A 10-Year Agenda for Environmental Research and Education at NSF: *Draft for Community Comment*

National Science Foundation
June 2002

Dear Colleagues:

On behalf of the NSF Advisory Committee on Environmental Research and Education (AC-ERE), we invite you to review and comment on the agenda for environmental research and education we are preparing to recommend to the National Science Foundation later this year. In preparing this agenda, we are assuming a 10-year horizon and focusing on interdisciplinary areas. Disciplinary environmental research continues to be an important part of the NSF portfolio and is guided by many different NSF Advisory Committees. The AC-ERE directs its attention primarily to those environmental activities that cross NSF's organizational boundaries or that support NSF's entire environmental portfolio.

In developing the agenda, we have taken into account many community reports in environmental research areas issued in the last five years. We were particularly aware of the advice of the National Science Board (*Environmental Science and Engineering for the 21st Century*, 2000) and the National Research Council (*Grand Challenges in the Environmental Sciences*, 2001). The NSB report gave overall guidance to the NSF, but not address specific programs. The NRC report outlined major challenges to be accomplished by all research agencies. Although these challenges will be addressed by collaborations among federal agencies, this new report will provide programmatic guidance specifically aligned with NSF's mission.

This is an agenda rather than an implementation plan. It does not provide a timetable, suggest budgetary priorities, or identify specific research projects. Rather it attempts to integrate a large and thoughtful body of community-generated recommendations and identify areas of opportunity for NSF research and education efforts. These opportunities were selected on the basis of their timeliness and feasibility, their compelling intellectual character, and their importance to the progress of knowledge and of society. What will follow this agenda depends on specific community advice in the areas identified in the report and consideration by NSF of how best to implement the advice in new or existing programs, taking into consideration available funds and readiness of the community.

Please enter your comments in the form provided on the NSF website (http://www.nsf.gov/ere), using the pull-down menu to match your remarks with various sections of the draft document. This will help us sort your comments for review by the Advisory Committee. We will not be able to incorporate every suggested change, but we will give them all serious consideration.

The comment period will end on August 10, 2002. Your comments will be treated as confidential advice to the Committee, and will be available only to the Committee and NSF staff who are working with us. We will not quote you in the report without your permission. A list of respondents will be prepared and publicly available, but comments will not be attributed or linked with their authors.

The final draft will be enhanced by inclusion of "sidebars" or "boxes" that briefly describe and illustrate some of NSF's present and past activities in environmental research and education. These "sidebars" will help to clarify the content of the NSF environmental portfolio and demonstrate some of the future challenges. If you have suggestions for material or topics for these "sidebars" please include them in your feedback.

We appreciate your help in making the 10-year agenda a representative and comprehensive expression of the advice of the science and engineering community.

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Chair, NSF Advisory Committee on Environmental Research and Education

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(NSF Advisory Committee on Environmental Research and Education)

(inside front cover)

About the Advisory Committee for Environmental Research and Education (AC-ERE)

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

- Provide advice, recommendations and oversight concerning support for the 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 the 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.

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PREFACE

This NSF Advisory Committee document contains the recommendations of the Committee regarding the direction of environmental research and education at the National Science Foundation during 2003-2012. NSF is one of several government agencies that together provide the federal research funds for environmental research and education. This document addresses the particular NSF contribution to fundamental environmental research, but with the recognition that agencies often work in collaboration to support and manage complex environmental research.

During the two years of preparation of this Agenda and a public comment period, the Advisory Committee consulted with professional societies and individual scientists and researchers (list to be added). The plan also responds to and incorporates where appropriate the recommendations for interdisciplinary environmental research contained in several recent reports produced by the science, engineering and educational community, particularly *Environmental Science and Engineering for the 21st Century* (National Science Board) and *Grand Challenges in Environmental Sciences* (National Research Council).

Building on the foundation provided by these reports and comments, this plan identifies major challenges that should be addressed within this decade. It suggests a specific agenda for the interdisciplinary environmental research and education that NSF is uniquely poised to carry out. During the next ten years, the Committee may issue periodic updates and progress reports.

INTRODUCTION

The most challenging scientific and engineering problems we face at the beginning of the 21st century are environmental, including rapid climate and ecological change, the degradation of freshwater resources, the globalization of disease, the threat of biological 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 has a significant impact on nearly all of the environmental systems on the planet. Increasingly, we are becoming the designers and managers of the complex relationships among people, ecosystems and the biosphere. Human and environmental health are often 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 imagery, 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, the necessity to move beyond disciplinary boundaries, and even the prospect of developing entirely new methodologies and fields of knowledge. These new capabilities have expanded the horizons of what we can study and understand about the environment, including the terrestrial, aquatic, marine and sedimentary environments, the atmosphere, and near-Earth environments in space. New and developing tools are allowing us to answer 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 challenges for the present and future include connecting across disciplines, connecting across scales, supporting synthesis studies and activities, and linking science and decisionmaking.

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 necessary to support and enhance this education, are the foundation for a creative, diverse, and adaptable environmental workforce, including scientists, engineers, teachers, technicians and an informed public. Environmental education should also produce researchers who can work in an interdisciplinary environment where results can have more 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 decisionmakers 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, 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 maintain and improve the robustness, health and well-being of environmental systems. These qualities are related and interwoven, 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 between human health and the health of other species, and more broadly, ecosystems. Infectious diseases, contaminated water, environmental disruptors, 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 primary 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 human economic and social systems. Understanding 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 important research priorities that advance scientific and engineering understanding, strengthen environmental institutions, and provide critical information for policy-makers and citizens.

One of the keys to understanding, maintaining and improving environmental robustness, health, and well-being is to strengthen the linkage and interaction between scientific knowledge 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 interwoven 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. Another set of challenges includes the design of processes and creation of systems that are as environmentally benign as possible and the development of technological and policy solutions for the prevention and mitigation of human-related adverse impacts.

Synthesis: Environmental Science and Engineering at the Frontier

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

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 and adaptation. Integrated models of environmental systems require the incorporation 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 and development of the theory, methods and research framework to work across scales, a research framework sectors, and disciplines.

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 issue or region under study and generate an associated set of research, education and outreach materials.

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 scientific conclusions. In this non-traditional area of scientific 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 tools for scientists, engineers, policy-makers, educators, students and the general public.

ENVIRONMENTAL RESEARCH FRONTIERS: 2003-2012

In order to advance the fundamental scientific knowledge necessary to address critical environmental challenges, the Advisory Committee recommends increased attention in three 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.

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 use of diverse data sets and approaches. These significant challenges must be met in order to achieve the purposes of environmental research: to discover and understand natural phenomena and processes, to develop new practices for preservation and use of environmental resources and services, and to understand human behavior and decisions with respect to environment and resources.

(A) Coupled Human and Natural Systems

This research area focuses on complex interactions among human and natural systems at diverse scales. The focal questions are how people use the environment, how this use changes the environment, and how the resultant environmental changes affect people. Coupled human and natural systems research seeks to understand the complex web of environmental feedbacks.

The topic builds on several existing disciplines and tools, including geography, demography, civil and environmental engineering, sociology, population ecology, ecosystem ecology, genomics, hydrology, and oceanic and atmospheric systems science. The integration of these tools and disciplines leads to new research questions that cannot be answered by discipline-based inquiry.

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

1) Land, Resources and the Built Environment

Humans are major forces and conscious architects of urban, rural, natural and protected ecosystems - terrestrial, coastal and aquatic. The natural environment is modified by physical processes (hurricanes, precipitation, etc.), by activities of plants, animals and people (shading, grazing, mining, damming, etc.), and by chemical processes (oxidation, reduction, acidification, etc.). The forces influencing the dynamics of human resource use 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 and reuse of resources, and the design of long-term strategies, require a comprehensive understanding of the systems and their problems, and new and appropriate technologies and solutions. Projected population growth, migration and development will increase the extent and complexity of the co-evolution between human and natural systems. Therefore, understanding the complex relationships between human and natural systems as they relate to land and resource use is of critical importance.

Examples of relevant research questions include:

- How can population, ecosystem and socioeconomic models be integrated to improve understanding of landscape fragmentation, including how coupled human and natural landscapes function?
- How do development processes and urbanization patterns affect water and resource use and nutrient distribution, and what are the effects of different engineering and policy options?
- What new engineering principles can inform the design and re-design of areas to minimize impacts of cars, roads, industries and other human activities on ecosystems and species?
- How will coastal human and natural systems respond to climate variability and change, and can dynamic spatial simulation techniques be developed to model the response of these systems?

2) Human Health and the Environment

Emerging infectious diseases, agents that alter ecosystem processes, invasive species, spread of regional and global contaminants, and biological warfare are among the most important environmental issues of this century. 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). The spread of pathogens, toxins and contaminants is mediated by regional and global transportation systems, as well as other human and natural vectors.

The relationship between human health and environmental change is a critical one, particularly given the potential for global change and increasing climate variability. Human health is affected by nutrition, contact with allergens, pathogens and chronic levels of various contaminants in air, water and foods, as well as the basic genetic composition of the individual.

Subtle changes in the environment that affect vital resources such as the quantity or quality of fresh water or the distributions of species may have profound impacts on human, animal and plant health. There are many historical examples of disastrous unintended effects of human actions. The study of 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.

Examples of relevant research questions include:

- What are the patterns of regional and global transport and transformation of contaminants/pathogens as they move through the dynamic environment (constructed, atmospheric, aquatic, biologic)?
- What microbial ecosystem knowledge and tools must be developed to analyze the spread of invasive species and pathogens, and what can they contribute to mitigating their unintended effects?
- What new technologies can be developed to analyze air, drinking water and foods for presence of existing and emerging harmful chemical and microbiological contaminants and to assist in alleviating their detrimental effects?
- What genomic methods for identifying organisms and understanding their mutations and life cycles can be developed?

3) Freshwater Resources and Environmental Change

The distribution, abundance and quality of freshwater resources are vital for the sustenance of life on Earth. Fresh water 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.

Research is necessary to improve understanding of the natural and human processes that govern the quantity, quality and availability of freshwater resources in natural and human-dominated ecosystems. The integration of the terrestrial, aquatic, atmospheric, and subsurface systems and processes within watersheds requires new, multi-disciplinary approaches, if we are to maintain a viable freshwater supply for human needs and ecosystem functions.

There is still limited understanding and predictive ability with respect to hydrological forecasting, and substantial opportunity for advancement of theory, methods and models. However, recent developments in remote sensing of precipitation, soil moisture, 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 relevant research questions include:

- How can we understand and predict the flux of organisms, sediments, organic matter and nutrients through inland waters?
- Can we more effectively model and track the processes and mechanisms of watersheds and the human activities that affect them?
- How can we develop novel engineering solutions for the protection of water resources and the rehabilitation of damaged or degraded watersheds in urban and rural areas?
- How can we enhance research in polar regions, where water is balanced between liquid and solid phases, in order to understand climate-driven hydrological and biological responses?

4) Environmental Services and Valuation

Natural systems provide many tangible and intangible items that people use for food, fiber, fuel, 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 fresh water; the climate system regulates temperature and maintains sea level; and oceanic upwelling fertilizes fisheries.

All these elements are critical to present-day functioning of society, and yet some of them are undergoing significant changes. Therefore, a fundamental challenge is to understand and determine the economic and social value of human dependence on natural systems. 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.

Scientists from a range of fields have begun to study the use, effects, and value of accounting for natural services in economic decisionmaking 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 question is whether these methods can capture non-market values or the environmental costs and benefits for future generations.

Examples of relevant research questions include:

- Which structures, functions and processes in the natural world provide the resources and services for human survival and development?
- How do humans place values on natural systems and the services they provide, and how do people consider the value, nature, quality, and availability of these services in making decisions about natural resource use?
- What new avenues of research can elucidate the relationship between individual and group environmental values, and what are the dynamics of group valuation?
- What is the impact of environmental scarcity on individual and group behavior, and what is the relative effectiveness of various strategies for improving access to resources?

(B) 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 interlock and interact with each other. This research builds on several existing disciplines and tools, including ecology, geology, chemistry, molecular biology, genomics, soil sciences, conservation biology, demography, atmospheric, oceanic and earth systems science, hydrology, and GIS (geographic information systems). The integration of these tools and disciplines is fundamental to the understanding of the climate system, nutrient cycles, ecosystems and biodiversity.

Three of the major research challenges in biological and physical systems are the following:

1) Biogeochemical Cycles

Six nutrient elements—carbon, oxygen, hydrogen, nitrogen, sulfur, and phosphorus—form the biochemical foundation for life. The cycling of these elements, as well as certain trace elements, in their biological, geological, and chemical forms, constitutes the major biogeochemical processes that support life at multiple scales. The availability or utilization of these elements has both direct and indirect influences on individual organisms and environmental systems.

Understanding the sources, sinks and fluxes of essential elements is critical, in order to determine their behavior under specific environmental conditions. This area includes the development of models to evaluate the consequences of human perturbations on essential nutrient cycles. For example, biogeochemical models have been used to assess major pools for global carbon storage, anthropogenic and natural aerial transport of elements, and multiple element interactions that affect ecosystem productivity.

A major challenge is to understand how the 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 if reduction of ecosystem harm can be achieved through modification of human behavior and application of relevant technologies.

Examples of relevant research questions include:

- How can we better quantify sources and sinks of nutrient elements, and improve our understanding of the biological, chemical, physical, and climate-related factors affecting them?
- What are the impacts of human perturbations of biogeochemical cycles (including release of contaminants) on ecosystem functioning and the chemistry of the atmosphere and oceans?
- How can we analyze the effectiveness of various technological approaches for maintaining or restoring essential nutrient cycles?
- What is the role of microbial communities in the cycling of nutrients, including trace metals?

2) Climate Variability and Change

There is an increasing need to improve predictions of climate variability, from extreme events to annual and decadal time-scales, to understand how this variability may change in the future, and to assess its impact on natural and human systems. It is equally important to increase understanding of the role of human activity in causing climate change, as well as the feedback between human actions and climate variability and change. As scientific understanding of global shifts in atmospheric and oceanic conditions improves, research turns toward regional climate impacts, including the effects on agricultural, forests, water and fisheries systems.

However, understanding how a climate phenomenon like El Niño or climate change will affect a local region is as much a question of understanding social and economic characteristics as it is of obtaining the appropriate results from a climate model. For example, drought impacts on crop production are mediated by access to adaptive technologies such as irrigation, fertilizer, and seeds; and are affected by crop prices, subsidies and coping mechanisms such as insurance.

Improved understanding of the geographic range and potential extremes of climate variability will provide insights into local vulnerability. This research may also facilitate more effective and timely private sector and institutional responses, adjustments and adaptation to projected climate change and variability.

Examples of relevant research questions include:

- How can we create useful regional scenarios of climate change and variability, including decadal climate shifts and seasonal forecasts?
- How can we provide integrated climate models that take human responses and impacts (for example, the production of aerosols) into account?
- How can we develop technologies that could reduce impacts of long-term or abrupt climate change and variability on coupled human-natural systems?
- What research can be developed on potential institutional responses to climate impacts, such as economic incentives, governmental policies, and risk communication?

3) Biodiversity and Ecosystem Dynamics

Biodiversity (all of the species of organisms, including their genetic diversity) and well-functioning ecosystems (species, their habitat, and the multiple interactions among these components) are interdependent. Ecosystems and the diversity of species they support underpin human well-being in important though often under-appreciated ways. However, increasing human populations and activity are threatening the existence of some species, modifying or eliminating the ecosystems in which they live, and disrupting natural ecological processes, including regional and global climate. Collectively, humanity is playing a major role in increasing the extinction rate of species and the loss of genetic diversity.

The scientific challenges are to understand the complex relationships between biodiversity and ecosystem dynamics, to grasp the regulation and functional consequences of biodiversity, and to understand ecosystem structure and function. There is also an increasing focus on both microbiology and molecular scale research related to diversity of species. The robustness and health of species and ecosystems is a function of not only the individual components and processes of the system, but also external stressors, many of which have human causes, and the cumulative and interactive impacts of those stressors.

In addition, because of the rapid pace of species loss and habitat destruction, current scientific knowledge must be used efficiently to develop conservation tools and strategies for both biodiversity and ecosystems. 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 relevant research questions include:

- Can we develop improved observing systems, analyses and classifications for assessment of biological diversity at all scales?
- How can we better understand and explain the relationships at all scales among biological diversity, ecosystem functioning, biogeochemical cycling, and climate change; and how can we better understand how ecosystems are organized and evolve?
- Can we develop spatially explicit models that explore the relationships among changes in land use, habitat and biodiversity, and can these models be used to

understand and manage biological diversity in periods of environmental variability and change?

- How can population, ecosystem and socioeconomic models be integrated to assess how biological reserves function, the efficacy of their design, and how multiple stressors and human behavior influence the operation and viability of the biological reserves?

(C) People and Technology

The overarching objectives of this research area are to determine how people as individuals and through human institutions interact with the natural environment, how they use environmental resources, and how they create and implement new technologies to protect and improve the environment. This area builds on tools utilized and research conducted in many existing disciplines, including economics, sociology, political science, psychology, industrial ecology, chemistry, engineering, geography, 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.

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

1) 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. Such information can lead to new technologies that meet the materials and energy needs of society.

For example, industrial ecology develops theoretical and practical approaches to addressing the interaction between technology, the environment and institutions. It relies on environmental research disciplines to identify environmental challenges and then works to develop ways to respond to them, while simultaneously enabling technology to provide heating, electrical power, pharmaceuticals, and all the other products that improve quality of life around the world.

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 include studying product design and development, life-cycle assessment, and the potential for re-use and loss - in order to design in rather than just add-on environmentally sound technology. This understanding of materials and energy depends on research ranging from the molecular scale to the ecosystem level. It also requires development of new methods and models to acquire and evaluate large, complex, and heterogeneous datasets in order to assess lifecycles (from raw materials through manufacturing, use and disposal or recycling). The challenge is to develop an understanding of the budgets and cycles of key materials used by people, and to understand how these budgets and life cycles can be modified.

Examples of relevant research questions include:

- How can we develop models and methods for more complete recycling and recovery of technological materials, and develop new materials and disposal technologies that present less damage to the environment and human health?
- How can we develop spatially and temporally explicit budgets and cycles for selected key materials, including the ways in which human activities define perturb, dominate or limit materials flow and supply?
- What are the fundamental research challenges with respect to alternative sources and uses of energy production such as solar, wind, and biochemical (hydrogen, methane and other bio-produced fuels)?
- How can we understand the patterns and driving forces of human consumption of resources, and identify policies and practices that influence materials and energy use decisions, including incentives?

2) Decisionmaking and Uncertainty

Environmental and human systems are sufficiently complex that knowledge of them and 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 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. 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 decisionmaking 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 with 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 may vary depending on the cultural, historical, and political context in which they occur. Scientific tools that support incremental, adaptive decisionmaking are especially valuable, particularly those that emphasize observation, assessment, and carefully monitored experimentation based on active cooperation between researchers and decisionmakers.

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 decisionmaking frameworks. Decisionmakers and managers need to develop strategies for dealing with complex environmental problems and uncertainty. Integrating research on abrupt environmental changes with research on the decisionmaking and communication process could be valuable.

Examples of relevant research questions include:

- What models can be developed and used for environmental disturbance scenarios for a range of structural assumptions, including alternative treatments of uncertainty?
- What are the best practices for communication of scientific information and uncertainty to policymakers and the public, and how is the information is received, understood, and acted upon?
- What decisionmaking strategies, forms of governance, and institutions can be developed to most effectively deal with uncertainty?
- What decision processes effectively combine analytical, deliberative, and participatory approaches to understanding environmental choices and thus guide scientists toward generating decision-relevant information?

3) Institutions and Environmental Systems

People interact with the natural environment on a personal level, but much of the impact humans have on the environment stems from the activity of collective entities – 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.

A wide range of institutions regulate access to and use of land, water, minerals, the atmosphere, forests, fisheries and other natural resources. Such institutions have increasingly 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 is pivotal 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 not in a form 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. Better understanding of the conditions under which institutional structures work effectively is needed, as well as the factors that influence the environmental and social consequences of various institutional forms. These questions should be addressed at multiple scales.

Examples of relevant research questions include:

- How do institutions affect, filter, and evaluate the dissemination of scientific knowledge about natural systems and the environment?
- How can we conceptualize and assess the role that institutions play in management of global common-pool resources and their associated environmental conditions?
- How can we test the applicability of scientific and engineering knowledge from successful local resource management to problems in other regions and at other scales?
- What are the conditions, potential contributions and pitfalls associated with particular institutional behavior and policy instruments?

BUILDING CAPACITY TO ADDRESS ENVIRONMENTAL RESEARCH CHALLENGES

In order to fulfill this research agenda, the Advisory Committee recommends a number of improvements in environmental education, training, infrastructure and technical capacity. It will be necessary to educate a new generation of environmental professionals—researchers, technicians, educators—who are capable of crossing disciplines, integrating diverse information, and working together to solve problems. The creation and strengthening of the observational and cyber-infrastructure to support a global research effort are also part of this challenge.

Environmental researchers are important contributors to education, government and industry. Outreach and public education are therefore needed to educate a new cadre of astute 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 may be the most effective means of addressing multi-scale environmental challenges.

(A) Environmental Education and Workforce

Quality environmental education and training is based on both the natural and social sciences. It prepares students for broad career horizons and integrates new technologies, such as information technology. Students not only gain knowledge but also acquire skills such as problem solving, consensus building, information management, communication, and critical and creative thinking. In coming decades, the public will be called upon more and more frequently to understand complex environmental issues, assess risk, and evaluate proposed environmental plans. Creating a scientifically informed citizenry requires a concerted, systematic approach to environmental education grounded in a broad and deep research base and 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, technicians---and to raise the environmental literacy of the general public.

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, 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 train individuals to undertake interdisciplinary, collaborative, and synthesis activities.

1) Elementary and Secondary Education

By the time they enter high school, more than 80% of students have decided that they are not interested in careers in physical or biological sciences, mathematics, or engineering.[1] Children without an adequate foundation in mathematics and science by the sixth grade will not be 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 an heuristic tool to help attract students not only to careers in environmental sciences and engineering, but to other scientific and technical areas. Early research results[2] support the claim that the environment, when used as an integrating concept, improves student interest, attitude, achievement, and attendance in school.

Many successful programs offer students hands-on experiences through field trips or "backyard science" in urban areas. These place-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.

Challenging questions relating to environmental education include the following:

- To what extent can environmental education contribute to accomplishing broader educational goals and attract students to science and engineering careers?
- Should environmental education be integrated into all disciplines across the curriculum or should specialized interdisciplinary environmental courses be developed?
- How effective are various instructional materials and teacher training methods that take advantage of environmental themes?
- Would a national assessment of environmental education be helpful in measuring progress in environmental literacy, and how should testing instruments be developed?

2) Two and Four Year Colleges and Research Institutions

Quality undergraduate and graduate programs are critical for development of the future environmental science and engineering workforce. Disciplinary fields of study will remain important, and new interdisciplinary programs may develop, but all of tomorrow's scientists and engineers will need to be prepared to contribute effectively to

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[1] NSF. 1994. *Indicators of Science & Mathematics Education.*

[2] Gerald A. Lieberman, Ph.D. and Linda L. Hoody, M.A., *Closing the Achievement Gap*. 2001. State Environmental Education Roundtable.

collaborative teams that include researchers with many disciplinary backgrounds, resource managers, and policy makers.

In developing educational programs, community colleges are often overlooked. In the case of environmental education, such an oversight would have serious adverse consequences. Community colleges are the starting point for more than XX% of students who obtain 4-year degrees in science, engineering, and science education. Approximately a fifth of all teachers start their programs and take their science courses at community colleges.[3] 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.

Both undergraduate and graduate environmental science and engineering programs need to be re-examined to ensure that they are adequately preparing professionals for the future. Leadership activities in curriculum development, in partnership with states and professional societies, would advance the education of teachers as well as environmental scientists and engineers. New programs should incorporate sound education research results, convey the excitement of the research process, and insist on best practices for effectively mentoring students.

The trends toward integration of the environmental sciences and engineering and use of 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.

Some questions for research in this area are:

- How can we enhance community college environmental curriculum, faculty research participation, and networking with other institutions?
- Are the needs of environmental research best served by disciplinary environmental science degrees, such as environmental biology or environmental chemistry, or by an interdisciplinary environmental science degree?
- What new features should be included in graduate training to help students learn how to build stronger links to the diverse partners needed for environmental study, training, and awareness?
- How can information and networking technologies be used to enhance environmental science, engineering, and technology education?

3) 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

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[3] Source citation on community college data to be added.

education should create opportunities for citizens to expand their understanding of and curiosity about environmental science. 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 long afterwards. Much remains to be understood about the most effective ways to activate adult learning 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 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.

Some questions for research in this area are the following:

- What informal education methods are most effective for life-long environmental education?
- What role should scientists and engineers play in communicating environmental research results to the public?
- What role should two- and four-year colleges and research universities play in lifelong environmental learning for adults?
- What are best methods for assessing the effectiveness of outreach programs, museum activities, and other informal education for improving environmental literacy?

4) Diversity

Participation by African Americans, Hispanic Americans and Native Americans 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 is not readily available. For technical areas as a whole, these three minority groups represent only about 5% of all employed doctoral scientists and engineers. While these minority groups earn approximately 15% of bachelor's degrees, 11% of the masters degrees, and 8% of doctoral degrees in science and engineering overall,[4] the percentages for environmental sciences may be as low as 5% at each of these degree levels. Increased participation in environmental education and research by members of minority groups is imperative to achieving and shaping the current and future environmental research and education

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[4] NSF. 2000. *Women, Minorities, and Persons With Disabilities in Science and Engineering.*

agenda. Fortunately, there is evidence that environmental themes can be particularly useful in attracting young women and minorities to science.[5]

Attracting and retaining minorities demands a multi-faceted approach and sustained commitment. Students and their families need to be exposed early to environmental science education. For students this should occur by elementary teachers equipped with high quality, teacher-friendly materials. Media presentations and other informal education activities and field trips that include families when possible are valuable. A particularly effective vehicle for attracting minority students may be K-6 education in urban areas. Here students could 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.

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 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.

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 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 and faculty.

Some questions for research in this area are:

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[5] Jeffrey Weld. 1999. "Achieving Equitable Science Education," Phi Delta Kappan. Vol. 80 (10), p. 756-758. (check citation)

- How can we conduct a credible and comprehensive analysis of present and projected career opportunities in environmental science and engineering, including disciplinary and interdisciplinary areas?
- How can we effectively expand hands-on and research oriented environmental programs in urban areas to attract and retain minority students?
- What types of programs or networks need to be established to help minority students transition from one institution to another, e.g., from high school to college?
- What is the most effective way to form support networks for minority faculty members in environmental science and engineering?

5) Interdisciplinary Teams, and Interagency and International Partnerships

Expansion and extension of interdisciplinary research that integrates natural sciences, engineering, and social sciences requires a team approach. 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 produce research results and 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.

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

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. Through partnerships with agencies having policy missions or management responsibilities, NSF can facilitate communication of research findings and speed their translation into policies and resource management. Ongoing relationships with other agencies also help identify research gaps and needs.

Advances in environmental research and practice rely on experience, observations, resources, and facilities distributed around the globe. NSF should enhance support for interdisciplinary linkages 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 global 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. It is foreseeable that regional nodes will develop to support virtual networks among institutions, both national and international. These networks would pursue, consistent with their various capacities and interests, particular research questions, 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.

Among issues to be explored are:

- What paradigms and structures are effective for interdisciplinary team formation, management, and assessment, and are these transferable across research areas and projects?
- For interdisciplinary research and education team activities, what patterns and durations of financial support are effective, and what steps can teams take to institutionalize their activities?
- What is an appropriate role for NSF in development of cyberinfrastructure for international environmental research activities?
- What steps can NSF take to encourage interdisciplinary partnerships with sister federal agencies and with international entities?

(B) 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, cyber-networks of interdependent sites linked by a common purpose and a research and education strategy may well be the ultimate means to undertake these challenges. Answers to today’s and tomorrow’s research questions rely on the ability to carry out critical field observations at multiple scales and locales 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, instantaneous real time 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, and citizens. All these groups are concerned about improved capability to 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.

1) 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 levels—technical, financial, and cultural. Progress in environmental research and the utilization of its results are stymied without this infrastructure and 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. Interoperability and common modeling frameworks are required to integrate contributions from many environmental communities. A unique challenge for environmental research is the integration of 4-dimensional (spatio-temporal) data and digital data to obtain a holistic view of earth and human systems. Also important are the curation and mining of unprecedented volumes of environmental data, which is often heterogeneous in time, space, format, content, and location, as well as legacy data. 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.

Some questions that need to be answered include:

- What is the most effective approach to developing an integrated framework and plan for interdisciplinary environmental cyberinfrastructure?
- What organizational structure is needed to provide long-term support for data storage, access, model development, and services for a global clientele of researchers, educators, policy makers and citizens?
- How will effective interagency and public-private partnerships be formed to provide financial support for such an extensive and costly system?
- How can communication and coordination among computer scientists and environmental researchers and educators be enhanced to develop this innovative, powerful, and accessible infrastructure?

2) Observing Systems and Tool Development

A wide range of platforms, field sites, instrumentation, telemetry and software is needed to observe, analyze, and model environmental materials, populations and communities, and processes. The development of tools to investigate heterogeneous, extreme, inaccessible, or toxic environments requires utilizing advances in many fields, including microelectronics, photonics, telemetry, robotics, in addition to physical, chemical, and biological sensing systems, and can also inspire advances in these fields.

The observing systems of the future will be highly instrumented and will take advantage of sophisticated cyberinfrastructure. Fixed and mobile observational 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 this 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 almost real time analysis and distribution to decisionmakers.

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.

Interdisciplinary approaches are now being developed that consider environmental impacts comprehensively and stress avoidance, prevention and efficient process and product design. For example, in order to protect ecosystems from damage from materials processing and manufacturing and to produce sustainable technologies, designers have learned more about the nature and functioning of ecosystems and incorporated 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.

New powerful and sophisticated instruments are enabling identification, detection and location, and dynamics of molecular species as they move through physical systems and organisms. Genomics research is revealing the microbial ecology of complex water and soil environments. 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 connect knowledge across scales from molecular to global. Although, for example, 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..

Questions for research in this area include the following:

- What is needed to encourage formation of collaborations between those who frame environmental questions and those who develop sophisticated tools for addressing those questions?
- What long-term partnerships are necessary to develop observing systems that provide rapid analysis and response to environmental change?
- How can observing systems be designed to accommodate new technologies while maintaining consistent time series information?
- How can inclusion of processes at all scales, from molecular to global, be incorporated into comprehensive environmental models?

3) Experimentation and Modeling

Interdisciplinary environmental research and education relies on a balance among experimentation, environmental observations, synthesis, and modeling. Experimentation in laboratory settings is of critical importance, but so are field experiments that include not only observations and surveys, but also manipulations at small and large scales. These experiments can reduce uncertainty and provide data and understanding 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 plots of land or areas 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, 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.

Understanding complex systems increases the demand for development of sophisticated interdisciplinary conceptual, mathematical, 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 and across multiple time and space scales. These models provide critical information needed to guide research. Simulation models and the use of artificial intelligence are often required, but the limits of certainty and generalizability of predictive models 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 decisionmaking and implementation strategies would also yield new insights. Further development of these new approaches to scientific discovery will require consideration of new means to provide long-term financial support and management.

Some questions for research in this area are as follows:

- How can risks involved in large scale manipulative experiments be estimated and minimized?
- How can the need for a setting aside and maintaining a geographical area for long-term research be justified, given increasing demand for other uses?
- What creative approaches, support mechanisms and rewards are necessary to encourage synthesis research, including meta-analysis and the synthesis of information for decisionmakers?
- What mathematical and computational questions must be solved to promote development of more effective climate, ecosystem, and institutional models?

4) Long-term Archives and Centers

Interdisciplinary work requires access to the vast amount of data generated from many disciplines. The study of dynamic environmental processes, some of which take place over long time scales, requires consideration of legacy data and maintenance of newly-developed information. For example, ice core data and satellite images have proved invaluable in answering a series of scientific questions that have continued to emerge since these data were collected. This raises concerns about conversion and cataloguing of existing data as well as development and long-term maintenance of 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, and decisionmakers 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, climate, geographic, demographic, and museum collections and make significant advances in understanding emerging diseases, exotic species, and ecological restoration, and many other environmental questions.

Approaching research with an emphasis on synthesis implies the need for increased capacity to understand environmental systems at the regional level. Some regional centers that have been established to support long-term, multi-disciplinary research and education and the associated community partnerships necessary for environmental synthesis work may serve as models.

Some questions for research in this area include:

- How will the design features of long-term digital repositories for environmental data be determined, and what is an appropriate structure for a system of digital repositories from various disciplines?
- What resources are needed for ongoing support of archives and repositories, and what should NSF contribute to this area?
- Is each regional center for environmental research and education essentially unique, or would organizing centers into a larger association be beneficial?
- What are appropriate roles for NSF to play in supporting regional centers that may involve non-research activities, such as public outreach, policy forums, and community involvement, in addition to research?

CONCLUSION

This plan outlines major directions in environmental research and education that the AC-ERE recommends that NSF follow over the next decade (2003-2012). If this research is adequately funded, supported and carried out, we should be able to significantly expand our base of knowledge of environmental systems and technologies. These investments in people, ideas and tools should 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 scientific frontier, but this plan should move us towards the goal of achieving long-term environmental robustness, health, and well-being.

In order to move ahead in this decade, environmental researchers need clearly articulated programs with 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, within and between 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 managing the complex relationships among people, ecosystems and the biosphere. In this exciting and productive next decade, environmental research and education will be critical for local, national and global security, health and prosperity.

(inside back cover)

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 environmental research and education (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 interdisciplinarity 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 the study of the 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 Long-Term Ecological Research Networks, 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 the 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; modeling and 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 - Biocomplexity. 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 biological 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.