have begun to study the use, effects, and value of accounting for natural services in economic decision-making processes. To the extent that the value of environmental goods and services can be determined and related to other items for which economic values have been established, the marketplace could serve as the setting for maintenance and protection of the natural environment. However, these accounting approaches are controversial, even among economists and other social scientists, and they require significant further development. One issue is whether these methods can effectively capture non-market values or the environmental costs and benefits for future generations.

Examples of research and education areas include:

- Determining the structures, functions, and processes in the natural world that provide the resources and services for human survival, development, and well-being.
- Understanding the value humans place on natural systems and the services they provide, and how people from various cultures consider the value, nature, quality, and availability of these services in making decisions about natural resource use.
- Exploring the relationship between individual and group environmental values, as well as the dynamics of group valuation.
- Evaluating the effects of environmental scarcity and abundance on individual and group behavior, and the relative effectiveness of various strategies for improving access to resources.



Downstream Geomorphic Impacts of Large Dams on American Rivers, William L. Graf, University of South Carolina. The many economic benefits from dams (including flood control, water supply, and hydroelectric power production) are products of the ability of dams to change the natural flow of rivers to better serve society's needs. However, the installation and operation of large dams can cause radical changes in aquatic habitats, riparian forests, and river landscapes for many miles downstream. This work is the first nation-wide assessment of fundamental changes to environmental processes near the nation's largest dams. Using aerial photography, computer mapping, and field investigations we can map what happens to rivers when dams are installed. In many plains and desert rivers, wholesale changes in channels and flood plains downstream from dams have resulted in a dramatic expansion of riparian forests over the past 50 years. These forests provide valuable habitat for birds, including game and endangered species. In eastern rivers, channels have lost their sand bars and many of their mid-channel islands so that the aquatic habitats for fishes have changed, sometimes to the detriment of native species. This information is being increasingly used by decision-makers who intend to remove dams. Working through the Heinz Center for Science, Economics, and the Environment, this work has been used to create a guide that government agencies and citizens can use for assessing the potential outcomes of dam removal (*Dam Removal: Science and Decision-Making*, Heinz Center, Washington, 221 pages). Top: Despite its name, the Sandy River (Oregon) in this reach is a gravel-bed stream because all the fine sediments are trapped by dams. Bottom: The Norris Dam on the Clinch River is part of the Tennessee River system and is an example of a large dam that strongly influences downstream river reaches and their ecosystems. NSF grant BCS-9708240.



Open Ocean Iron Fertilization Experiments: A Tool for Biogeochemical Studies of the Ocean

Ken Johnson, Monterey Bay Aquarium Research Institute

Just 15 years ago, there were intense debates about the role of iron in controlling biogeochemical processes in the ocean. Before that time, the analytical challenges of detecting trace (picomoles per liter) iron concentrations from iron ships using gear suspended on an iron wire precluded oceanographers from making accurate measurements of iron in seawater. Laboratory experiments were invariably conducted with samples that were seriously contaminated with iron. We now recognize, through greatly improved methodologies, that iron is a key regulator of phytoplankton communities throughout vast regions of the ocean. Small changes in iron concentration may produce large variations in the rates of phytoplankton processes, the taxonomic structure of phytoplankton communities, the biomass of phytoplankton that accumulate, and the export of particulate organic carbon from the ocean's sunlit surface layer into deep-sea sediments. This realization has enabled a new experimental approach for the assessment of biogeochemical processes in the ocean—open ocean iron fertilization experiments. A few hundred kilograms of iron spread over a 50 km^2 area can have a profound impact on biogeochemical cycling. We have entered a new era of experimental studies of the processes that control the flow of carbon and nutrients through the ocean.

Eight open ocean iron fertilization experiments have been conducted during the past decade in the High Nitrate, Low Chlorophyll waters of the Equatorial Pacific, the Southern Ocean, and the Sub-Arctic North Pacific. The areas with added iron and the inert tracer sulfur hexafluoride (SF_6) have been tracked for time periods up to one month. All of the experimental areas have shown enhanced rates of primary production and biomass accumulation. The impact of biomass accumulation is reflected in concentration changes of chemical parameters such as dissolved oxygen (concentration increases with increased photosynthesis), nutrients, and carbon dioxide (concentration decreases as chemicals are taken up by phytoplankton).

As a result of these experiments, oceanographers have developed a greatly improved understanding of the processes that occur during phytoplankton blooms. The challenge now is to extend observational periods so that the processes occurring at the end of the blooms, and the factors that control carbon export from the surface to deep-sea sediments, are as well understood. NSF grant OCE-0000364.

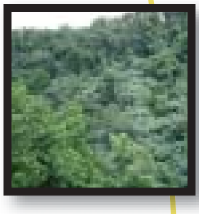
Figure: The SOFEX North experiment 27 days after addition of 2 nM iron to Southern Ocean waters in January 2002. The SF_6 tracer and a small amount of iron remain in surface waters. Chlorophyll concentrations have increased over twenty-fold, which is reflected in the large chlorophyll fluorescence signal within the same area that contains elevated iron and SF_6. Increased rates of photosynthesis have driven oxygen concentrations to levels well above equilibrium with the atmosphere in the fertilized waters.

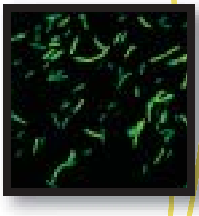
Coupled Biological and Physical Systems

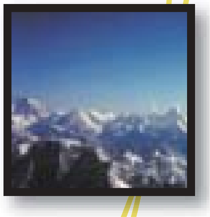
This research area focuses on measuring and understanding the processes and dynamics that shape the physical, chemical, and biological environment. The challenge is to understand the systems that form the environment from the molecular to the planetary scale, and to understand how these systems are linked and interact. This research builds on, supports, and integrates many disciplines and tools, including ecology, geology, chemistry, molecular biology, genomics, soil sciences, conservation biology, demography, atmospheric, oceanic and Earth systems science, hydrology, environmental engineering, and GIS (geographic information systems). The integration of these tools and disciplines goes beyond discipline-based inquiry and is fundamental to the understanding of the climate system, nutrient cycles, ecosystem functions, and biodiversity.

The following are three interrelated major research challenges in biological and physical systems:

- Biogeochemical Cycles
- Climate Variability and Change
- Biodiversity and Ecosystem Dynamics





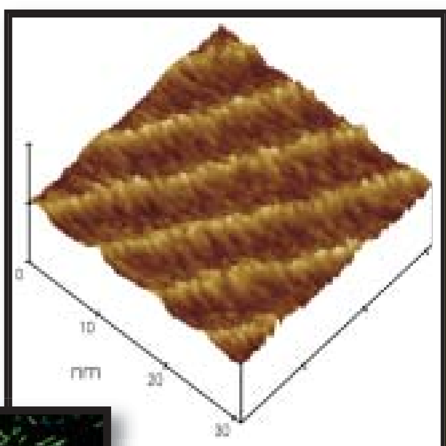


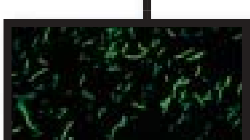
Biogeochemical Cycles

Life on Earth is supported by the biogeochemical cycling of carbon, oxygen, hydrogen, nitrogen, sulfur, and phosphorus, as well as the contributions of calcium, iron, silicon, and other elements. The availability and interaction of these elements at multiple scales has both direct and indirect influences on individual organisms and environmental systems.

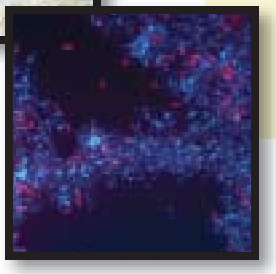
Understanding the sources, sinks, transformations, and fluxes of these essential elements both above and below surface is a critical step in determining their behavior under specific environmental conditions. This area includes the development of models to evaluate the consequences of human perturbations on essential nutrient cycles in soils, sediments, and other systems. For example, biogeochemical models have been used to assess major pools for global carbon storage, human and natural aerial transport of elements, and multiple element interactions that affect ecosystem productivity.

A major challenge is to understand how Earth's major biogeochemical cycles are being affected by human activities, including agriculture, development, and energy production and use. It will be important to predict the impact of these changes at multiple scales, and to determine whether ecosystem harm can be reduced through modification of human behavior and application of relevant technologies.





Biosurfactants and Toxic Metal Contaminants, Raina M. Maier, Jeanne E. Pemberton, University of Arizona, and Cynthia K. Larive, University of Kansas. Surfactants, or surface active agents, are substances that lower the surface tension, a membrane-like barrier between different liquid phases that affects the ability of molecules to move from one phase to another. In addition to synthetically produced surfactants, these substances are also produced by a wide diversity of microorganisms. Certain of these "biosurfactants" can bind tightly to toxic metals such as lead and cadmium. Some biosurfactants also adhere strongly to surfaces, sometimes completely changing the properties of the surface. We want to know how biosurfactant production in soil systems influences the behavior of toxic metal contaminants. To answer this question, a microbiologist, a surface chemist, and an expert in NMR spectroscopy are working together to: (1) discover how much of the class of biosurfactants known as rhamnolipids are produced in soil, (2) discover how these rhamnolipids complex toxic metals such as lead and cadmium, and (3) determine how these biosurfactants interact with soil surfaces in the presence and absence of metals. This information is a critical piece of the puzzle required for understanding how metals are mobilized and immobilized under both natural and engineered conditions. NSF grant CHE-0133237.



Environmental Chemistry and Biogeochemistry of Metal Sulfides, Robert Hamers, University of Wisconsin-Madison, and Jillian Banfield, University of California, Berkeley. Naturally occurring metal sulfide minerals such as pyrite, arsenopyrite, and galena can cause significant health hazards associated with water acidification due to the release of toxic metals into water supplies. These hazards can be greatly exacerbated by human activities, leading to phenomena such as Acid Mine Drainage (AMD). Despite the extremely harsh environmental conditions associated with AMD formation, microbes play a key role by controlling the local chemistry that is responsible for decomposition of the minerals into toxic metals. By understanding how the microbes use inorganic chemical process to induce chemical transformations, it is possible to break down the complex problem into a series of simple, quantifiable chemical steps. For example, key intermediate species that exist on the mineral surfaces, such as elemental sulfur, can play an important role in the release of toxic metals into the environment. By simultaneously studying the inorganic and organic processes, we can explain how the microbes, minerals, and the aqueous phase all operate together as a system in the environment. Top: Iron Mountain, where the high concentrations of metals give the water vivid colors. Bottom: Epifluorescence image showing microorganisms in acid mine drainage. All cells are stained with a DNA-binding probe (blue) and *Sulfobacillus sp.* cells are labeled with a probe (red). *Sulfobacillus* cells mediate oxidation of intermediate sulfur compounds to sulfate, key acid-producing reactions. NSF grant CHE-9807598.

Examples of research and education areas include:

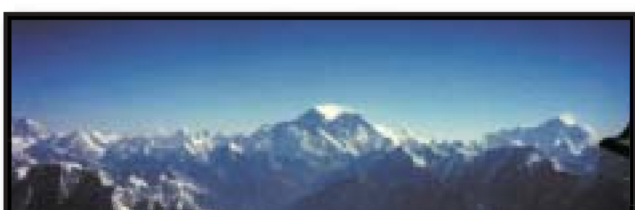
- Quantifying sources and sinks of nutrient elements, and improving our understanding of the biological, chemical, physical, and climate-related factors affecting them.
- Identifying the effects of human perturbations of biogeochemical cycles (including release of contaminants) on ecosystem functioning on land, and in the atmosphere and oceans.
- Developing new strategies and tools for maintaining or restoring essential nutrient cycles and relevant stoichiometric ratios and analyzing the effectiveness of new and existing tools and approaches.
- Identifying the functional genomics of microbes in soils and sediments, and assessing the role of microbial communities in the cycling of nutrients, including trace metals.

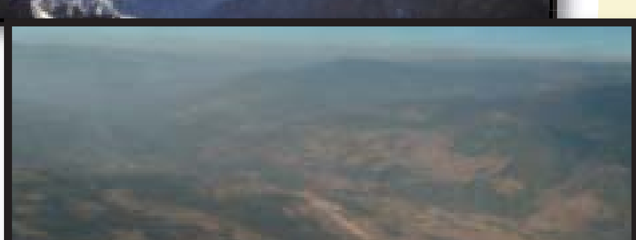
Climate Variability and Change

There is an increasing need to improve predictions of climate variability, from extreme events to gradual changes, and from annual to decadal time scales and longer; to understand the causes of this variability; and to assess the impact of climate change on natural and human systems. It is equally important to better understand the feedbacks between human activity and climate variability and change. The integration of new observations into climate models, called data assimilation, is a significant challenge.

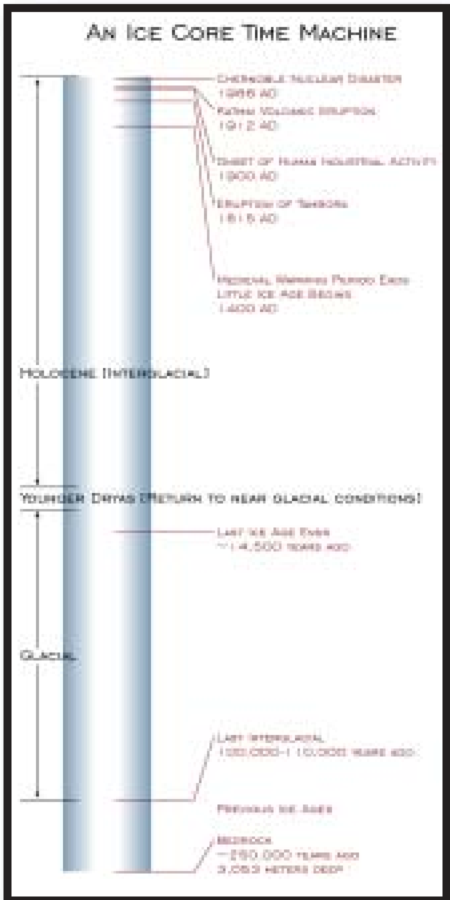
As scientific understanding of global shifts in atmospheric and oceanic conditions improves, research can turn toward regional climate impacts, including the effects on air quality, soils, agriculture, forests, ice sheets, snowpack, water, and fisheries. To understand how a periodic climate phenomenon such as the El Niño Southern Oscillation, or a gradual, long-term increase in ocean or air temperature, will affect a region requires obtaining relevant and useful results from climate models, and understanding and integrating the region's biological, social, and economic characteristics and trends. For example, drought's impact on crop production can be mediated by access to adaptive technologies such as irrigation, fertilizer, and seeds, but is also affected by crop prices, subsidies, and coping mechanisms such as insurance.

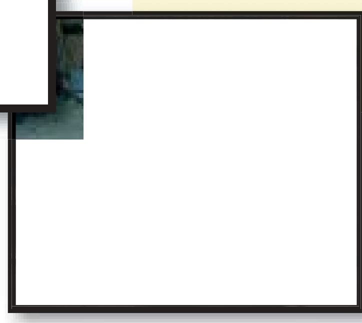
Improved understanding of potential climate extremes, and the geographic range that might be affected by it, will provide insights into local vulnerability. This research can facilitate more effective and timely private-sector and institutional responses, adjustments, and adaptations to projected climate change and variability.





Asian Brown Haze Over the Southern Himalayas, Veerabhadran Ramanathan, University of California, San Diego. During the dry season from January to April, the brown sky seen over Nepal is typical of many areas in South Asia. The dry northeast monsoonal winds carry this anthropogenic haze thousands of kilometers south and southeastward and spread it over most of the tropical Indian Ocean between 25° N to about 5° S. These aerosols pose the largest uncertainty in model calculations of the climate forcing due to man-made changes in the composition of the atmosphere. The bottom photo shows the South Asian brown haze over the Nepalese town of Phaplu, taken on 25 March 2001, approximately 30 km south of Mt. Everest (top photo), from a flight altitude of about 3 km. Both photographs were taken from the same location, one viewing north (top) and the other south (bottom). (Ramanathan, V., P. J. Crutzen, J. T. Kiehl and D. Rosenfeld, 2001, Aerosols, Climate and the Hydrological Cycle, *Science*, 294, 2119-2124). NSF grant ATM-0136239.





Tracing Climate History Through Ice Cores, Ice Core Working Group. Our ability to understand climate change, to decipher the influence of human activity, and to predict future climate change depends on a coupled investigation of both modern and past climate. Ice cores, through polar ice sheets and tropical ice caps, provide remarkable archives of climate and environmental change, preserving ancient atmosphere, DNA, organisms, and meteorites, and recording temperatures, atmospheric aerosols, and human impacts on the environment in detail and scope unequaled by any other medium. Ice core records of environmental change are cornerstones of global change research, providing data necessary for evaluating the behavior of the Earth system and our impact on it.

In 1993 the Greenland Ice Sheet Project Two (GISP2) successfully completed drilling to the base of the ice sheet in central Greenland. GISP2, along with its European companion projects, developed a 110,000 year annually resolved paleoenvironmental record from the Northern Hemisphere. These Greenland ice cores uniquely showed that massive reorganizations of the ocean-atmosphere system repeatedly caused large climate changes across much or all of Earth, with changes of different size and type in different places, but as much as 16° C on the ice sheet. Because these changes occurred in a decade or less, and the altered climate persisted for centuries or more, recurrence could drastically affect humanity. Photo courtesy Mark Twickler, University of New Hampshire. Ice core graphic by Sheryl Palmer, University of New Hampshire. NSF grant OPP-9617009. (More on ice cores on p. 8.)

Examples of research and education areas include:

- Creating useful regional scenarios of climate change and variability, including seasonal forecasts and decadal climate projections.
- Providing integrated climate models that take human perturbations and climate responses into account.
- Developing technologies, including those using alternative energy sources, that could reduce the impacts of climate variability and long-term or abrupt climate change on coupled human-natural systems.
- Understanding potential institutional responses, at multiple scales, to the impacts of climate change, such as economic incentives, governmental policies, and risk communication.

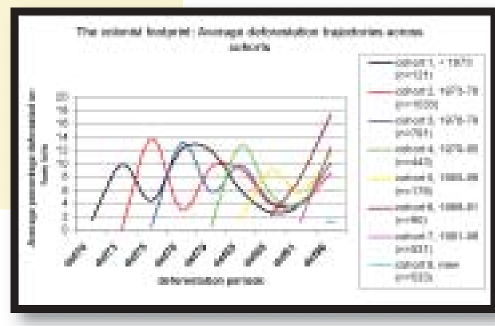
Biodiversity and Ecosystem Dynamics

Biodiversity (all species of organisms, including their genetic diversity) and functioning ecosystems (species, communities, their habitat, and the multiple interactions among these components) are interdependent. Ecosystems and the diversity of species they support are critical to human well-being and environmental security at all scales. However, increasing human population and activity are threatening the existence of some species by changing their behavioral patterns, modifying or eliminating the ecosystems in which they live, disrupting natural ecological processes and food webs, and altering climate conditions. Collectively, humans are playing a major role in increasing the extinction rate of species and populations and the loss of genetic diversity.

The scientific challenges are to understand the complex relationships between biodiversity and population dynamics, to grasp the regulation and functional consequences of biodiversity on ecosystem dynamics, and to understand ecosystem structure and function. There is also an increasing focus on both microbial and genomic research related to species diversity. The robustness of species and ecosystems is a function of the individual components, processes, and stressors of the particular system (including human stressors), and the cumulative and interactive impacts of those elements.

Hurricanes as a Creative Force of Nature, Ariel Lugo, USDA Forest Service, International Institute of Tropical Forestry. The passage in 1989 of Hurricane Hugo over the Luquillo Experimental Forest Long-Term Ecological Research site gave us the opportunity to study the ruin and recovery of a tropical forest subjected to four hours of hurricane-strength winds. Observations after the hurricane (middle photo) reflected the ruin of the forest, due to the apparent devastation caused by the event. The highest ever measured rate of primary productivity occurred during the first five years after the hurricane. The regenerating forest exhibited rapid reorganization, closed the canopy, and re-established forest conditions (bottom photo). Studies of this rain forest suggest that a large and infrequent disturbance event such as a hurricane is a creative force in nature because it allows species to re-sort themselves into new combinations that respond to changing environmental conditions. In synergy with other environmental factors such as trade winds, these disturbance events shape the canopy structure of Caribbean forests. Stand characteristics such as dominant age classes, high species dominance, no emergent trees, low biomass, fast nutrient cycles, and high turnover of organic matter reflect the effects and frequency of hurricanes. The life history traits of plants and animals in this forest also reflect such periodic disturbances. NSF grant DEB-9705814.

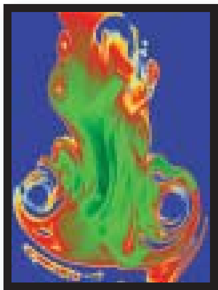
Families Going to the Amazon Manage Their Land, Emilio F. Moran and Elinor Ostrom. The Center for the Study of Institutions, Population, and Environmental Change (CIPEC) focuses on determining how and why some forests seem to be growing and thriving, while others are rapidly disappearing and becoming increasingly fragmented. The Center has developed innovative methods for comparative analysis linking biophysical and social data across a variety of scales. Researchers use satellite time-series data, vegetation and soil inventories, social survey research, and demographic and institutional analyses using common protocols for data collection. One of the many notable findings to date is from the Center's research in the Brazilian Amazon where we have discovered that migration does not correlate with steadily increasing deforestation as commonly thought. Instead migrants follow a consistent general pattern. Only for the first five years do they follow the expected pattern of steadily increasing deforestation. This is followed by a steadily decreasing rate of deforestation. This pattern was followed by households that arrived to the frontier even when there was little economic opportunity in the late 1980s. Macroeconomic conditions did not impact the trajectory of deforestation by households, but did affect its magnitude (see figure). This research shows that families going to the Amazon learn to manage their land within one generation, and that they are conscious of the need to manage their forest clearings and to conserve a portion of their forested land. A similar finding can be noted under the very different biophysical and social context of Central America. NSF grant SES-9521918.



Because of the rapid pace of species loss and habitat destruction, current scientific knowledge must be used efficiently to develop conservation and management tools and strategies for biodiversity, populations, and ecosystems in terrestrial and aquatic environments. Information science has the potential to develop accessible databases and models of species and ecosystems to assure that scientific results can be quickly and effectively incorporated into management and policy decisions.

Examples of research and education areas include:

- Developing improved observing systems for analyses, classifications, and assessment of phenotypic and genetic diversity at all scales.
- Understanding and explaining the relationships, at all scales, among biological diversity, ecosystem functioning, biogeochemical cycling, and climate variability and change, and understanding how ecosystems are organized and change.
- Developing spatially explicit models that explore the relationships among changes in land use, habitat and biodiversity, and assessing how these models can be used to understand and manage biological diversity in periods of environmental variability and change.
- Integrating population, ecosystem and socioeconomic information and models to assess how parks and biological reserves function, the efficacy of their design, and how multiple stressors and human and animal behavior influence their operation and viability.



Sensor Materials for Efficient Engine Design and Diagnostics

Manoosh Koochesfahani, Michigan State University

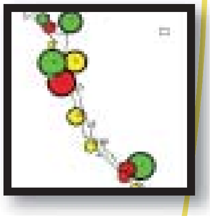
Researchers at Michigan State University's Materials Research Science and Engineering Center (MRSEC) have developed a laser flow visualization technique that is guiding the development of a gasoline injection automotive engine. Visual mapping of fluid flow creates images that show precisely how gasoline vapor mixes with air in engine cylinders. Special light-emitting chemicals mixed with fuel generate pictures that show how the distribution of gas and liquid changes over time. These experiments are giving automotive engineers a quantitative understanding of what happens within an engine cylinder, helping them to optimize the shape of the cylinder and the characteristics of the fuel spray. The result will be an engine with high fuel economy and low carbon dioxide emissions. Top: Turbulent mixing of two fluids visualized with fluorescent mapping. Middle: Two-color laser induced fluorescence imaging reveals the flow and mixing patterns when a vortex ring impinges on a solid wall. Bottom: A grid of laser lines tags the molecules that will provide the velocity field information in an optically accessible IC engine using the technique of Molecular Tagging Velocimetry (MTV). NSF award number DMR-9809688.

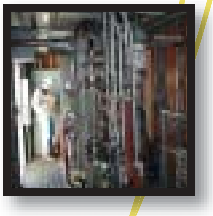
People and Technology

The overarching objectives of this research area are to determine how people as individuals and through human institutions interact with the environment, how they value and use environmental resources, and how they respond to environmental change and natural hazards. Additional objectives are to create new technologies that protect and improve the environment and to understand how people respond to the implementation of these technologies. This area builds on, supports, and integrates tools used and research conducted in many existing disciplines, including economics, sociology, political science, psychology, ethics, industrial ecology, chemistry, engineering, geography, demography, archeology, cultural anthropology, and management and decision science. The integration of these disciplines and tools and the development of improved models are fundamental for increased understanding of individual and collective human behavior and for the successful implementation of new environmental technologies and policies.

The following are three of the major research challenges regarding the role of individuals, industry, and institutions in the environment:

- Materials and Process Development
- Decision Making and Uncertainty
- Institutions and Environmental Systems





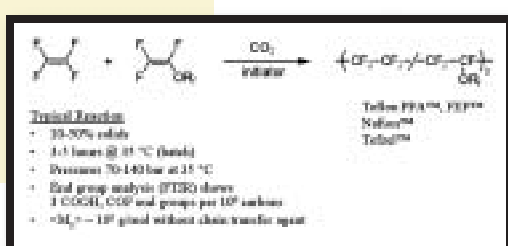
Materials and Process Development

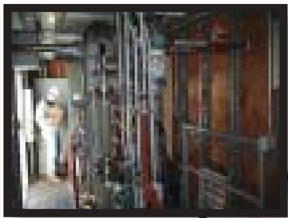
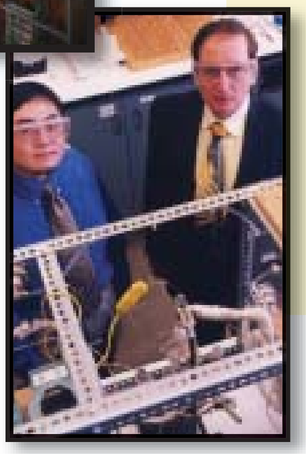
Understanding the sources, uses, and potential for the human employment of materials and energy is vital for both economic development and environmental preservation. The exploitation, distribution, use, and disposal of resources are intertwined with social, behavioral, and economic systems. Equally important is the development of innovative alternatives to current technological systems. This information can lead to new technologies that meet the materials and energy needs of society.

Industrial ecology and related fields develop theoretical and practical approaches for addressing the interactions among technology, the environment, and institutions. These approaches synthesize and integrate many disciplines to identify environmental challenges and develop ways to respond, while simultaneously enabling technology to provide heating, electrical power, pharmaceuticals, and other products that may improve human quality of life.

Historically, the relationship of materials and process development to the environment has largely been one of extraction, capturing pollutants as they are produced during extraction and processing, and remediating past environmental damage. New approaches stress prevention and life-cycle assessment, reduce water and solvent demands, and optimize process and product design. Chemical synthesis and manufacturing processes *design in* rather than just *add on* environmentally sound technology. This understanding of materials and energy depends not only on research in the physical and engineering sciences from the molecular scale to the ecosystem level, but also on economic, behavioral, and health research to understand human resource use and its effects.

Fluropolymer Resins from Supercritical Carbon Dioxide, Joseph M. DeSimone, University of North Carolina, Chapel Hill. DuPont Fluoroproducts has introduced the first commercial DuPont™ Teflon® fluoropolymer resins made using proprietary and fundamentally new manufacturing technology that replaces traditional water-based polymerization with a process based on supercritical carbon dioxide. According to DuPont, the new technology produces Teflon® with enhanced performance and processing capabilities, while generating less waste. The new process is first being used to make select melt-processible products for applications such as wire and cable insulation and jackets, flexible tubing, and industrial films. It also can be used to make other melt-processible fluoropolymers whose applications include high-purity fluid handling systems. The new products will be targeted at the data communications, semiconductor, automotive, and other industrial markets. The new products are being manufactured at the company's Fayetteville, N.C., plant in a new $40 million facility that started up in late 2000. The new technology was developed jointly by DuPont and scientists at the University of North Carolina, Chapel Hill. NSF grant CHE-9315429.



Discovery of Environmentally Benign Catalytic Process Leads to Cleaner Air During Manufacture of Paper, Israel E. Wachs, Lehigh University. The pulp and paper industries generate waste streams with large amounts of methanol and mercaptan that have been discharged into streams and rivers for many years. The remediation voluntarily adopted by many major mills in the United States—incineration and bioremediation—has been expensive and produces global-warming carbon dioxide and acid rain gases. During the course of our research we have discovered a novel catalyst that selectively converts methanol and mercaptan in pulp mill waste streams to formaldehyde via a non-polluting route. Formaldehyde is a valuable starting material used in large quantities in manufacturing. If producing 2,000 tons of pulp per day, a company can generate a profit of $500,000 to $1 million per year from the products of this technology. This catalytic process produces marketable chemicals from renewable resources—trees rather than fossil fuels—and provides an environmentally sound alternative for meeting emissions standards and turning a profit at the same time. Pollution prevention through redesign of a manufacturing process eliminates costly end-of-pipe pollution cleanup. This new class of reactions, which is an example of a sustainable technology, immediately suggests novel solutions for the natural gas and petroleum industries. NSF grant CTS-9901643.

For example, to protect ecosystems from damage from manufacturing and to produce sustainable technologies, industrial designers have to incorporate ecosystem functioning into total system analyses. Engineers and physical scientists are important members of teams dealing with problems such as maintaining safe and sustainable water supplies, exposure to trace contaminants, smog reduction, and carbon sequestration.

The assessment of life cycles (from raw materials through manufacturing, use, recycling, and disposal) also requires development of new methods to acquire and new models to evaluate large, complex, and heterogeneous datasets. The challenge is to develop an understanding of the budgets and cycles of key materials, both those used by people and those significantly perturbed by human activity, and to discover how to modify those budgets and life cycles appropriately.

Examples of research and education areas include:

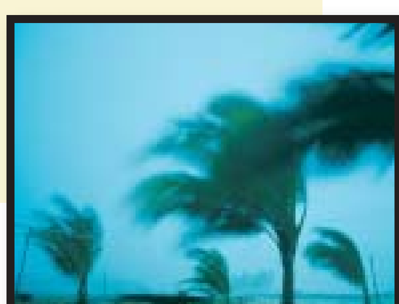
- Developing models and methods for more complete recycling and recovery and reduced use of technological materials and energy, as well as developing new materials, integrated chemical and engineering approaches, and product and process technologies that minimize damage to the environment and human health.
- Developing spatially and temporally explicit budgets and cycles for selected key materials and energy, including the ways in which human activities define, perturb, dominate, or limit materials flow and supply.
- Exploring the technological and behavioral challenges and environmental effects associated with alternative sources and uses of energy production such as solar, wind, and biochemical (hydrogen, methane, and other bio-produced fuels).
- Understanding the patterns and driving forces of human consumption of resources, and identifying policies and practices that influence materials and energy use decisions, including incentives.

Decision Making and Uncertainty

Environmental and human systems are sufficiently complex that knowledge of them and the ability to project future conditions will never be perfect. In cases where time horizons are short, and predicted events occur frequently, the probabilities of outcomes and impacts can be validated, and forecast skill can be improved through experience. In other instances, particularly at certain spatial scales or where time horizons are longer, the tools for estimating these probabilities may not yet exist, or there may be irreducible uncertainty about how these systems will behave. In some cases, environmental changes may be irreversible. Research into the nature and dynamics of uncertainty is therefore a critical aspect of efforts to quantify, anticipate, and respond to future environmental change.

Environmental decision making often involves making difficult choices about resource allocation, both in the present and across future generations. How do people attach values to aesthetic, recreational, and cultural aspects of nature? For example, how are trade-offs made between present-day jobs in the timber industry and the preservation of old growth forests and the species that depend on them for future generations? And how can society handle complex problems such as global warming? These decisions vary depending on the cultural, historical, and political context in which they occur. They involve a consideration of social science, including political ecology and the analysis of class, race, and power relationships across a hierarchy of human behavioral and institutional structures. Scientific tools that support adaptive decision making are especially valuable, particularly those that emphasize observation, statistical and probabilistic assessment, and carefully monitored experimentation based on active cooperation among researchers, decision makers, and affected communities.

Impacts and Adaptation to Sea-Level Rise, Hadi Dowlatabati, Carnegie Mellon University. Despite the unpredictability of storms, our research shows that it is possible to simulate the complex process of storms, repairs, and development as well as housing markets in coastal areas. At Carnegie Mellon's Center for Integrated Study of the Human Dimensions of Global Change, researchers measured the impact of sea-level rise on human behavior by noting that coastal areas suffered their greatest losses during storms. Inundation is a slow and predictable process, but long before its occurrence, higher sea levels increase the energy carried by storm surges inland, causing greater damage than would otherwise be the case. This new approach revealed coastal zone impacts to be dependent on how often a given property was damaged before it was inundated rather than where a property was located with respect to the shoreline as in earlier, less-sophisticated models. The key to successful adaptation to sea-level rise therefore was found to be how people respond to storm damage. A wise recovery strategy can limit future vulnerability of coastal property and total damage accrued over time. Our simulations have been used to arrive at simple modifications to local development regulations that used storm damage to identify vulnerable structures and remove them from further risk. This simple strategy reduces long-term cumulative damage from sea-level rise by an order of magnitude or more. NSF grant SES-9521914.



Collaborative Research on Spatial Decision Making, Piotr Jankowski, University of Idaho and Timothy Nyerges, University of Washington. Multiple stakeholder groups undertaking salmon habitat restoration in the Duwamish Waterway of Seattle Washington (top map) now find it easier to negotiate a consensus about where to develop restoration sites. This project developed decision-support software using geographic information system (GIS) tools to allow groups of people to identify, describe, rank, and then visualize site options. A new type of "consensus map" was devised to allow groups of people to visualize both the priority of their preferred rankings as well as the consensus status about those priorities (bottom map). Because the maps are generated in an interactive manner within the GIS, multiple scenarios can be developed to take into consideration multiple stakeholder views of what might be best for habitat restoration. Encouragement from many groups lead us to redevelop the software, generalizing it so that it could be used for any site selection problem. The redeveloped version, call GeoChoicePerspectives, is now being used in classrooms around the United States and in Europe to enhance education in collaborative geographic decision making. It has been used for transportation, public health, environmental cleanup, and a variety of other complex geographic problems. NSF grant BCS-9411021.

In addition to flexibility and resilience in the face of changing conditions, and taking advantage of new knowledge and technologies, adaptive management also depends on improved decision making frameworks. Decision makers and managers need to develop strategies for dealing with complex environmental problems and uncertainty. Research on abrupt and gradual environmental change must be integrated with research on decision making, communication, and behavior.

Examples of research and education areas include:

- Developing and using models for environmental disturbance scenarios for a range of structural assumptions, including probabilistic and non-probabilistic treatments of uncertainty.
- Developing decision-making strategies and institutional approaches to most effectively solve problems and deal with uncertainty.
- Identifying decision processes that effectively combine analytical, deliberative, and participatory approaches to environmental choices, which will guide scientists and engineers toward the generation of decision-relevant information.
- Determining the best practices for the communication of scientific information and uncertainty among scientists, policy makers, and the public, and understanding how the information and uncertainty about outcomes are received, understood, and acted upon.

Institutions and Environmental Systems

People interact with the natural environment on an individual level, but much of the impact humans have on the environment stems from the activity of collective entities, for example, informal and formal organizations, corporations and other economic entities, and governments. These collective entities operate within a framework of institutional arrangements—markets, legal structures, regulatory arrangements, and international conventions. Institutions foster or impede relationships between groups or individuals, and they result in organizational structures in both government and civil society that influence the relationship between humans and the environment. It is important to address the role of institutions across multiple scales from small, informal associations of local participants to large, multinational trade and environmental agreements.

A wide range of institutions manage access to and use of land, water, minerals, the atmosphere, forests, fisheries, and other natural resources. These institutions have often been designed by state, national, or international entities to address large scale and global problems of open-access resources, such as fisheries. Understanding the character and role of these institutions and knowing how to apply this understanding is essential to better manage resources and to enhance resilience in the face of environmental change.

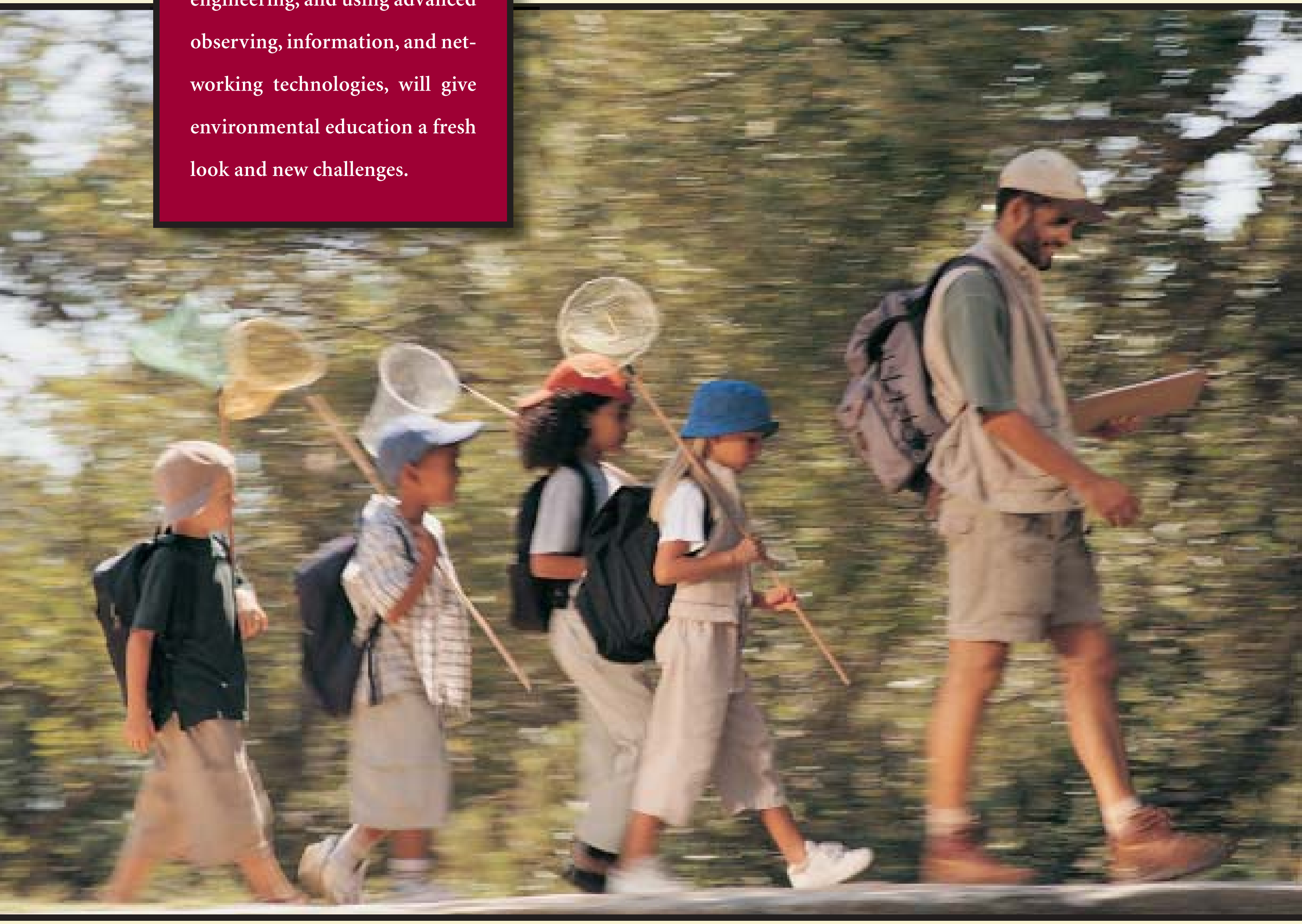
Various institutions around the world have assembled useful data about and strategies for resource management, but this information is often not in a form that is readily accessible or easily communicated. Certain systems of water rights, for example, have led to serious depletion of aquifers in some areas, while elsewhere, institutions governing access to water have helped maintain water levels and water quality. A better understanding of the conditions under which institutional structures work effectively is needed, as well as the factors that influence the environmental and social benefits and consequences of various institutional forms. These questions should be addressed at multiple scales.

Examples of research and education areas include:

- Determining how institutions affect, filter, and evaluate the dissemination of scientific knowledge about natural systems and the environment.
- Conceptualizing and assessing the role that institutions play in the use and management of global, national, and local common-pool resources and their associated environmental conditions.
- Testing the applicability of scientific and engineering knowledge from successful local resource management to problems in other regions and at other scales.
- Understanding the conditions, potential contributions, and pitfalls associated with particular organizational structures, institutional behavior, and policy instruments.

Integrated Municipal Sanitation Systems, Garrick E. Louis, University of Virginia. The goal of this project is to assure the sustainable capacity for safe, reliable, and affordable municipal sanitation services (MSS) to under-served communities worldwide. Through empirical research, education, and outreach activities we are extending existing theoretical methods in risk assessment and performance evaluation to several sanitation utilities. The services in question are drinking water supply, wastewater and sewage treatment, and municipal solid waste management. Our work also identifies, documents, and disseminates information on best practices in MSS delivery. Top Photo: Garrick Louis, graduate student Jeff Rogers, and Systems Engineering REU student Amanda Singleton get a report on the Richmond Water Treatment Plant, Tobago, August 2002 (case study, Tobago, Republic of Trinidad & Tobago). Bottom: Garrick Louis lends a hand at the Shipman Water Project, September 2000. NSF grant BES-9984318.

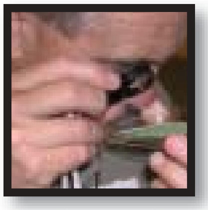
The trends toward integrating the environmental sciences and engineering, and using advanced observing, information, and networking technologies, will give environmental education a fresh look and new challenges.

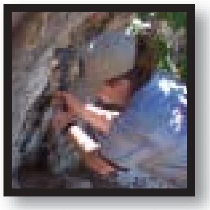


Building Capacity to Address Environmental Research Challenges

To fulfill this research Outlook and to better integrate research and education, the AC-ERE recommends a number of improvements in environmental education, training, infrastructure, and technical capacity. Scientists and engineers need to understand that every decision related to the use of technology is an environmental decision. Consequently, it will be necessary to educate a new generation of environmental professionals – researchers, technicians, resource managers, and educators – who are capable of crossing disciplines, integrating diverse information, and working together to solve problems. The creation and strengthening of the observational and cyberinfrastructure to support a global research effort are also part of this challenge.

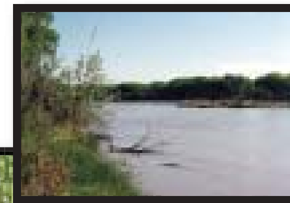
Environmental research and education requires not only understanding problems, but also developing a diverse workforce to solve them. Environmental researchers are important contributors to education, government, and industry. Outreach and public education are needed to educate a new generation of informed decision makers, inquisitive students, and concerned citizens. Developing a new culture of collaboration and long-term, dynamic partnerships that cross national and regional jurisdictions and international boundaries can be the most effective means of addressing multi-scale environmental challenges.

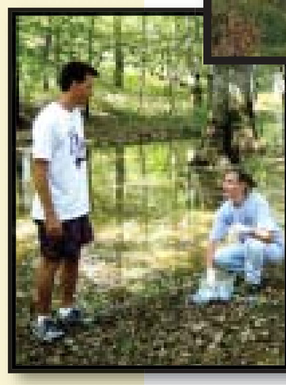




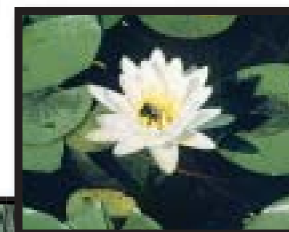
Freshwater Sciences Interdisciplinary Doctoral Program

Amelia K. Ward, University of Alabama and Clifford N. Dahm, University of New Mexico





Maintaining availability of high-quality freshwater is regarded by many as the most critical issue facing the 21st century. Funded by the NSF Integrative Graduate Education and Research Training (IGERT) program, the Freshwater Sciences Interdisciplinary Doctoral Program provides Ph.D. students with unusual opportunities to prepare for careers that effectively address this issue. The program is a collaboration between the University of Alabama and the University of New Mexico, which are located at similar latitudes, but with contrasting humid/wet and semi-arid climates. Interdisciplinary areas of aquatic ecology, environmental geology, and hydrology are emphasized. Students broaden their perspectives by designing components of their dissertation research that are cross-regional and that allow them to explore similarities and differences in approaches and questions in geographic regions with distinctly different climates.



The program has a specially designed, four-course curriculum that includes distance education classes where students and instructors at both universities interact during class periods. The classes are constructed to strengthen interdisciplinary perspectives of students beyond what they encounter in traditional, disciplinary courses. Students also participate in internships with state or federal agencies that have management and restoration of freshwater ecosystems as major goals. Through their internships, students are able to apply knowledge gained in their fundamental, academic research to real-world problems.

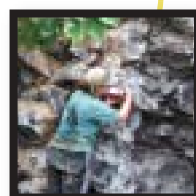
As of fall 2002, 21 Ph.D. students from both universities are participating in this program. Approximately half of the students have completed the four courses and are deeply involved in research projects, while the rest are in the process of completing the courses and designing their research projects. Students are investigating ecological, hydrological, and geochemical attributes of streams, rivers, and ground waters of the Mobile River and Middle Rio Grande basins. They have formed links with organizations such as the South Florida Water Management District, Everglades National Park, the Nature Conservancy, and the Bosque Improvement Group, which are involved in large-scale management and restoration of major southeastern and southwestern freshwater ecosystems. Students and faculty from both universities confer and meet regularly, share research results, and compare field research. An integrated, interdisciplinary, and interinstitutional approach to studying freshwaters will better prepare the next generation of aquatic scientists. NSF grant DGE-9972810.

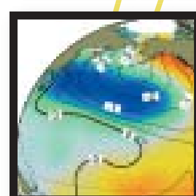
Environmental Education and Workforce

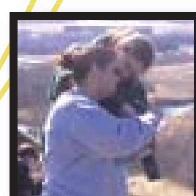
In the coming decades, the public will be called upon more frequently to understand complex environmental issues, assess risk, evaluate proposed environmental plans, and understand how individual decisions affect the environment at local to global scales. Creating a scientifically informed citizenry requires a concerted, systematic approach to environmental education grounded in a broad and deep research base that offers a compelling invitation to lifelong learning. NSF's goals in environmental education should be twofold: to prepare the future environmental workforce at many levels—researchers, teachers, resource managers, and technicians—and to raise the environmental literacy of the general public.

Quality environmental education and training is based on the natural, engineering, and social sciences, utilizes current educational technology, and prepares students for a broad array of careers. Students also acquire skills in problem solving, consensus building, information management, communication, the integration of quantitative and qualitative data, and critical and creative thinking.

Environmental scientists and engineers increasingly consider the interplay of physical, biological, and social factors and are required to use advanced observational, database, and networking technologies. As a consequence, there is a growing need for scientists, engineers, managers, and technicians who have the ability to work on multidisciplinary and cross-cultural teams; to use sophisticated new instrumentation, information systems, and models; and to interpret research results for decision makers and the general public. Fresh and innovative approaches to education are needed to train individuals to undertake interdisciplinary, collaborative, and synthesis activities.



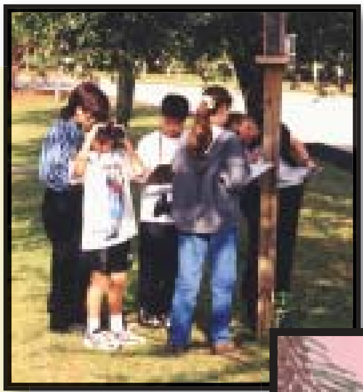


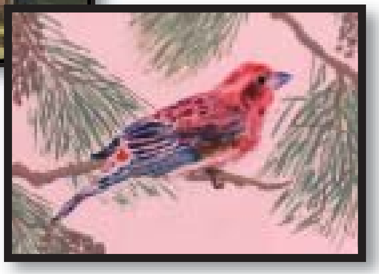


Elementary and Secondary Education

By the time they enter high school, more than 80% of U.S. students have decided that they are not interested in careers in the physical or biological sciences, mathematics, or engineering (*Indicators of Science & Mathematics Education,* 1994, National Science Foundation). Children without an adequate foundation in mathematics and science by the sixth grade are not positioned to take the classes necessary to prepare for college. Although this is a national problem that requires multiple solutions, many believe that environmental themes could be used as a heuristic tool to help attract students not only to careers in environmental sciences and engineering, but also to other scientific and technical areas. The environment, when used as an integrating concept in pre-school, elementary, and secondary education, often improves student interest, attitude, achievement, and attendance in school.

Many successful programs offer students hands-on experiences through field trips, internships, and "backyard science" in urban areas, sometimes with parental involvement. These place- and field-based activities help students make connections to local neighborhoods or traditions, thus enhancing their motivation and increasing the likelihood that environmental science will be a life-long interest. Teacher education and pre-service and in-service professional development opportunities can also be critical components of environmental education programs.





Classroom FeederWatch, Richard E. Bonney, Cornell University. Classroom FeederWatch is a research and interdisciplinary education curriculum designed for students in grades 5-8. The information collected for this project is used each year by ornithologists to track changes in the abundance and distribution of bird species that use feeders. By counting birds in the Project FeederWatch and Classroom FeederWatch programs, students and teachers permit scientists to understand the movement patterns and population fluctuations of many common birds and help ensure their survival. This project also gives teachers a chance to integrate science with language arts, visual arts, social studies, math, and technology. Students produce a newsletter describing their findings and their feelings about the project. They discuss questions with students in classrooms all over the country by communicating electronically. Classroom FeederWatch highlights many of the important features of next-generation environmental science education: interdisciplinary approach, student involvement in research, use of networking technology, and linking science with quality of life and public outreach. Purple Finch in Pines by Sang-Hoon, 9th Grade, Charlottesville, VA. NSF grant ESI-9550541.

Research Experience for Teachers, George Flynn, Director EMSI, Columbia University. Columbia University has an active high school teacher recruitment plan that brings local teachers to the university for summer research activities. During those summers, teachers conduct research in chemistry, geochemistry, and engineering with members of the Environmental Molecular Sciences Institute (EMSI) team. Participating teachers share their research experiences and new skills with their students and fellow teachers. The program's ongoing analysis of the effects of teacher participation on student outcomes shows that students of participating teachers demonstrate an increased interest and performance in science. NSF grant CHE-9810367.

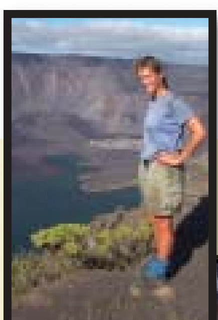
Examples of research and education areas include:

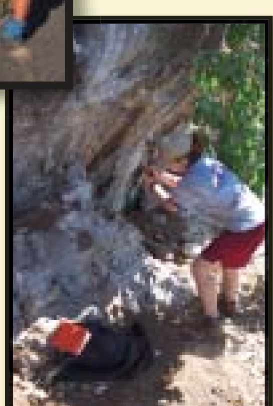
- Understanding how pre-school, elementary, and secondary environmental education can contribute to accomplishing broader educational goals and attract students to science and engineering careers.
- Exploring the relative merits of integration of environmental education into all disciplines across the curriculum or development of specialized interdisciplinary environmental courses.
- Developing and assessing the effectiveness of inquiry-based and hands-on instructional materials and teacher training methods that take advantage of environmental themes.
- Developing new testing instruments to measure progress in environmental literacy and education.

Two and Four Year Colleges and Research Institutions

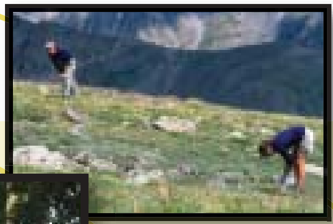
Quality undergraduate and graduate programs are critical for developing the future environmental science and engineering workforce. Disciplinary fields of study will remain important, and new interdisciplinary programs will develop, but all of tomorrow's scientists and engineers will need to be prepared to contribute effectively to collaborative teams that include researchers with many disciplinary backgrounds, resource managers, and policy makers. Faculty members will be called on to partner across institutional boundaries to develop innovative programs that provide a continuous route of advancement for students.

In developing educational programs, community colleges, and other post-secondary programs are often overlooked. In the case of environmental education, such an oversight would have serious adverse consequences. Community colleges are the starting point for many students who obtain four-year degrees in science, engineering, and science education. Approximately one-third of all K-8 teachers start their post-secondary programs at community colleges and over 50% take their mathematics and science courses at these institutions (American Association of Community Colleges). Community colleges are also the most significant source of future technicians, and many technical programs are explicitly focused on environmental technology. Unfortunately, teaching and administrative loads for community college faculty are such that little time is available for research or development of collaborative programs.





Teaching Through Research: Interdisciplinary Studies of the Northern Galapagos Volcanoes, Karen Harpp, Colgate University. With support of a NSF-CAREER grant, several undergraduate students have participated in my fieldwork in the Galapagos Archipelago, mapping the islands and generating geochemical analyses to study the role of a geological hotspot in the formation of these islands. Hotspots are places where excessive amounts of magma upwell from the mantle to form volcanoes or lava plateaus. We are investigating the origins of a series of enigmatic volcanoes in the northern Galapagos Islands whose presence cannot be explained by the current hotspot paradigm. We also contribute images and geological explanations of biological phenomena from this research to the BIRDD CD-ROM produced by Beloit College, which provides raw evolutionary data about the Galapagos finches for students and researchers. In addition, I have organized a science outreach program at Colgate University in which undergraduates take hands-on science experiences to area schoolchildren to illustrate how science is actually all around us, every day. NSF grant CHE-9733597.



At the undergraduate level, leadership activities in curriculum development, in partnership with states and professional societies, would advance the education of teachers and future environmental researchers. New programs should incorporate sound education research results, convey the excitement of the research process, and promote best practices for effectively mentoring students.

The trends toward integrating the environmental sciences and engineering, and using advanced observing, information, and networking technologies, will give environmental education a fresh look and new challenges. Global collaborations can simultaneously advance environmental research, environmental science education research, and curriculum development. Both undergraduate and graduate environmental science and engineering programs need to be re-examined in this context to ensure that they are adequately preparing professionals for the future. Developing academic institutional structures and incentives for interdisciplinary environmental research and education is an important part of this process.

Examples of research and education areas include:

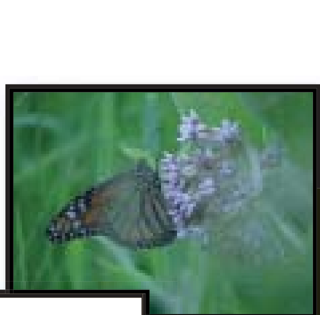
- Developing tools and methods to enhance community college environmental curricula, faculty research participation, and networking among institutions.
- Understanding the relative merits of disciplinary environmental science degrees, such as environmental biology and environmental chemistry, compared with interdisciplinary environmental science degrees.
- Developing new graduate training methods and programs to help students learn how to collaborate effectively with diverse teams and partners.
- Developing tools, skills, and information and networking technologies to enhance environmental science, engineering, and technology education.

Informal Education

One of the most compelling challenges of our time is to enhance the public's access to and understanding of complex environmental information. Informal environmental education should create opportunities for citizens to expand their understanding of and curiosity about environmental science and engineering via museums, zoos, parks, nature centers, mass media, and community and citizen-scientist monitoring partnerships. It should also provide the knowledge that people need to make informed decisions about the environment as it relates to their personal, work, and community lives.

Learning about the environment starts before formal schooling and continues past retirement. Much remains to be understood about the most effective ways to activate adult learning through the sciences, humanities, and media so that new scientific information is assimilated into the public's base of environmental knowledge.

Environmental researchers must be more effective in communicating their findings to the general public and other users of scientific information. In technical areas, there is often a need for "translation" to bridge the gap between the minds of scientists and engineers and the needs of decision makers. NSF should support programs that teach researchers how to improve their communication skills, develop outreach programs, and establish links to groups that provide public education. Similarly, education communities should be supported to expand these facets of informal environmental education and link them to research activities.



Monarch Butterfly Larval Monitoring, Karen S. Oberhauser, University of Minnesota. The University of Minnesota is implementing a nationwide citizen science project focused on the life cycle of monarch butterflies. Scientists from the university are training naturalists and environmental educators throughout the United States at eleven host sites. Participants in the first round of training will then train volunteer monitors. The target audience for volunteers is adult/child teams. The project web site shows temporal and spatial data and will provide interpretations of volunteer observations. Listservers support the project, and augment a monthly newsletter and the web site. In addition, mini-exhibits have been created to highlight the project at participating nature centers. These exhibits focus on monarch and insect ecology and conservation, as well as local and population-wide monitoring efforts. It is estimated that 90-150 nature centers will participate in the regional training, and they will in turn train almost 5,000 volunteers. NSF grant ESI-0104600.

Coral Reef Adventure, Greg MacGillivray, MacGillivray Freeman Films. We are producing a large format film about exploration and new scientific research aimed at understanding and responding to changes in coral reef ecosystems. The film will feature researchers who are a part of the global effort to understand and protect coral reef ecosystems. They will be documenting reef diversity and animal behavior, investigating symptoms of reef degradation, providing information on past environmental change through core sampling, and exploring life in extreme ocean environments. The film will examine the complex behavior and interactions among unique Pacific coral reef animals at five coral reef sites, illustrate the role of scientific research in addressing the declining health of reefs, and stimulate public interest in pursuing further learning and careers in coral reef and marine science. Related outreach materials will include a Museum Resource Guide, Family Fun Sheet, Activities for Informal Education Groups, Teacher Guide, Web Site/Virtual Field Trip, and Scientist Speaker Series. Photos are printed with permission, copyright, MacGillivray Freeman Films. NSF grant ESI-0003650.

Examples of research and education areas include:

- Developing effective informal education programs and models for life-long environmental education, including those that involve schools, colleges, and research institutions.
- Designing and testing methods, incentives, and training programs for scientists and engineers to communicate environmental research results to decision makers and the public.
- Developing novel methods for informal environmental education, including enhanced Internet formats and mass media.
- Developing tools to assess the effectiveness of informal education for improving environmental literacy, including outreach programs at museums, parks, and public lands and facilities.

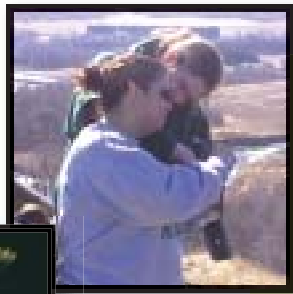
Diversity

Participation by under-represented groups in environmental education and careers is extremely low, but estimating the level of involvement is difficult. The environmental science and engineering community is more loosely defined than more traditional disciplinary communities, and data are not readily available. For technical areas as a whole, African Americans, Hispanic Americans, and Native Americans represent only about 5% of all employed doctoral scientists and engineers. While these minority groups earn approximately 15% of bachelors degrees, 11% of the masters degrees, and 8% of doctoral degrees in science and engineering overall (*Women, Minorities, and Persons With Disabilities in Science and Engineering,* 2000, National Science Foundation), the percentages for environmental sciences at each of these degree levels may be even lower. Increased participation in environmental education and research by members of minority groups is imperative to achieving and shaping current and future environmental research and education. Fortunately, environmental themes can be particularly useful in attracting young women and minorities to science.

Attracting and retaining minorities demands a multi-faceted approach and sustained commitment. Students and their families need to be exposed early to environmental science and engineering education. For students this should occur during elementary school by having teachers equipped with high-quality, teacher-friendly materials. Media presentations and other informal education activities and field trips that include families are valuable. A particularly effective vehicle for attracting minority students may be K-6 education in urban areas, where students can benefit greatly from hands on experiences in "backyard" or "schoolyard" laboratories.

One of the most important factors for students deciding whether to pursue environmental science is their familiarity with career options and rewards and what life would be like if the student were to pursue this area. Stipends, however modest, for high school students who participate in research or restoration projects send a powerful message. Throughout the educational and career pathway, mentors are essential. The role of mentors is not sufficiently valued, however, and institutions should recognize and reward teachers and faculty for their mentoring activities.

Research experiences in environmental areas are very important for undergraduates as well as high school teachers and students. While in some disciplines there is a strong tradition of research experiences, this is not always the case in field-oriented sciences, and special efforts are needed to increase opportunities for student involvement. Because a large percentage of minority students begin their post-secondary education in community colleges, more resources should be directed to environmental research experiences in those programs.



Encouraging New Entrants into Geological Sciences, Phil Gerla, University of North Dakota. Indians into Geological Sciences (INGEOS), which began at the University of North Dakota in September 2001, has three goals: (1) increase the number of American Indians earning undergraduate and graduate degrees in the geology and other Earth sciences, (2) engage American Indians in scientific research early in their college careers, and (3) prepare Native Americans for professional employment in a variety of communities. To meet these goals, the UND's Department of Geology and Engineering Sciences established a program of eight points of success. This program assures that every participant, including the coordinators and principal investigators, strives toward success in areas crucial to academic achievement: spiritual health, physical health, social health, mental health, financial management, technical exposure, research involvement, and community education. INGEOS also conducts activities related to youth, who are our future, and elders, who want to know that their groundwork is helping us reach our goals. NSF grant GEO-0119849.

One way to help retain minority students is to develop consortia of institutions of various levels and types, including high schools, colleges, research centers, museums, parks, and industrial and community partners. These should be designed to help students "bridge" between educational levels and find peer mentors, to enable institutions to share resources needed for laboratory and field experiences, and to develop an integrated environmental curriculum. In addition, strengthening environmental research and education at institutions such as Historically Black Colleges and Universities and Minority-Serving Institutions is an important part of the strategy.

Support for minorities does not end with an advanced degree. New minority faculty members are often isolated, and workshops and other programs that enable minority faculty to network with peers and colleagues can form lifelong associations that encourage them to persist in faculty and resource management positions, where they serve as important role models. In addition, diversity training and cultural competency training can help institutions create a climate that aids in recruiting and retaining minority students, faculty, and environmental workforce members.

Examples of research and education areas include:

- Conducting a credible and comprehensive analysis of present and projected career opportunities in environmental science and engineering, including disciplinary and interdisciplinary areas.
- Designing and expanding hands-on and research-oriented environmental programs in urban areas to attract and retain minority students.
- Determining what types of programs or networks should be established to help minority students transition from one institution to another, for example, from high school to college, or from graduate school to faculty and environmental management positions.
- Assessing effective ways to form support networks for minority faculty members and other mentors in environmental science and engineering.

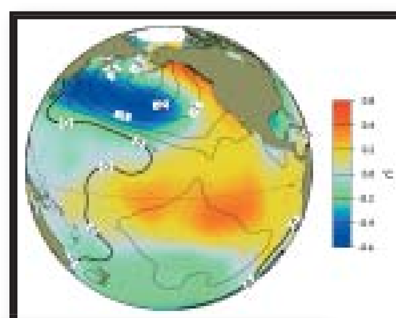
Interdisciplinary Teams, and Interagency and International Partnerships

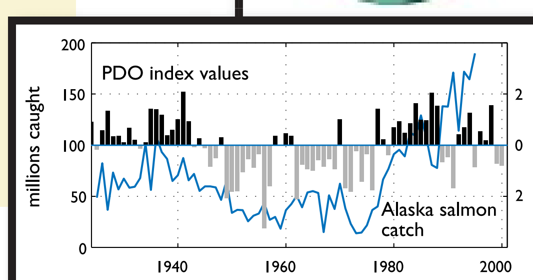
Expanding and extending interdisciplinary research that integrates natural sciences, mathematical sciences, engineering, and social sciences requires a team approach at both small and large scales. Attention must be paid to building diverse collaborative teams of scientists, engineers, and educators. Teams often also need outreach and information specialists, citizen-scientists, and resource managers. These groups should be able to not only produce research results, but also translate their results for local or regional users. A range of skills is also necessary to effectively partner with other educational institutions, such as schools of education and state departments of education, and private sector organizations.

To enhance collaborations, a better understanding of interdisciplinary team formation and management is necessary. Anecdotal evidence indicates that teams that sequentially develop new theories, integrate knowledge and practices, and conduct experiments generally require eight- to ten-year financial commitments to produce the best results.

The integrated model for discovery, learning, and communication also fuels the formation of institutional partnerships among federal agencies and with foreign partners who share common goals. Partnerships among federal agencies are vital. Many agencies, for example, the Environmental Pro-

Climate Variability and Predictability (CLIVAR), David Legler, U.S. CLIVAR Office. The U.S. CLIVAR program, a project organized under the auspices of the World Climate Research Programme and supported through activities of over 60 countries, seeks to answer several unresolved questions about the climate system that will contribute to better predictions of those features that have major societal implications. For example, scientists using a combination of existing instrumental data, available proxy records, and results from numerical models have identified a few prominent patterns of variability that occur on decadal and millennial time scales, including the "Pacific Decadal Oscillation" (see figures, courtesy of Nathan Mantua, University of Washington, Seattle). While this pattern of decadal climate variability has impacts all across the Pacific Rim, it has an unusually large expression in North America. In the western U.S. and Canada it has a significant impact on water resources, thereby affecting hydropower, agriculture, wild fires brought on by drought conditions, and biological populations including salmon. Major contributors to the U.S. CLIVAR Program include the National Science Foundation (NSF award OCE-0004049), the National Oceanic and Atmospheric Administration, the National Aeronautics and Space Administration, and the Department of Energy.





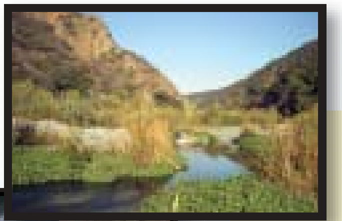
Infrastructure to Develop a Human-Environment Regional Observatory (HERO) Network, Brenton M. Yarnal, Pennsylvania State University. Researchers working on the HERO project are developing a collaboratory of scientists studying global change in far-flung places. Collaboratories go beyond email and instant messengers to include such novel ideas as web-based videoconferences, electronic Delphi tools for collective discussion and decision making, shared notebooks and data bases, and interactive maps and graphs. The images here show HERO investigators holding a meeting. Although the individuals are at the central meeting site in Pennsylvania, HERO team members from Kansas, Arizona, and Massachusetts join the discussion through a web-based videoconference. This tool makes it possible for scientists from around the world to meet routinely at nominal expense. The techniques being explored by HERO have greatly facilitated collaboration, and demonstrate the utility of this approach for researchers engaged in a broad range of topics. Photos by Chaoqing Yu, Pennsylvania State University. NSF grant SBE-9978052.

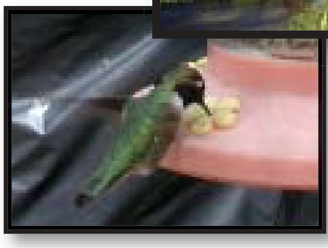
tection Agency and the Department of Energy, have research interests essential to their missions and complementary to those of NSF. In addition, they operate facilities and laboratories that are valuable centers for cooperative research and education. Strengthening and expanding ongoing relationships among agencies can help identify research gaps and needs, leading to joint research interests. Through partnerships with agencies having policy missions or management responsibilities, NSF can facilitate communication of the research findings of its grantees and speed their translation into policies and resource management.

Advances in environmental research and practice rely on experience, observations, resources, and facilities distributed around the globe. NSF should enhance support for interdisciplinary links that cross geographic boundaries. Partnerships involving developing countries can be particularly challenging and rewarding. NSF-supported projects that strengthen the capacity of researchers in other countries to participate in environmental research efforts help those countries build the capacity they need to address their own environmental problems more knowledgeably. The growth of cyberinfrastructure will make partnerships easier to sustain.

Examples of research and education areas include:

- Developing paradigms, structures, and incentives for interdisciplinary team formation, management, and assessment that are transferable across research areas and projects.
- Determining patterns and duration of financial support that are effective for interdisciplinary research and education team activities, and what steps teams can take to initiate and institutionalize these activities.
- Developing an appropriate role for NSF with respect to infrastructure for international environmental research and education activities.
- Exploring steps NSF can take to encourage interdisciplinary partnerships with sister federal agencies and with international entities.





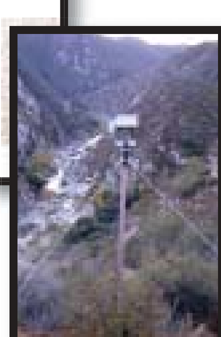
Remote Observations of the Environment

Kimberly Mann Bruch, High Performance Wireless Research and Education Network

With recent advances in wireless networking and sensor technology, we are now able to observe our environment on a continuous basis, giving us more data to understand basic ecological and Earth science processes, and providing a new infrastructure in which to conduct multidisciplinary research and make policy decisions. One example of such a multidisciplinary wireless sensor network is being developed by researchers at the University of California, San Diego. The High Performance Wireless Research and Education Network (HPWREN), continues to build its 45 megabits-per-second backbone that spans more than 2500 square miles in southern California (see figure). HPWREN links together a range of disciplines, including ecology, seismology, astronomy, and education.

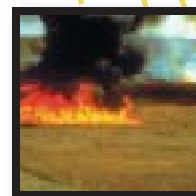
Last year, the HPWREN team connected San Diego State University's 4,344-acre Santa Margarita Ecological Reserve to their broadband network, which now allows ecologists to stream sensor data directly from the field to their campus laboratories for analysis (see photos). Water quality and hydrology sensors along the Santa Margarita Watershed allow hydrologists to remotely measure parameters such as water acidity and pressure while network-connected acoustic sensors allow biologists to track animal calls and other wildlife activity such as bat sonar—without even being at the reserve. Meanwhile, cameras at the reserve linked to HPWREN allow researchers to catch a glimpse of a biologically diverse area with mountain lions roaming, golden eagles nesting, and hummingbirds sipping nectar. These cameras deliver more than three megapixels per image, and are controlled from a remote server across the Internet. For instance, Rolf Baumberger, a biology researcher at the University of Zurich is now able to log onto his computer in Zurich, Switzerland and use the Reserve's camera stations to conduct his research on the role of hummingbirds, bees, and moths in the pollination of southern California's bush monkey flower.

HPWREN's extension of the information superhighway to the dirt road is exactly the type of infrastructure needed to support a wide range of multidisciplinary activities envisioned by the U.S. scientific research community. This kind of national broadband telecommunications network would allow for simultaneous transmission of signals (e.g., voice, data, video) so that ecologists and geoscientists around the world could easily share their field data collections with one another and also communicate their findings to the general public, students, government agencies, and policy makers. NSF grant ANI-0087344.

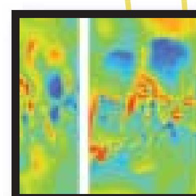


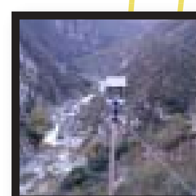
Infrastructure and Technical Capacity

Infrastructure for environmental research and education must be enhanced and expanded to address the environmental challenges of the coming decade. In fact, networks of interdependent sites linked by a common purpose and an integrated research and education strategy are needed to undertake these challenges. Answers to present and future research questions rely on the ability to carry out critical field observations at multiple temporal and spatial scales and to access the cyberinfrastructure needed to archive, mine, integrate, and interpret vast amounts of data.



Demand is increasing for faster access to data bases and models, real-time access to data from observing platforms, and remote control of complex instruments. Design of these technologies must be guided by the needs of a variety of potential users: scientists and engineers in many disciplines, educators, students, public and private-sector decision makers, policy makers, resource managers, and citizens. All of these groups are concerned about improved capability to observe, synthesize, and forecast the interactive and cumulative effects of environmental processes on humans and other living organisms as well as development of new ways to reduce environmental harm.





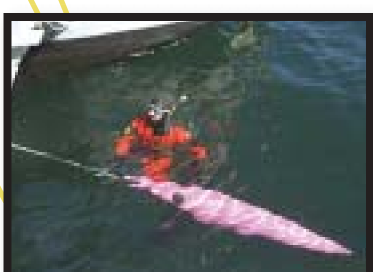
Observing Systems and Tool Development

A wide range of platforms, field sites, sampling strategies, instrumentation, telemetry, and software is needed to observe, analyze, and model environmental materials, populations and communities, and processes at multiple scales. The selection of field sites and sampling strategies requires a synthesis of the current knowledge of environments and their variability. The development of tools to investigate heterogeneous, extreme, inaccessible, or toxic environments requires coordinating advances in many fields, including microelectronics, photonics, telemetry, and robotics, in addition to physical, chemical, and biological sensing systems. New tools can also inspire advances in these fields, and together with the development of interdisciplinary teams and related tools, can accelerate the transition of methods and technologies.

The observing systems of the future will need to be highly instrumented and take advantage of sophisticated cyberinfrastructure. Fixed and mobile systems that can provide sustained time-series observations will be essential for research on phenomena ranging from earthquakes and ocean circulation patterns to changes in ecosystem and mineral resources. As autonomous, self-calibrating sensors for environmental processes of all types and scales are developed, an astounding amount of data will flow in from these sources and be added to the torrent of data received from remote sensing satellites and genetic sequencing. Much of these data will be received in real-time and, if associated with areas of potential hazard, such as fault lines, flood plains, or vulnerable ecosystems, will require near real-time analysis and distribution to decision makers.

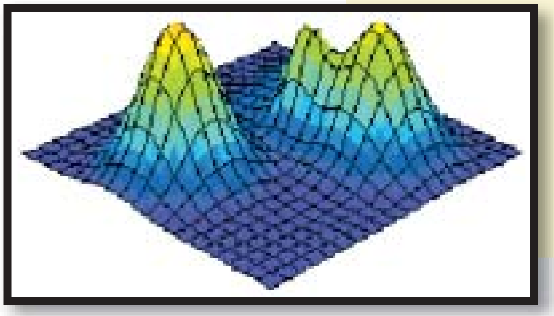
Long-term nano- to global-scale observations require sensing devices and systems that are persistent, robust, non-polluting, self-calibrating, and capable of distinguishing the desired signal from the background noise. Research on distributed, self-configuring environmental sensor networks, and the creation of standards for sensors, platforms, and user interfaces, are both critical for advancing the development of observing systems. Sensor test beds where new environmental sensor technologies and associated data or network architectures can be deployed and tested would speed progress.

New powerful and sophisticated instruments and methods are enabling identification, detection, location, and dynamics of molecular species as they move through physical systems and organisms. Genomics research is revealing the microbial ecology and biogeochemistry of complex water and soil



Autonomous Gliders Measure Ocean Parameters in Four Dimensions, Charlie Eriksen, University of Washington, and Mary Jane Perry, University of Maine. The Seaglider is one of several autonomous undersea vehicles that enable oceanographers to measure hydrographic, chemical, and biological indicators on long sections across the oceans. This particular instrument can measure about 1000 profiles from the surface to a depth of 2 km over a track of about 6000 km. Each time it surfaces it transmits its data via satellite, at which time its course can be reset. NSF grant OCE-9911037.

Measuring Chemical Air Emissions Using Environmental CAT Scanning, Lori Todd, University of North Carolina. We are developing an innovative, real-time method for measuring, visualizing, and quantifying chemical air emissions and emission rates that could be applied to volatile organic compounds, pesticides, and gases from fugitive sources such as chemical and agricultural waste lagoons, landfills, and spray fields. Using an environmental CAT (computer assisted tomography) scanning system that couples the chemical detection technology with the mapping capabilities of computer assisted tomography, we are able to generate two-dimensional pollutant concentration maps of large areas. These maps allow concentrations to be spatially resolved in real-time over large areas with far fewer measurements than conventional samplers require to obtain the same level of detail. Maps can be generated for multiple chemicals that have been measured simultaneously in air, typically at part-per-billion or part-per-million detection levels. This is important because most agricultural and industrial processes emit complex mixtures of chemicals. Two-dimensional pollutant maps are important for monitoring and reducing emissions from large non-uniform area sources that are otherwise difficult to evaluate. Accurate pollutant emission rates are crucial as input for dispersion models to estimate emissions downwind of area sources and for development of prevention and control strategies. Figure: Simulated reconstruction of a chemical in a room at three locations. The peak heights represent concentrations. The squares respresent the length and width of the room. NSF grant BES-0001385.



environments and is providing new information on the evolution of organisms that inhabit these systems. Membrane technologies, ultrahigh vacuum, and elegant laser methods are having profound impacts in areas of geology and environmental engineering where knowledge of surfaces is important. These developments have created a new challenge—to obtain molecular-scale information for important environmental processes and to connect knowledge across scales from molecular to global. For example, while the carbon cycle is known at some precision on the global scale, many molecular-scale processes that govern carbon flow are too poorly known to be accurately incorporated into the models.

In the social sciences, field-based measurements, such as household surveys and longitudinal studies, can provide important data when coupled with other forms of environmental measurement and observation. Some technical obstacles and challenges exist for this crucial merging of social and biophysical data, and certain special considerations, such as confidentiality, are unique to the collection and dissemination of social science data. Nonetheless, the linking of *in situ*, remotely sensed, social and qualitative data will be increasingly important for environmental research.

Examples of research and education areas include:

- Incorporating processes at all scales, from molecular to global, into comprehensive environmental models.
- Enabling long-term partnerships necessary to develop and sustain observing systems that provide rapid analysis and response to environmental change.
- Determining what is needed to encourage formation of collaborations between those who frame environmental questions and those who develop sophisticated tools for addressing those questions.
- Designing observing systems to accommodate new technologies while maintaining consistent time-series information.

Cyberinfrastructure

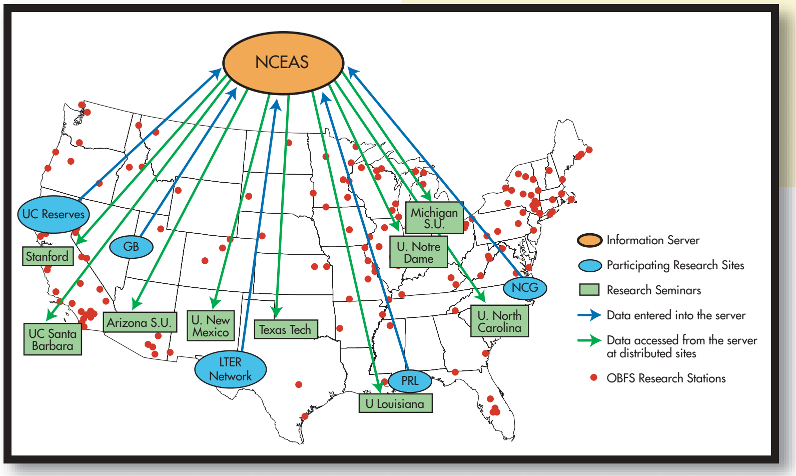
Cyberinfrastructure refers to advanced data assimilation and curation, networking, modeling, and simulation tools for large-scale, systems level, integrated applications. Cyberinfrastructure provides the capability to change data systems into knowledge systems. Nonetheless, building cyberinfrastructure is a serious undertaking on many technical, financial, and cultural levels. Progress in environmental research and the use of its results are stymied without this infrastructure. NSF, with its broad scope, should take the lead in developing this capability. New modes of support and financial incentives from research funding agencies are necessary to ensure that adequate attention is devoted to long-term data management, archiving, and access, and to education.

While computing power, storage capacity, metadata, and networking technology are needs common to many sciences, environmental research faces special challenges at both the national and international scale. Interoperability and common modeling frameworks are required to integrate contributions from many environmental communities. A unique challenge for synthetic environmental research is the integration of four-dimensional (spatio-temporal) data, digital data, and social science data to obtain a holistic view of complex Earth and human systems. Also important are the curation and mining of large and increasing volumes of environmental data, which are often heterogeneous in time, space, format, content, and location, as well as legacy data. The curation of environmental genomic data and associated metadata will become particularly critical in the future with the continuing development of large DNA sequencing facilities. Data assimilation, including networking and management of distributed, real-time, multi-scale observing systems, and decision-support systems are also needed for resource allocation, disaster management, and other societal planning.

Examples of research and education areas include:

- Developing an integrated framework and plan for interdisciplinary environmental cyberinfrastructure, including interagency and public-private partnerships that can support an extensive system.
- Fostering communication and coordination among computer scientists and environmental researchers and educators to develop this innovative, powerful, and accessible infrastructure.
- Developing the organizational structure to provide long-term support for data storage, access, model development, and services for a global clientele of researchers, educators, policy makers, environmental workforce members, and citizens.
- Developing centers for genomic data storage and bioinformatics that allow the incorporation of relevant environmental metadata.

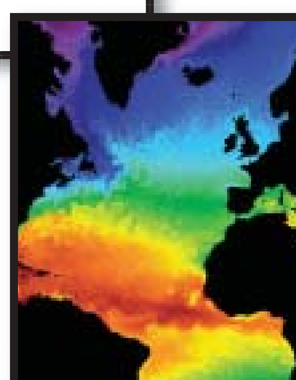
Disentangling Biological Complexity Through Knowledge Networking, Sandy J. Andelman and Melinda Smith, University of California, Santa Barbara. Biocomplexity, an emergent property of living systems, arises from interactions among living organisms and the environment at all levels of biological organization. Understanding biocomplexity and other dimensions of ecological systems necessitates a holistic approach that can be achieved only by identifying, retrieving, and synthesizing diverse data from distributed sources and by collaboration among scientists from a broad range of disciplines, investigating many different systems. The Knowledge Network for Biocomplexity (KNB), a research collaboration among the National Center for Ecological Analysis & Synthesis (NCEAS), the Long-Term Ecological Research (LTER) Network Office, the San Diego Supercomputer Center, and Texas Tech University is developing new software tools required to advance ecological understanding through discovery, access, retrieval, and management of distributed and heterogeneous ecological and environmental data. In addition, NCEAS is training a cadre of young investigators in cutting-edge techniques for management and analysis of ecological data, with particular emphasis on multi-scale integration and synthesis. The training model involves a series of distributed graduate seminars conducted simultaneously at multiple universities around the country. Students and faculty participants at each institution collaborate using KNB software tools to investigate questions related to the importance of spatial and temporal scale in understanding the relationship between biodiversity and ecosystem function. At strategic points during the course, students travel to NCEAS to participate in cross-site syntheses. The result of this distinctive training effort will be the generation of a cohort of young investigators well versed in ecological knowledge networking tools and collaborative approaches to multi-scale, interdisciplinary biocomplexity research. NSF grant DEB-9980154.



Experiments, Models, and Their Integration

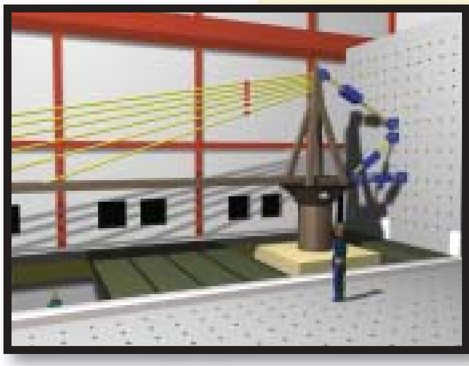
Interdisciplinary environmental research and education relies on the balance and integration of experimentation, observations, synthesis, and modeling. Experimentation in laboratory settings is of critical importance, as are field experiments that include not only observations and surveys, but also manipulations at small and large scales. Experiments can reduce uncertainty, provide data, and explore relationships that observation of chance events would not reveal. For example, investigating the effect of increased concentrations of carbon dioxide on plant or microbial diversity, or the effect of changes in nutrient concentrations on plankton growth, requires the manipulation of large plots of land or volumes of water.

Long-term investigations of ecosystems sometimes require protection of plots from other uses for extended periods. Some universities have set aside land for such experiments, but in other cases new partnerships with governmental and non-governmental land management entities, such as the National Park Service and the Departments of Energy and Defense, may be needed to advance learning about ecosystem functioning and responses to various environmental stressors. Other studies, such as sensor development and manufacturing process design, also depend on physical sites for experimentation and testing.



Ocean Turbulence: From Centimeter Salt Fingers to Planetary Gyres, W. Large, F. Bryan, R. Kerr, E. Saiki and J. Tribbia, National Center for Atmospheric Research. The oceans are a very effective thermal regulator of the climate system because they can store heat from seasons to centuries. The greatest challenge to understanding and predicting the ocean's influence on our changing climate is that the important turbulent processes span a very large range of space scales and interact in complex ways. The largest scales are illustrated in the model result shown in the bottom figure (Smith, R., M. Maltrud, F. Bryan and M. Hecht, 2000, *J. Phys. Oceanogr.*, 30, 1532-1561). Visible in the instantaneous sea surface temperature are non-linear, turbulent meanders in the Gulf Stream, a key link in the gyre circulation. Also evident at the 10-50 km scale are ocean mesoscale eddies, a ubiquitous feature of the ocean, but which have an as yet unknown role in Earth's climate. At the small end of the spectrum are centimeter-scale salt fingers, shown in the model result in the upper figure. These tiny features are known to release potential energy stored in an unstable salt gradient to small-scale turbulent convection, which is known to efficiently transport heat and salt in the vertical. However, the importance of this process to the ocean's global heat budget and climate is not yet understood. The major difficulty in making such assessments is that the computational demands of a comprehensive model encompassing this range of scales is far beyond foreseeable capabilities. NSF grant ATM-9820037.

Large-Scale, High Performance Earthquake Engineering Testing Facility, Michel Bruneau, Andrei Reinhorn, Michael Constantinou, Theva Thevanayagam, Andrew Whittaker, University at Buffalo. The University at Buffalo's (UB) Structural Engineering and Earthquake Simulation Laboratory will be a key node in a nationwide earthquake engineering "collaboratory"—the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES). In this network, earthquake engineers and students located at different institutions will be able to share resources, collaborate on testing, and exploit new computational technologies. The goal of UB's NEES node project is to develop the most versatile earthquake engineering research facility possible, providing testing capabilities that will revolutionize the understanding of how very large structures react to a wide range of seismic activity, even when tested to complete failure. One new technique UB will explore is called real-time dynamic hybrid testing in which shake table and/or dynamic force experiments on substructures are combined in real time with computer simulations of the remainder of the structure. This will provide a more complete picture of how earthquakes would affect large structures without the need to physically test the entire structure. NSF grants CMS-0086611 and CMS-0086612.



Understanding complex human and natural systems increases the demand for development of sophisticated interdisciplinary conceptual, mathematical, statistical, and computational models that can represent the non-linearity and feedbacks encountered in these systems, ingest environmental data for initialization or assessment, and integrate multiple components across multiple time and space scales. These models provide critical information needed to guide research and inform policy development and environmental management. At the same time, experiments provide data essential for ground-truthing and refining models, particularly those involving coupled human and natural systems. The limits of certainty and the ability to generalize predictive models also need to be better understood and better communicated. Information networks developed and maintained as part of the environmental cyberinfrastructure will become virtual repositories for models as well as data. Experiments with various decision-making and implementation strategies would also yield new insights into complex systems and feedbacks. Further development of these approaches to scientific discovery will require consideration of new means to provide long-term financial support and management.

Examples of research and education areas include:

- Improving modeling of complex systems through measurements obtained in experiments at appropriate duration and scales, from laboratory to field level, and developing statistical and probabilistic tools for the validation of complex computer models.
- Determining the utility and benefits of setting aside and maintaining a geographical area for long-term research, given increasing demand for other uses.
- Solving mathematical and computational problems necessary to develop more effective climate, ecosystem, and institutional and behavioral models, including those that cross a range of spatial and temporal scales.
- Estimating, understanding, and balancing the potential risks and benefits involved in large-scale, manipulative experiments.

Long-Term Archives and Centers

Interdisciplinary work on dynamic environmental processes, some of which take place over long time scales, requires consideration of a vast amount of data generated by many disciplines, including legacy data, and maintenance of newly developed information. For example, ice cores, paleo data, and satellite images, properly archived, are invaluable in answering scientific questions that have emerged since these data were collected. These great infrastructure needs raise concerns about conversion and cataloguing of existing data as well as development and long-term maintenance of local, national, and international digital databases and libraries. What will the nature of future knowledge repositories be? For instance, will there be an integrated set of sites that serve as virtual repositories, with a unified database structure that allows for standardized input and capacity to test and validate new data? These archives could be designed to facilitate inter- and intra-site queries and new developments in data mining. Modular and open architecture could allow optimization and modification by a large number of users.

The need for existing field stations, museums, and repositories will continue. In addition, these institutions will need to be enhanced to become part of larger organizations that support the field stations and networks, marine laboratories, and expeditionary facilities of the future. Scientists, engineers, data managers, computer and information experts, resource managers, and decision makers at all levels will be engaged in solving common problems. In the process they need to develop a language and culture that adds value to cyberinfrastructure. These collaborations can combine information from ecological, genomic, taxonomic, climate, geographic, demographic, and museum collections and lead to significant advances in understanding emerging diseases, exotic species, ecological restoration, and many other environmental questions.

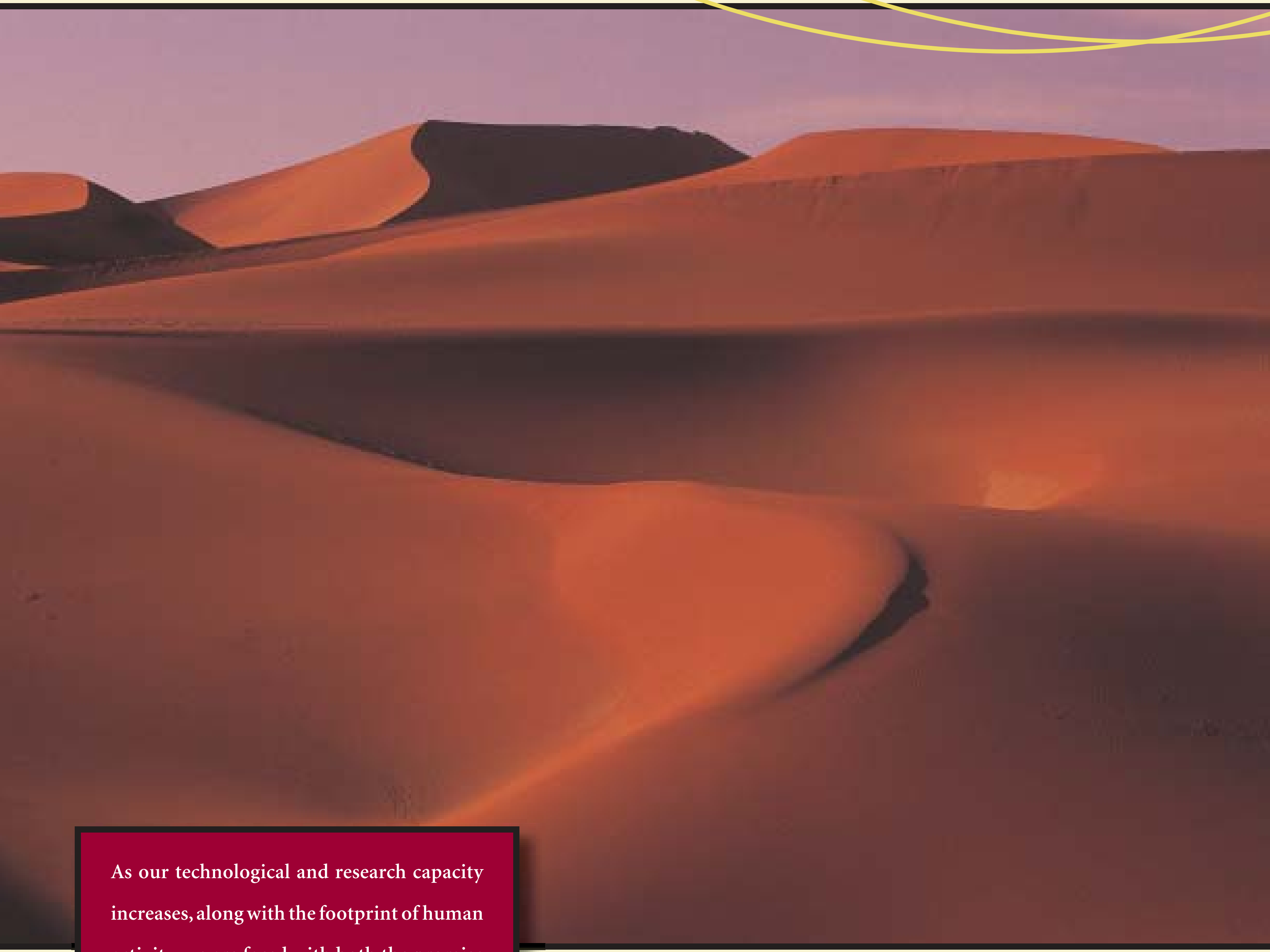
Approaching research with an emphasis on synthesis requires understanding environmental systems at regional and "place-based" scales. Place-based scales are those scales of analyses that are determined by the location of the research and not by some universally applicable standard or norm. Research at place-based scales includes developing questions in consultation with policy makers and the public, maintaining long-term observations, and providing opportunities for meaningful hands-on learning and outreach. Studies at this scale are important for refining models as well as understanding how systems adapt to stress.

International Long-Term Ecological Research Network. The Long Term Ecological Research (LTER) network is a collaborative effort involving more than 1100 scientists and students investigating ecological processes over long temporal and broad spatial scales. The network promotes synthesis and comparative research across sites and ecosystems and among other related national and international research programs. The LTER network offers the broader environmental biology research community, including students and foreign scientists, the opportunity to use the sites for both long- and short-term projects appropriate to individual sites, a group of sites, or the network as a whole. As of May 2002, 25 countries have established formal national LTER programs and joined the ILTER network. Top: Prescribed fires in the Konza tallgrass prairie LTER site. Bottom: Near the Fushan Forest Field Station, ILAN, Taiwan. NSF grant DEB-9634135.

Some regional centers that have been established to support long-term, multidisciplinary research and education and the associated community partnerships necessary for environmental synthesis work may serve as models. It is foreseen that regional nodes will develop to support virtual networks among national and international institutions. These networks should pursue particular research questions consistent with their various capacities and interests, thus fostering understanding of natural processes and enabling the creation of new technologies to protect and improve the environment. They would also foster collaborative training and outreach activities among institutions, including those in the private sector, to provide the best information available to aid decision-making processes.

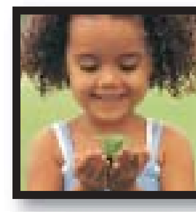
Examples of research and education areas include:

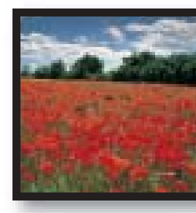
- Determining the design features of long-term digital repositories for environmental data and the appropriate structure for and functions of a system of digital repositories.
- Understanding what resources are needed for ongoing support of archives and repositories, and the appropriate NSF contribution to this area.
- Determining the appropriate roles for NSF to play in supporting regional centers for environmental data, research, and education, that may involve activities outside of NSF's purview, such as policy making, monitoring, and long-term local resource management.
- Developing creative approaches, support mechanisms, and rewards to encourage synthesis research, including establishing teams, centers, meta-analysis, and the synthesis of information for decision makers.



As our technological and research capacity increases, along with the footprint of human activity, we are faced with both the promise of understanding the environment and our relationship to it, and the responsibility of making wise decisions about the design and use of technology and about managing the complex relationships among people, ecosystems, and planetary processes.

Conclusion





This Outlook developed by the AC-ERE recommends major directions in interdisciplinary environmental research and education that NSF should follow over the next decade (2003-2012). If these research directions are adequately funded and supported, and productive research is carried out, we will be able to significantly expand our base of knowledge and synthesis of environmental systems and technologies. These investments in people, ideas, and tools, when combined with the efforts of NSF's many partners, can provide solutions to some of today's environmental problems and enable continued growth in our capability to respond to new challenges. There will always be a new scientific and engineering frontier, but this Outlook will move us toward the goal of achieving long-term environmental robustness, health, and well-being.

To move ahead in this decade, environmental researchers need clearly articulated programs with sufficient long-term funding horizons so they can incorporate interdisciplinary approaches and address complex environmental questions and problems. Programs must respond to the needs of individuals, small groups, and large groups, as well as collaborations within and among institutions. It often takes several years for interdisciplinary teams to learn how to work together, make progress in innovative directions, and synthesize the results. The need for long-term funding is therefore particularly acute for environmental research and education.

The first years of the 21st century are already presenting serious environmental challenges, including climate change and an array of biological threats. As our technological and research capacity increases, along with the footprint of human activity, we are faced with both the promise of understanding the environment and our relationship to it, and the responsibility of making wise decisions about the design and use of technology and about managing the complex relationships among people, ecosystems, and planetary processes. In this exciting and productive next decade, environmental research and education will be critical for local, national, and global security, health, and prosperity.

References

Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change (U.S. Global Change Research Program, 2001).

Environmental Science and Engineering for the 21st Century (National Science Board, 2000).

Expanding the Human Frontiers of Science: Bringing Minority-Serving Institutions into the Mainstream (National Science Foundation, 2001).

Grand Challenges in Environmental Sciences (National Research Council, 2001).

In Pursuit of a Diverse Science, Technology, Engineering and Mathematics Workforce (American Association for the Advancement of Science, 2001).

Nature and Society: An Imperative for Integrated Environmental Research (lsweb.la.asu.edu/akinzig/report.htm, 2001).

NSF Geosciences Beyond 2000: Understanding and Predicting Earth's Environment and Habitability (National Science Foundation, 2000).

Our Common Journey: A Transition to Sustainability (National Research Council, 1999).

The State of the Nation's Ecosystems: Measuring the Lands, Waters, and Living Resources of the United States (The H. John Heinz III Center for Science, Economics, and the Environment, 2002).

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

Women, Minorities, and Persons With Disabilities in Science and Engineering (National Science Foundation, 2000).

Nobel Prize for Environment-Relevant Economics, Daniel Kahneman, Princeton University, and Vernon L. Smith, George Mason University, shared the 2002 Nobel Prize in Economics. Kahneman (left), who has been supported by NSF for many years, was honored "for having integrated insights from psychological research into economic science, especially concerning human judgment and decision-making under uncertainty." His research (much of which was done with the late Amos Tversky of Stanford University) shows that individuals evaluate decisions in terms of gains and losses from a reference point (typically, the status quo). These results conflict with standard economic models that assume people evaluate decisions in terms of their impact on total wealth. Moreover, most individuals are more averse to losses than they are partial to gains of the same size. Loss aversion is one source of the discrepancy between "willingness-to-pay" and "willingness-to-accept" methods of valuing environmental goods. NSF grant SES-0214411.

Sources of Public Comment

The AC-ERE invited 62 professional societies and groups to a briefing at NSF on July 24, 2002. Those able to attend are listed below.

- American Anthropological Association (AAA), Amy Beckrich, Government Relations Department
- American Association for the Advancement of Science (AAAS), Richard Weibl, U.S. Editor, "Science's Next Wave" and Connie Bertka, Project Director, DoSER
- American Chemical Society (ACS), Raymond Garant, ACS Liaison, Committee on Environmental Improvement
- American Institute of Biological Sciences (AIBS), Jeffrey Goldman
- American Society of Limnology & Oceanography (ASLO), Adrienne Froelich, Director of Public Policy
- American Society for Microbiology (ASM), Ted Cartwright, Manager, Public Affairs
- Association of American Geographers (AAG), Douglas Richardson, Director, Division of Research & Strategic Initiatives
- Association of Environmental Engineering & Science Professors (AEESP), Michael Aitken, President
- Consortium of Oceanographic Research & Education (CORE), Ronald O'Dor, Census of Marine Life Senior Scientist and Thomas Jones, Deputy Director of External Relations
- Council on Undergraduate Research (CUR), Emily Leary, Membership Coordinator
- Earth Force, Laurie Perry, Director of Development
- Ecological Society of America (ESA), Jason Taylor, Director of Education
- Estuarine Research Federation (ERF), Linda Schaffner, President
- Material Research Society (MRS), Marilee Mayo, MRS President-Elect
- National Council for Science & the Environment (NCSE), Daniel Braden, Outreach Assistant, David Blockstein, Senior Scientist, and Craig Schiffries, Senior Scientist
- Project Kaleidoscope (PKAL), Lisa B. Lewis, Scientist-in-Residence
- Society of Toxicology (SOT) Toxicology Education Foundation, Betty J. Eidemiller, Director of Education and Membership
- The H. John Heinz III Center for Science, Economics & the Environment, Kent Cavender-Bares, Fellow & Research Associate
- World Wildlife Fund (WWF), Judy Braus, Environmental Education

A draft ERE Outlook was posted on the web for comment June 10-August 10, 2002. The respondees are listed below.

- Alma Aguirre, Thomas Jefferson High School, San Antonio Independent School District
- Aldo Leopold Wilderness Research Institute, Kari Gunderson, Janet Hering, P. Dee Boersma, Ruth De, Anne Giblin, Robyn Hannigan, Robert W. Howarth, Ann P. Kinzig, Emir Macari, Brenda L. Norcross, Sandra Shumway, Peter Whiting, Susan Williams
- Kingsley Allan, Illinois State Water Survey
- Dennis M. Allen, Estuarine Research Federation
- American Anthropological Association, Mary Margaret (Peggy) Overbey, Pete Brosius, David Guillett, Kendall Thu, Michael Paolisso

- American Society for Microbiology, James Tiedje
- American Society of Limnology and Oceanography, Education and Human Resources Committee, Wayne Wartsbaugh, Jonathan Cole
- Warren Aney, Resources Northwest Consultants
- Peter Arzberger, University of California San Diego
- Association of Environmental Engineering and Science Professors; Morton Barlaz
- Robert Baier, University at Buffalo
- Mark Bain, Cornell University
- Roger Bales, University of Arizona
- Julia Bartkowiak, Clarion University of Pennsylvania
- Richard Bartlett, Mary Kay, Inc.
- Archie Beaton, Impact Environmental Education
- Sarah Bednarz, Texas A&M University
- David Blockstein, National Council for Science and the Environment
- Grady Price Blount, Texas A&M University, Corpus Christi
- Dee Boersma, University of Washington
- Mitch Boretz, University of California Riverside, College of Engineering, Center for Environmental Research and Technology
- Joceline Boucher, Maine Maritime Academy
- Susan Brandon, American Psychological Association
- Ed Brown, University of Northern Iowa
- Paul Buck, Desert Research Institute
- Pam Camblin, Poquoson Elementary School
- Keith Clarke, University of California Santa Barbara
- Neil Cobb, Merriam-Powell Center for Environmental Research
- Jonathan Cole, Institute of Ecosystem Studies
- Mary A. Coleman, Overbrook High School Earth Force
- John Cook, The Environmental Careers Organization
- Bruce Coull, University of South Carolina
- Council of Environmental Deans and Directors, Anthony Michaels
- Council on Undergraduate Research, Mitchell Malachowski
- Kevin Coyle, National Environmental Education and Training Foundation
- Ed Curley, Pima County Wastewater Management
- Richard Dame, Coastal Carolina University
- Ruth DeFries, University of Maryland
- R. Ford Denison, University of California
- John Dennis, National Park Service
- David Dow, National Oceanographic and Atmospheric Administration/National Marine Fisheries Service/ Northeast Fisheries Science Center, Woods Hole Lab
- Laura Downey, Kansas Association for Conservation and Environmental Education
- Jenny Eckman, Tri-District Community Cultures/Environmental Science Elementary School
- Ecological Society of America, George Middendorf, Leanne Jablonski
- Ecological Society of America's Research Committee, James Clark, Nany Grimm, Ann Kinzig, Matthew Liebold, Mary Power
- John Ehrenfeld, International Society for Industrial Ecology
- Alan Ek, National Association of Professional Forestry Schools and Colleges
- Robert Engelman, Population Action International
- Paul Epstein, Harvard Medical School Center for Health and the Global Environment

- Ann Fisher, Pennsylvania State University
- Dana Fisher, Department of Sociology and Columbia Earth Institute, Columbia University
- David Flemer, Environmental Protection Agency Office of Water Health and Ecological Criteria Division
- Allan M. Ford, ACS Division of Environmental Chemistry
- Barry Fox, Cooperative Extension
- James Galloway, University of Virginia
- Marc Giaccardo, Texas Tech University
- Sally Goerner, Triangle Center for the Study of Complex Systems
- Ellen Goldberg, Sante Fe Institute
- Greg Greenwood, California Resources Agency
- Nancy Grimm, Arizona State University
- Andrew Groover, Institute of Forest Genetics
- Charles Hall, State University of New York Environmental Science and Forestry
- Lawrence Hamilton, University of New Hampshire
- Royce Hanson, Center for Urban Environmental Research and Education, University of Maryland, Baltimore County
- Earl R Heithaus, Kenyon College
- Janet Hering, California Institute of Technology
- Elaine Hoagland, Council on Undergraduate Research
- Judy Hoff, State Arboretum of Virginia
- Institute of Ecosystem Studies, Gene Likens, Jonathon Cole, Michael Pace
- Institute for Development Anthropology, Chika Watanabe
- Stephen T. Jackson, University of Wyoming
- Stephen Jordan, Sarbanes Cooperative Oxford Laboratory
- Peter Jumars, University of Maine
- Brian Keller, National Oceanographic and Atmospheric Administration/Florida Keys National Marine Sanctuary
- Diana King, National Audubon Society
- Ann Kinzig, Arizona State University
- Crystal Kirmiz, University of California Davis
- Megan Knight, California Institute of Technology
- Jason Link, National Oceanographic and Atmospheric Administration/National Marine Fisheries Service/Northeast Fisheries Science Center
- Steve Lohse, Consultative Group to Assist the Poorest
- Mingming Lu, University of Cincinnati
- Loren Lutzenhiser, Environment and Technology Section, American Sociological Association
- Walter Lyon, University of Pennsylvania
- Thomas Malone, University of Maryland Center for Environmental Science
- Todd Marse, University of New Orleans
- William Martin, Eastern Kentucky University
- Anne Meltzer, Lehigh University
- Judy Meyer, University of Georgia
- Robert Miller, University of Massachusetts Boston
- Steve Miller, Great Bay National Estuarine Research Reserve
- Peter Milne, National Science Foundation
- Ronald Mitchell, University of Oregon, Department of Political Science
- Janice Monk, University of Arizona

- Teresa Mourad, Environmental Education Council of Ohio
- National Association of Professional Forestry Schools and Colleges, C. Patrick Reid
- North American Association for Environmental Education, David Wicks
- Philip Nyhus, Franklin and Marshall College
- Robert Oddo, Horace Greeley High School
- Carolyn Olson, U.S. Department of Agriculture, National Resources Conservation Service
- Marcie Oltman, Minnesota Children's Museum
- Hans Paerl, University of North Carolina, Charleston, Institute of Marine Sciences
- Michael Paolisso, University of Maryland, Department of Anthropology
- Simon Peacock, Arizona State University, Department of Geological Sciences
- Nancy Rabalais, Louisiana Universities Marine Consortium
- Mary Jo Richardson, Texas A&M University
- Ronald Rindfuss, University of North Carolina
- GP Robertson, Michigan State University
- William Robertson, The Andrew W. Mellon Foundation
- Andrew Rorick, United States Department of Agriculture Forest Service
- April Rust, Minnesota Department of Natural Resources
- Joseph Salah, Massachusetts Institute of Technology
- Mary Santelmann, Oregon State University
- Dawn Shank, Virginia Department of Conservation and Recreation
- Sarah Simon, Shaw Environmental and Infrastructure
- Daniel Sivek, University of Wisconsin, Stevens Point
- Jan Peter Smith, Massachusetts Bays National Estuary Program
- V. Kerry Smith, North Carolina State University
- Alan Steinman, Grand Valley State University, Annis Water Resources Institute
- Patrick Stewart, Arkansas State University
- Geoffrey Swain, Florida Institute of Technology
- Jim Taylor, City of Thousand Oaks
- Nancy Trautmann, Cornell University
- Michael Turelli, University of California, Davis, Section of Evolution and Ecology
- Julian Tyson, University of Massachusetts, Amherst
- Bob Vargo, University of Pennsylvania
- Robert Vincent, Bowling Green State University, Department of Geology
- Kerstin Wasson, University of California, Santa Cruz
- Judith Weis, Rutgers University
- Paul Wennberg, California Institute of Technology
- Anthony Wexler, University of California, Davis
- Susan Williams, University of California, Davis, Bodega Marine Lab
- Wayne Wurtsbaugh, Utah State University
- Xubin Zeng, University of Arizona

The NSF Environmental Research and Education Portfolio

Environmental challenges are often exceedingly complex, requiring strengthened disciplinary inquiry as well as broadly interdisciplinary approaches that draw upon, integrate, and invigorate virtually all fields of science and engineering.

National Science Board, Environmental Science and Engineering for the 21st Century, p. xi.

The National Science Foundation (NSF) was established by Congress in 1950 "to promote the progress of science: to advance the national health, prosperity and well-being; to secure the national defense; and for other purposes." NSF's current activities related to environmental research and education (ERE) respond directly to these national goals. As the largest federal supporter of environmental research and education in academe and one of the major federal supporters of all such research, NSF promotes research necessary for improved understanding of complex environmental and global change processes at multiple scales.

NSF activities related to ERE involve support of basic disciplinary research, focused interdisciplinary research, and a broad range of educational, international, and outreach functions that cut across the entire spectrum of scientific, technological, and educational interests related to the environment. Each of NSF's research directorates and its education directorate support a wide array of research and education about the environment as well as participate in agency-wide initiatives focused on the interdisciplinary aspects of ERE. Certain environmental research activities are also managed as partnerships between agencies.

Disciplinary-Based Research. Much of NSF's support for environmental research is focused on understanding fundamental processes involved in physical, biological, and human system interactions. Examples include research in the areas of ecosystem dynamics, cell function, atmospheric chemistry, biogeochemical cycles, political or economic institutional processes, coastal ocean processes, population biology and physiological ecology, Earth system history, solar influences, and interactions responsible for the ozone hole.

NSF also supports research activities across all scientific and engineering disciplines to address issues related to the preservation, management, and enhancement of the environment. Areas of interest include air and water quality, biodiversity, environmental technology, natural disaster reduction, water and watersheds research, and risk assessment.

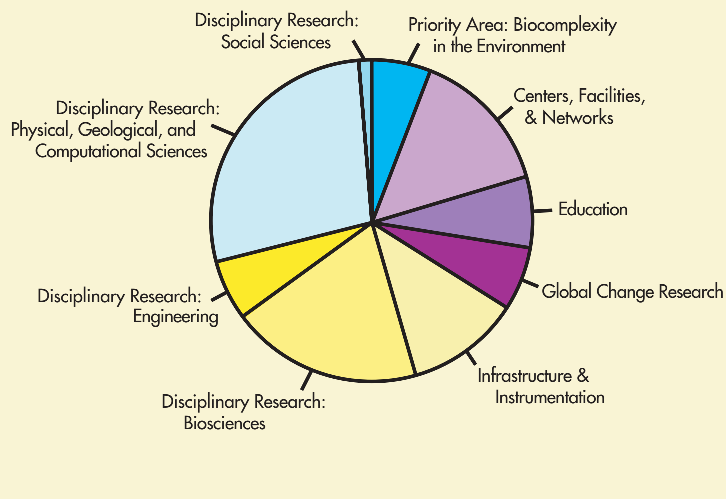
Environmental Education. A cornerstone of NSF programs is the integration of research and education. Most research projects have educational components targeted at students and teachers at all levels and the general public. In addition, NSF supports many programs whose central focus is education. Examples of those that have an environmental concentration include the Integrative Graduate Education and Research Traineeship program, the Math and Science Partnership program, the Digital Libraries Initiative, and the Course, Curriculum, and Laboratory Improvement program.

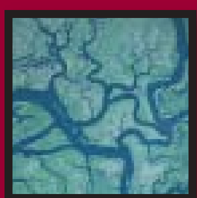
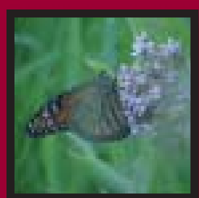
Environmental Infrastructure. NSF supports environmental research and education through centers, facilities, and networks. Examples include the Long-Term Ecological Research Network, a collaborative effort of scientists and students investigating ecological processes over long temporal and broad spatial scales; Environmental Molecular Science Institutes that focus on understanding the relationship of molecular scale phenomena in chemistry and geochemistry, and on the prevention and amelioration of environmental problems caused by societal activities that are energy- and pollution-intensive; and Science and Technology Centers such as the NSF STC for Environmentally Responsible Solvents and Processes.

Global Change Research. NSF has been one of the major participants in interagency climate research, including the U.S. Global Change Research Program. Support includes research on climate processes and interactions, and seasonal to interannual variability; monitoring and research on ozone depletion and ultraviolet (UV) radiation; oceanic, atmospheric, vegetative, biodiversity, genomics, economic, and human dimensions of global change, including research on social dynamics, human interactions, and influences, as well as research on policy sciences and options for responding to environmental change.

NSF Priority Area. The current centerpiece of NSF's environmental research and education portfolio is the cross-agency program—Biocomplexity in the Environment. This program is a multi-year effort designed to enhance understanding of the dynamics of complex environmental systems. Research thrusts include coupled natural and human systems, coupled biogeochemical cycles, genome-enabled science and engineering, instrumentation development for environmental activities, and materials use in science, engineering, and society.

Distribution of NSF Environmental Research and Education Funding in FY 2002 ($825 M)



www.nsf.gov/ere

Sponsored by the National Science Foundation through an award to the University Corporation for Atmospheric Research.

Editing and design by Geosciences Professional Services, Inc.

January 2003