PRESIDENT'S COMMITTEE OF ADVISERS ON SCIENCE AND TECHNOLOGY (PCAST)
Teaming with Life: Investing in Science to Understand and Use America's Living Capital

PCAST Panel on Biodiversity and Ecosystems

March 1998

President Clinton established the President's Committee of Advisors for Science and Technology (PCAST) by Executive Order 12882 at the same time that he established the National Science and Technology Council (NSTC). The PCAST serves as the highest level private sector science and technology advisory group for the President and the NSTC. The Committee members are distinguished individuals appointed by the President, and are drawn from industry, education and research institutions, and other non-governmental organizations. The Assistant to the President for Science and Technology co-chairs the Committee with a private sector member selected by the President.

The formal link between the PCAST and the NSTC ensures that national needs remain an overarching guide for the NSTC. The PCAST provides feedback about Federal programs and actively advises the NSTC about science and technology issues of national importance.

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

March 6, 1998

President William J. Clinton
The White House
1600 Pennsylvania Avenue, N.W.
Washington, D.C. 20500

Dear Mr. President:

On behalf of the members of your Committee of Advisors on Science and Technology (PCAST), I am pleased to transmit to you "Teaming with Life: Investing in Science to Understand and Use America's Living Capital." This report responds to your January 14, 1997 letter requesting recommendations to strengthen the "...understanding and management of the biological resources..."

As noted in your Earth Day speech in 1993, Americans have for too long been told that we have to choose between the economy and the environment. At the United Nations this year during your address on climate change, you called for "... an understanding that we can grow the economy and still preserve the environment." In this report, we offer recommendations for research and education that will allow Americans to gain the understanding you described. The results of this research will enable "the Age of Biology" that you foresee for the 21st Century.

This report recommends directions for research on management of natural capital to ensure a sustainable future for our Nation. The research we envision should not be restricted to ecology, but rather should also incorporate economics, sociology, and information science into a biological research program that will serve both society and the environment. By doing this we will advance both ecosystem health as well as human health.

This report is unique in that it provides a road map to bring the vast advances in information technology to the field of biodiversity in order to develop a "next generation" National Biological Information Infrastructure. Such capabilities will allow researchers and resource managers worldwide to make full use of information generated on ecosystems and biodiversity. Further, the report describes, in detail, the research needed to integrate ecology and economics, so that the true value of our natural resources can become part of the national accounting system.

Specifically, we recommend that Federal expenditure on biodiversity and ecosystems research, which currently totals approximately \$460 million per year, be increased by approximately \$200 million per year in constant dollars, phased in over three years. These modest investment increases will yield substantial benefits toward our Nation's future prosperity.

Through agriculture, forestry, fisheries, pharmaceuticals, eco-tourism, and many other activities, our use of biodiversity and living capital contributes hundreds of billions of dollars to the U.S. economy each year. Much can be gained as a result of the development of strategies outlined in this report. Through the prompt ratification of the Convention on Biological Diversity by the United States, our country will gain further advantages through enhanced access to biodiversity from throughout the world, and by participating in the international effort to use it wisely. PCAST encourages you to continue to urge Congress to ratify the Convention.

This report was prepared by a distinguished panel of 20 eminent leaders in Academia and Industry chaired by PCAST Member Dr. Peter Raven. The full PCAST endorses this report and its recommendations, and we stand ready to assist you in highlighting the importance of biodiversity and ecosystems to the American public.

Sincerely,

John A. Young
Co-Chairman

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EXECUTIVE SUMMARY

Over the last few decades, a new paradigm has emerged: Improving and protecting our environment is compatible with growing the Nation's economy. As part of this paradigm, we have come to recognize the essential linkage between the economy and the environment. We now understand that the sustained bounty of our Nation's lands and waters and of its native plant and animal communities is the natural capital on which our economy is founded. We also realize that a sound forward-looking economic strategy requires that we protect this natural capital, rather than damage it and then spend millions or billions of dollars attempting to recreate what Nature has already given us. To protect our natural capital, our Nation's biodiversity and the ecosystems within which it thrives, we need to have an extensive and frequently updated environmental knowledge base. This knowledge base is required to evaluate alternative plans for managing biodiversity and ecosystems as we work to optimize the union between the environment and the economy.

Our Nation's environmental knowledge base and our skills at using what we have are not now sufficiently well-developed to permit us to formulate the coupled environmental and economic strategies that will be needed in the 21st Century.

Yet, we can harness advanced information theory and large capacity computational systems to draw our knowledge together into a clear vision of the biological world. We can revolutionize this field. At this moment, our society is blessed with a dazzling array of new tools, from gene sequencers to global satellites. These tools can enable us to explore environmental questions at several different scales simultaneously, from sub-cellular to global.

The message of this report is that new technology can provide us with the tools of discovery and techniques of analysis that will catapult us into position to meet the challenges of 21st century environmental and economic policy planning. In the age of biology, policies that enhance human health and wealth will be the same policies that protect the biological resources of our Nation and the world.

The PCAST Panel on Biodiversity and Ecosystems recommends, in this Report, certain targeted investments in research and education that will bring new tools to bear on old and new challenges alike. These investments are modest in comparison to the overall worth of the resources they are designed to enhance and protect, the yearly dividends Americans derive from natural capital, and current Federal expenditures in these areas. Thus, they represent a very cost-effective use of public funds.

The Panel recommends that the Administration:

· Integrate up-to-date knowledge into management, use, and conservation of biodiversity and ecosystems;

· Search out America's biological species, their genetic properties, and their interrelationships;

· Explore fundamental ecological principles in order to improve monitoring of ecosystem status, better predict change, and optimize sustainable productivity;

· Design new mechanisms for valuation of natural capital and create economic incentives to conserve it in order to encourage a sustainable relationship between economy and environment;

· Apply leading-edge information science and technologies to electronically organize, interlink, and deliver biological information for use by all sectors of society, and

· Educate Americans about the ecological and economic importance of biodiversity and ecosystems and the economic impact of choices in management of our natural capital.

Taken together, the recommendations will enable us to develop sustainable strategies for conservation, management, and use of biodiversity and ecosystems. Justification for these efforts, and details on the expenditures, agencies, and partnerships that might best achieve the desired results are provided. This Report outlines a unique interdisciplinary research program, and lays out steps to rapidly develop 21st-century information synthesis capabilities.

Humanity depends upon biodiversity (all the species of organisms, including their genetic diversity) and ecosystems (co-existing species, their habitat, and the multiple interactions among these components) for the very sustenance of life. Biodiversity and well-functioning ecosystems are themselves interdependent. Ecosystems and the diversity of species they support underpin our economy in very real, though often under-appreciated, ways. The living things with which we share the planet provide us with clean air, clean water, food, clothing, shelter, medicines, and aesthetic enjoyment. Yet, increasing human populations and their activities are disturbing species and their habitats, disrupting natural ecological processes, and even changing climate patterns on a global scale. These are greater stresses on the natural world than humanity has ever generated in the past, and we must take responsibility for alleviating the impacts of our own activities. It is becoming more and more important that we actively conserve biodiversity and protect natural ecosystems in order to preserve the quality of human life. We propose that this can be done by enhancing understanding of the interdependence of the economy and the environment. This understanding will make it possible to use America's precious natural capital to generate prosperity, and at the same time conserve it for future generations.

To achieve this understanding, the United States needs to fully utilize current scientific knowledge in its conservation strategies, and incorporate new knowledge into them as it is generated. In addition, because the strength of our economy is linked inextricably to that of the world economy, the United States should fully participate in management and conservation of global biodiversity resources by sharing information and expertise and assisting in building scientific infrastructure in developing nations, as well as by ratifying the Convention on Biological Diversity. In both the national and international spheres, we need greater knowledge than we now possess. We need to know more about the biodiversity that exists within the United States and the world, and about how biological systems function under both natural and managed conditions. In addition, we need means to incorporate explicitly the value of our natural capital within calculations of agricultural, industrial, and service-sector outputs, and to provide incentives for conservation by all the sectors of society that benefit from living resources.

We need to elevate the national biological information infrastructure (NBII) to a new level of capability—a "next generation"—that can make maximal use of, and fully and openly share on a global basis, the information generated by research on biodiversity and ecosystems. We need to focus information science research on biodiversity and ecosystems information to assure that scientific results can be incorporated effectively into management and policy decisions. And, we need to bring the results of a great deal of earlier research that are now only found in static media into electronic format, because the NBII is the mechanism whereby biological data and information about the environment can truly be made available for use by all sectors of society. Finally, to enable Americans to understand the scientific and economic issues associated with biodiversity and ecosystems, we need to bolster the scientific content of informal and formal education.

This Panel has made a number of specific recommendations for refocusing certain ongoing management and research efforts, and for the allocation or reallocation of resources toward specific areas of research and development. These recommendations are made in the spirit of improving the scientific knowledge and infrastructure that are needed to improve our stewardship of America's living capital. The biological, economic, and information science research, and the support for education, recommended in this Report will require the addition of up to $200 million annually to current Federal expenditures in these areas. However, this Panel believes the investment is essential, and that it is a justifiable and cost-effective use of Federal research funds.

The research that is needed is associated with many agencies in several departments of the executive branch of the Federal government, and will require participation by academia, state and local governments, non-governmental organizations, and the private sector including industry. Therefore, the National Science and Technology Council, particularly the Committee on Environment and Natural Resources, must actively and consistently coordinate the research program outlined in this Report.

The Panel strongly recommends:

Scientific Knowledge in Service to Society. At present, governmental agencies and other entities that are responsible for managing the Nation’s natural capital often do so in an uncoordinated—indeed frequently conflicting—manner, largely because they are operating from differing (and sometimes outmoded) knowledge bases. Also, many confrontations between advocates for the environment and defenders of commercial activities could be avoided or resolved by readily accessible, objective, scientific information. Conservation policy and management decisions ought to employ the best, most up-to-date scientific information available, and as new information is generated, evolve to incorporate it. Conservation and management should also be coordinated across all Federal, state, and local agencies and among governments and other managing entities. In fact, the United States should develop a comprehensive national conservation strategy, building from the elements which currently exist. To formulate such a strategy, we need to develop, through public-private partnerships (e.g., among government, industry, and academia), an objective, accessible knowledge base that includes what we know about species, their characteristics and interactions, their habitats and ecosystems, how human activities impact them, and what kinds of actions comprise best practices for managing them. This knowledge base can then be used to foster local, regional, and national conservation strategies that are biologically and ecologically appropriate and economically sustainable. The goal of these strategies should be net enhancement of natural capital, so that future generations may enjoy the bounties of nature as well as economic prosperity. These strategies should include mechanisms for managing and protecting ecosystems sustainably in the face of global change and guarding our natural capital in all its forms. There are already some excellent examples of such strategies that have been developed around the country under the leadership of non-governmental organizations (NGOs), elements of the private sector, or representatives from local, state, and Federal agencies. The expansion of the capability of the NBII to deliver, rapidly and accessibly, comprehensive and comprehensible information for devising strategies, making responsible management decisions, and resolving conflicts is an essential part of bringing scientific knowledge into the service of society.

Discovery of Species. Modern biological tools are making possible a new age of biological discovery during which we can seek out and catalog previously unknown species more rapidly than ever before. Scientists estimate that fewer than 30% of species that occur in the United States have been discovered and described (worldwide, the total is estimated to be fewer than 15%). Many described species have useful properties; it is reasonable to predict that some of those which have yet to be discovered also have beneficial attributes (genetic resistance to disease, food value, compounds that could become pharmaceuticals, etc.) that can be employed in sustainable agricultural and industrial development. The workers needed to perform this research can be Federal, state, university, or NGO employees, but all will require the facilities of natural history museums, botanical gardens, herbaria, culture collections, and other research collections as well as new tools for gene sequencing, phylogenetic analysis, and information synthesis and presentation. The Report recommends that total yearly expenditures for discovery of species and their genetic attributes be raised to a minimum of $130 million (compared to current annual expenditures of $74 million), phased in over three years. These funds will 1) enable taxonomists—scientists who identify and describe species—to inventory the Nation’s biodiversity wealth, 2) train new taxonomists, and 3) support institutions that house research collections and provide vital biodiversity information for a multitude of purposes. An effective and efficient NBII that is interconnected with similar systems in other countries will be an indispensable tool in this process of discovery.

Ecosystem Research and Monitoring. Interagency participation in and support for the Environmental Monitoring and Research Initiative of the CENR should be continued, especially promotion of the public-private partnerships involved in that activity. In addition, the capabilities of current ecological monitoring sites to provide useful data should be evaluated and any shortcomings corrected. At the same time, experimental research on biodiversity and ecosystems must be strengthened in order to increase our ability to use the results of monitoring to predict how ecosystems will respond to multiple stresses and to maximize the sustainable productivity of agricultural and forest ecosystems. This research can be conducted at universities, within governmental agencies, in public-private partnerships between Federal or state agencies and NGOs, or by other entities. However, the research should be anchored at a system of study sites that, in parallel to astronomical observatories, might be called "environmental observatories." The United States has a number of such sites—National Forest Research Laboratories, Long-Term Ecological Research Sites, some of the National Parks, etc.—but this system needs to be expanded to cover the full diversity of ecosystem types found in the country. Ecosystem research and monitoring also needs to be more fully interconnected by efficient and effective information management systems, namely the NBII envisioned above, and to make full use of the most effective current technology, such as laser technologies to measure gas fluxes, high resolution remote sensing, and non-invasive near-infrared techniques for environmental chemistry. Investments in these sites and their research-support facilities should be increased by approximately $55 million over the current $300 million per year. A certain proportion of this increase in research spending should be specifically targeted to theoretical research designed to discover fundamental ecological principles. There is new sophistication in analytic techniques, which can be used to further increase scientific understanding of ecosystems, their vital functions, and the impacts on them caused by human activities.

Economy and Environment. Steps should be taken to focus interdisciplinary economic, sociological, and ecological research on the relationship between the market economy and natural capital, between society and the biosphere. In recent years, and certainly in this Report, natural capital has been shown to be the source of a very large percentage of human economic wealth. Yet, this recognition is new enough that mechanisms for valuating natural capital and the means to incorporate that value into assessments of economic output, or long-term costs to society caused by use of natural capital, have yet to be articulated. These mechanisms, once defined, can be used to devise incentives for conservation that will encourage industry, government, and communities to conserve while still receiving benefits from sustainable use of biodiversity and ecosystems. The new approaches to the integration of information from widely differing fields that are now available will facilitate this research at the interface of biological and social science with economics. The Panel believes this to be a vital area of research that can help to reduce the perception of conflict between the needs of the environment and the strength of the economy. However, there is currently no mechanism for supporting research directed at valuation and at development of incentives. The Panel recommends that the National Science Foundation take the lead in an interagency granting program to make approximately $24 million per year available for these highly interdisciplinary, extremely important, but currently unfunded areas.

National Biological Information Infrastructure. The research initiatives described above, and resource management decision-making, require a dramatic increase in the analytical and synthetic capacities, as well as the information content, of the National Biological Information Infrastructure (NBII). The Federal government should push forward to the "next generation NBII" because in its current form, the NBII is inadequate. At present, the NBII can be used to access information in databases held by various Federal agencies and other institutions around the country. However, the system can be used to access only one database at a time, and for the most part, collation and correlation of data from multiple databases requires hours of human involvement. The demands of policy, management, and scientific investigation are such that collation, correlation, analysis and synthesis of information must be automated so that people may concentrate on decision-level and creative tasks. Furthermore, 1) databases that are online are by no means as numerous as they ought to be, 2) those that exist are uneven in the types of information that they hold, and 3) standards for data exchange in the biodiversity and ecosystem information domain have yet to be widely adopted. Direct support to the NBII should be increased at least fivefold to promote the development of standards and to increase the information content of the NBII in its current incarnation while the "next generation NBII" is being constructed. The Federal government should enable development of the "next generation NBII" by investing a minimum of $40 million per year for five years (and reasonable maintenance thereafter) in a system of regional nodes at which computer scientists, information scientists, biodiversity and ecosystem scientists, and sociologists, using leading-edge tools and technologies, will work together to develop true interoperability among multiple database types, new software tools for gathering, analyzing and synthesizing data, new means of scientific collaboration, new means of presenting computational results so that biodiversity and ecosystems research findings can be more readily applied in management and policy, and so on. Among other useful attributes, such a system will enhance the ability of industry to develop new products, provide much better outputs for use in education and in management of biodiversity and ecosystems than is possible now, and further facilitate scientific advances. Importantly, the enhanced NBII will add value (at relatively minor cost) to the vast datasets of physical environmental parameters that the US obtains from its earth-orbiting satellites by making it possible to readily correlate them with biological datasets in various combinations. The Panel emphasizes that this "next generation NBII" is fundamentally important to the accomplishment of all of the research, management, and education recommendations that form the remainder of the Report. The NBII envisioned by the Panel will eventually become at least in part self-sustaining—as did the Internet itself—but the initial impetus for its creation must come from the Federal government.

Education. Environmental education should be centered on science. An electorate that does not understand the natural world or the nature of the tradeoffs that must be made in managing it wisely and sustainably cannot make informed decisions. Communities that do not have an understanding of the workings of the ecosystems within which they live will be unable to function as responsible stewards, and will thereby too often cause and suffer from losses of biodiversity and ecosystem services. The Panel recommends that professional development opportunities be multiplied so that 10,000 teachers per year can increase their skills for teaching about the interdependence of society and the biosphere in an unbiased way. The recommended increase (of about $15 million to the current $72 million per year) in informal educational opportunities will strengthen the environmental literacy of the American public, and initiate a mechanism for development of scientifically sound curricula and teaching materials that would improve the environmental component of science education in the Nation's schools.

The Panel is convinced that continuation of traditional resource use patterns and their unanticipated results (for example, global climate change) will lead to diminishing economic benefits and degradation of the other services that we derive from our living resources. To reverse the trend, we must make sustainable use of the products of biodiversity and ecosystems, and conserve natural capital for our children and the generations to follow. To do that, we need to know more than we do about the living world. This Report provides a framework for research and information infrastructure about the economy and the environment that will enable the Nation to reconcile the needs of both, a goal the Panel believes is necessary to meet the challenges of conservation and sustainable use. The Panel's recommendations call for specific investment increases that total less than $200 million per year (phased in over three years) for research, education, management, and the information infrastructure to support them all. Current Federal expenditures for biodiversity and ecosystems research and monitoring (which total approximately $460 million per year) are too low when compared to the threats that global change and growing populations present to our natural capital. The Panel believes the investments recommended in this Report are just that—modest but vitally important investments in a knowledge base that will yield an incalculable return by enabling us to preserve our living capital resources as a sustainable foundation for America's future prosperity.

INTRODUCTION

Biodiversity and Ecosystems are Natural Capital Assets

The tremendous natural wealth with which the United States has been endowed contributes greatly to its strength and prosperity and remains the foundation for the well-being of current and future citizens. This wealth exists in the form of fertile land, abundant fresh water, a diversity of biological species adapted to many different ecological habitats, productive forests, fisheries and grasslands, and favorable climatic conditions. From these, society derives an array of important life support goods and services, including medicine, clothing, shelter, agricultural products, seafood, timber, clean air and water, and flood control. The natural wealth from which these goods and services arise is a capital asset of enormous magnitude. The value of this natural capital has yet to be established in formal economic terms, but the goods and services that flow from it are worth hundreds of billions of dollars per year to the United States' economy. As with any such asset, if our natural capital is properly managed, it can yield a sustained flow of benefits for future generations.

With industrialization and the development of modern technologies, the human species has emerged as the dominant force on the planet. We have wrought massive changes that rival or exceed those caused by natural biological and geological processes. While human impacts were once local and reversible, they are increasingly becoming global and much less reversible. The collective activities of American society are changing the chemistry of land, water, and atmosphere far more dramatically than are natural processes. It is already apparent that some of these changes are adversely affecting our natural capital and its ability to support us sustainably.

Collectively, all human beings, including Americans, are playing a crucial role in the sixth major extinction event to occur in the course of more than three billion years of life on Earth, and the first in the past 65 million years. Species are being driven to extinction thousands of times faster than new ones can evolve. During the history of the United States, more than 500 of its known species have been eliminated (half of these since 1980) by various causes, including destruction of habitat by human activities or invasive species. Each of these species was associated with dozens of additional, mostly unnamed and unstudied, species that were wholly or partially dependent on it, so that the actual number of life forms lost is much greater.

Past and current usage practices have disturbed ecosystems and threatened ecosystem services. For example, urban and suburban development of watersheds has been detrimental to natural water purification by ecosystems at a time when human populations are growing and needing more water. Overuse of and excess application of chemicals to soils have disrupted natural processes. Habitat loss, air pollution and chemical pesticides have reduced populations of natural pollinators and natural control agents for agricultural pests. Overfishing and agricultural runoff have diminished marine biodiversity and increased the frequency of toxic algal blooms that cause poisoning of economically valuable fish and shellfish. And, chemical byproducts from human activities are damaging the stratospheric ozone layer that shields Earth's surface from ultraviolet radiation. Fortunately, these trends can still be reversed. However, we need to know more than we do, and properly apply what we do know, in order to make that reversal possible.

The dramatic deterioration of the natural capital of the United States already has had major economic and social consequences (see Box 1). These consequences are only just now being recognized. For example, land-use changes have seriously compromised the effectiveness of natural water purification processes, which in turn has imposed massive capital costs on many communities. More than one-third of our agricultural soils have been lost to erosion and unsustainable agricultural practices. Decimation of pollinating insects has imposed large costs on agriculture. Deterioration of wetlands and other natural aspects of drainages has left communities vulnerable to flooding and mud slides that destroy homes and disrupt utility, communication, transport and other services and infrastructure. Population explosions of harmful algae have destroyed or seriously impaired fisheries and recreational opportunities and created human health hazards. Invasive species such as killer bees, zebra mussels, fire ants, and the Mediterranean fruit fly annually cause billions of dollars of damage to agricultural and natural systems, pose threats to the health of our human population, and seriously affect populations of native species.

Without far-reaching changes in the quality of our stewardship of our natural assets, problems of this sort will escalate in both number and intensity as human populations and consumption of goods and services increase. Worse, solutions to and mitigation of these problems will become more difficult and costly to implement. The tradeoffs that individuals and society face in the course of pursuing the basic material ingredients of well-being will become more vexing, in both ethical and practical dimensions, as resource scarcity and growing waste increasingly constrain our options. The wise resolution of these tradeoffs requires explicit recognition of the costs as well as the benefits of the use of natural capital assets, so that an economically and socially optimal strategy can be devised.

We envision a new framework for managing the biodiversity and ecosystem assets of the United States. Under this framework, economic development efforts would be refocused in explicit recognition that a very large percentage of our economy is completely dependent on natural capital. This recognition would require new means of determining the economic value of biodiversity and ecosystems, and using these values to develop economic incentives for good ecosystem management and responsible stewardship of the Nation's natural capital. We believe this framework would be economically profitable, socially acceptable, scientifically sound, politically feasible, and environmentally sustainable.

Putting this framework in place requires taxonomic, ecological, economic and sociological understanding that we do not now possess. In this report, we recommend investments in biological, economic, and information science research to gain that understanding so that future generations of Americans can enjoy lives as bountiful as those we enjoy today. The Recommendations are presented in the main body of the report, and concern:

- integrating up-to-date knowledge into management, use, and conservation of biodiversity and ecosystems;

- searching out America's biological species, their genetic properties, and their interrelationships;

- exploring fundamental ecological principles, which, when understood, can help us to improve monitoring of ecosystem status, better predict and mitigate change, and optimize sustainable productivity;

- designing new mechanisms for economic assessment of natural capital and creating incentives to conserve it in order to encourage a realistic relationship between economy and environment;

- applying leading-edge information science and technologies to electronically organize, interlink, and deliver biological information for use by all sectors of society, and

- educating Americans about the economic importance of biodiversity and ecosystems and the need to protect our natural capital.

The remainder of this Introduction provides the philosophical background for our recommendations for developing a more realistic and sustainable relationship among society, the economy, and the biosphere—in short, teaming with life to keep Earth teeming with life.

Box 1: The New York City Watershed

Problem: The Cost of Replacing a Watershed - $8 billion!

New York City has traditionally been famed for its clean water, which Consumer Reports once ranked among the best in the Nation. New York's water, which originates in the Catskills Mountains, was once bottled and sold throughout the Northeast. In recent years, the Catskill's natural ecological purification system has been overwhelmed by sewage and agricultural runoff, and water quality has dropped below EPA standards. This prompted the New York City administration to investigate the cost of replacing the natural system with an artificial filtration plant. The estimated pricetag for this installation was $6 to 8 billion in capital costs, plus annual operating costs of $300 million—a high price to pay for what once could be obtained for free.

Solution: Harnessing Market Forces for Environmental Preservation

This high cost prompted further investigation, which showed that the costs of restoring the integrity of the watershed's natural purification services— about $1 billion—would be a small fraction of the cost of the filtration plant.

Thus, New York City faced a choice: invest $6-8 billion in physical capital, or $1 billion in natural capital. The latter is the course that the city adopted. In 1997 it raised an Environmental Bond Issue, and is currently using the funds to purchase and halt development on land in the watershed, to compensate land owners for restrictions on private development, and to subsidize the improvement of septic systems.

In this case, a financial mechanism has been implemented to capture some of the economic and public health values of a natural capital asset (the Catskills watershed) and distribute these values to those with stewardship responsibilities for the natural asset and its services. Note that these calculations consider only a lower-bound estimate of the value of water purification services. However, the decision to conserve the Catskills ecosystem for water purification will also confer protection on other valuable services, such as flood control and carbon sequestration. This sort of financial mechanism could be extended to other geographic locations and other ecosystem services that would benefit municipalities and habitats throughout the Nation.

The Economic Value of Biodiversity and Ecosystems

The harvest and trade of products from biodiversity represent important and familiar parts of both the United States' and the global economy. The importance of the preservation of biodiversity to human economies has been explicitly recognized by more than 170 nations that had ratified the Convention on Biodiversity as of June, 1997. These nations recognize that biodiversity on one side of the globe can affect someone on the other side of the world, that the natural heritage of any nation is held in trust for all peoples, and that the management of that biodiversity is a matter for global discussion. The public and private sectors of these nations are full participants in the management of benefits derived from biodiversity and in the conservation of biodiversity for the future. At present, the United States is not a full participant in the discussions, nor in the management and conservation of global biodiversity, because it has not ratified the Convention. Neither the best interests of present and future Americans nor those of America's private sector industries that depend on biodiversity products are being served by our delay in ratification. This situation should be rectified immediately.

The Convention explicitly recognizes that economic goods are derived from the diversity of species that exist on Earth.

Examples of these economic goods include:

• *Agriculture.* Extractions from wild species in biodiversity's "genetic library" account for approximately 50% of annual increases in crop productivity accomplished by biotechnological and agricultural research and development. At present, just over 100 plant species directly or indirectly contribute 90% of the global human food supply, with only three — rice, corn, and wheat — supplying 60%, but thousands of plant species are cultivated or consumed from the wild somewhere on Earth. Some of these may be more nutritious or better suited to certain wide-spread growing conditions than are species currently widely cultivated.

• *Fisheries.* The annual ocean fish catch is worth $2.5 billion to the US economy, and $82 billion worldwide, yet fisheries are being depleted everywhere because of poor management of the stocks.

• *Forest goods.* Products from natural and managed forests include timber, fuel wood, game, fruits, nuts, mushrooms, honey, other foods and spices, and diverse natural products (e.g., gums and exudates, resins, dyes, waxes, insecticides) that serve as inputs to a wide array of chemical and biochemical industries. These wild products contribute between $3 and $8 billion per year to the US (between $84 and $90 billion globally).

• *Pharmaceuticals.* Nine of the top ten prescription drugs used in the US are based on natural compounds from plants, fungi, animals, and microorganisms. Thus, nine of the top ten drugs in this list are based on the products of biodiversity. In the US, the commercial value of pharmaceuticals exceeds $36 billion annually. Globally, about 80% of the human population relies on traditional medical systems, and about 85% of traditional medicine involves the use of plant extracts. Over-the-counter plant-based drugs have an estimated market value of $20 billion per year in the US and $84 billion worldwide.

• *Medical research tools.* Research on natural products also leads to basic scientific breakthroughs that may not lead directly to a pharmaceutical product, but may nonetheless have profound importance in biomedicine (e.g., the basis for protease inhibitors that are now used to treat HIV). Biodiversity also provides useful tools and models for research (e.g., neurotoxins from the skin of tropical frogs, bioassays for toxins or antibiotic properties that utilize small mammals or microorganisms, mechanisms for tumor suppression possessed by sharks), and indicators of environmental quality (e.g., egg shell thinning in raptors resulting from excessive use of DDT, fish die-offs from population explosions of marine algae).

• *Nature travel, horticulture and pets.* The beauty of nature and the enjoyment that humans obtain from interactions with other species are intangible but very real components of the fulfilled human experience. A breath of clear Rocky Mountain air scented by conifers on a glistening day in December, the joys of beachcombing for shells, the thrill of a chance encounter with an octopus while snorkeling are all of enormous value. In fact, "ecotourism" is worth approximately $100 billion per year within the United States alone (estimate by the World Wildlife Fund, 1997). The horticultural trade in orchids, bromeliads, cacti, and all those plants used in landscaping and gardening is worth hundreds of millions per year because of the enjoyment humans derive from being surrounded by the beauty of biodiversity. Interactions with dogs, cats, parrots and other animals has been shown to be beneficial for the elderly, children with debilitating diseases, and persons with depression. Indeed, many Americans enjoy the companionship of pets throughout their lives.

Biodiversity exists within ecosystems. An ecosystem is a fundamental unit of nature that includes living organisms and their non-living environment. One of the important factors in the maintenance of healthy ecosystem functioning is the maintenance of the diversity of species that participate in the system; the most effective way to maintain a single species or all of biodiversity is to guard the integrity of the interactions that form the ecosystem as a whole. The organisms obtain life-support benefits from their ecosystem interactions. This is no less true of human society.

We take "ecosystem services" for granted, but we should be paying close attention to the maintenance of the ecosystems from which those services come (see Box 1).

Examples of ecosystem services include:

• *Pollination*: The agricultural value of pollinator service by insects is estimated to be $40 billion per year in the US alone. One-third of all human food is produced by the 70% of crop plant species that require animal pollinators to produce seed. Despite their enormous value, thousands of pollinating insect species are threatened on a wide scale by pollution and the use of chemical pesticides.

• *Seed dispersal*: Attempts to restore vegetation on degraded lands are often hampered by the absence of natural seed dispersers. Human-facilitated dispersal is expensive, time consuming, cost-inefficient, and may not even succeed. Without thousands of animal species (primarily birds, rodents and insects) providing seed dispersal services, many plant species would fail to reproduce successfully because their seeds will not germinate or grow to maturity if they fall only in the shadow of the parent plant. For instance, the whitebark pine, a tree found in the Rockies and the Sierra Nevada - Cascade Mountains, cannot reproduce without the services of a bird called Clark's nutcracker, which chisels pine seeds out of tightly closed cones and disperses and buries them.

• *Grazing*: Grasslands support animals used for labor (e.g., horses, mules, asses, camels, and bullocks) and those (domesticated or wild) whose parts or products are consumed (such as meat, milk, wool, and leather). Grasslands are also the original source of most domesticated animals and crops.

• *Fisheries protection*: Coastal wetlands and mangrove swamps protect inland areas from storm surges and saltwater intrusion, provide habitat for many species including the eggs and larvae of commercially important ocean fish, and buffer open waters from many land-derived pollutants.

• *Removal and storage of atmospheric carbon dioxide*: More than half of the carbon dioxide produced by the combustion of fossil fuel does not accumulate in the atmosphere, but is removed and returned to nature. Proper management of forests, including reforestation, and new agricultural practices can significantly increase this carbon dioxide removal and storage service. Research suggests that this service is provided best by ecosystems with high biodiversity.

• *Flood control*: Every year, about 6 x 1025 cubic feet of water fall as rain onto the Earth's land surfaces. Soils soak up much of this water and gradually meter it out to plant roots or into aquifers and surface streams. Living vegetation—with its deep roots and above-ground evaporating surface—serves as a giant pump, returning water from the ground to the atmosphere. If this pump is missing or lowered in volume, stream flow increases, sometimes to disastrous levels. Experimental clearing of a New Hampshire forest led to 40% higher average stream flow; during one 4-month period of the experiment, runoff was more than five times greater than before. A study conducted by the non-governmental organization American Forests, using engineering formulas developed by the Natural Resource Conservation Service, found that a 20% loss of trees and other vegetation in the Atlanta metropolitan region produced an increase in stormwater runoff of 4.4 billion cubic feet. At $0.50 per square foot, it would cost at least $2 billion to build containment facilities capable of controlling this water.

Values of Species Diversity

The species that comprise the crops and livestock of US agriculture contribute an estimated $57 billion annually to our economy ($325 billion worldwide), species that are hunted $12 billion ($25 billion worldwide), and species that provide wood products yet another $8 billion ($84 billion worldwide). Protecting these large segments of our economy means protecting the non-cultivated species to which crop and livestock species are related because with genetic engineering, helpful traits in these wild relatives may be transferred to the crop species. Successful protection of these relatives requires the maintenance of well-functioning ecosystems. The following examples illustrate how non-cultivated relatives of crop species can be of significant importance.

Rice growing in the US is worth $1 billion annually. One-fifth of the yield of this crop is attributable to relatively recent genetic infusions from wild sources. And, yield increase is not the only advantage to be gained from wild diversity: In the early 1970s, a virus called "grassy stunt" posed a major threat to Asia's rice production: it was expected to destroy 30% to 40% of the crop, which would have brought great hardship and economic loss, and placed huge demands on the food supply of the rest of the world, including the US. The threat was avoided by introducing an immunity-conveying gene from a wild strain of rice into commercial varieties. It is important to note that the beneficial wild strain of rice was originally found in a valley that was soon thereafter submerged by a hydroelectric dam.

Corn (*Zea mays*) crop value worldwide is about $60 billion per year. Most of the commercial varieties in use are susceptible to seven main types of viral diseases. In fact, in the 1970s, a viral outbreak caused $2 billion in damage to US agriculture. However, a very local wild Mexican species closely related to cultivated corn, *Zea diploperennis,* possesses genes for resistance to several of these viral diseases. Commercial strains of virus-resistant cultivated corn, with resistance from *Zea diploperennis,* can be developed by transferring its resistance genes into *Zea mays.*

Wheat also benefits from germplasm introductions from wild relatives, although the existence of wild strains is threatened by human activities in wheat's native range in the Middle East. Current collections of wheat germplasm are probably inadequate to meet coming environmental challenges.

Because wheat, corn, rice, and other staple crops (e.g., soybeans) are immensely more abundant now than at any time in their evolutionary history, and because they are grown in monocultures, they are highly susceptible to the evolution or invasion of new crop diseases. The loss of one of the major grains to such a disease would destabilize the economy; the loss of two or more would be catastrophic. A principal defense against such loss is the preservation of maximal genetic and species diversity among these crops and their wild relatives.

Values of Genetic Diversity

The biotechnology industry and much of biomedical and biological research and development depends directly on products derived from studies of biodiversity. In particular, the ability to manipulate genes emerged from surveys of the properties of enzymes found in different species of bacteria. The commercial production of these enzymes and related products obtained from hundreds of bacterial species has been one of the factors contributing to the tremendous growth of knowledge in molecular biology during the past two decades. Studies of certain of these enzymes have already led to the development of new methods for medical and forensic diagnosis. It is anticipated that the future will bring the development of "gene chips" that will profoundly enhance our ability to diagnose human and animal diseases. It seems likely that as we progress toward the use of more environmentally benign technologies for chemical production and biomass utilization, many additional uses will be found for the enzymatic diversity represented in the natural world.

Agricultural biotechnology is in its infancy. However, based on thousands of field trials of genetically modified plants during the past five years, it seems apparent that many improvements in crop and forest species can be expected. It is anticipated that the US market for seeds of genetically modified crops will grow to $6.5 billion during the next ten years and the annual production value of the plants derived from those seeds will be many times that amount. Most conceivable applications of biotechnology in this sector depend upon manipulation of genes that exhibit significant intraspecies variation. For example, it will become possible to enhance tolerance of crop species to many abiotic stresses by transferring genes for traits such as cold tolerance or salt tolerance from non-crop species. There is also a possibility of accelerating the domestication of potential crop plant species by using directed genetic methods to alter traits that are currently impediments to widespread utilization, such as the presence of toxic constituents or architectural features such as pod shattering. Interestingly, many of the wild species with desirable characteristics are native to countries other than the United States. Access to these resources for US agricultural biotechnology companies would be enhanced if the US ratifies the Convention on Biological Diversity.

With the ability to transfer genes from one unrelated kind of organism to another, first achieved successfully in 1973, the genetic dimension of biodiversity assumed greatly increased commercial value. Transgenic plants, animals, fungi, and microorganisms may gain key importance in carrying out sustainable development. However, beneficial genes will continue to exist only as long as the species that carry them continue to thrive on Earth. For all practical purposes, genetically modified organisms can be produced only by combining thorough knowledge of the genetic composition of species at the level that is now being attained through genome sequencing projects with detailed knowledge of the relationship between these sequences and specific desirable characteristics of the organisms. Many useful genes have been identified in recent years from plants or other organisms that have never previously been useful to humans. It is essential that we preserve all species without regard to their immediately known utility, because it is now, and increasingly will be in the future, possible to discover as yet unknown beneficial genes in previously unsuspected sources. To allow species to disappear now may be to deprive ourselves and future generations of unique biological and genetic resources of great value.

Values of Ecosystems

The ecosystem as a synergistic entity provides services, such as water purification, flood control, waste disposal through decomposition, detoxification, soil production, and so on. Though at present it is extremely difficult to pinpoint the value of such ecosystem services accurately, various reasonable total annual global estimates are in *trillions* of dollars; those for the US alone are in the hundreds of billions. One set of very conservative estimates of economic benefits of particular services includes the formation of arable soil ($62 billion per year in the US and $760 billion worldwide), biocontrol of crop and forest pests ($17 billion annually in the US and $160 billion worldwide), and bioremediation ($22.5 billion in the US and $121 billion worldwide). Microorganisms in natural ecosystems also fix nitrogen in forms usable by plants ($8 billion US, $90 billion worldwide), and forest and ocean ecosystems assist in mitigating the greenhouse effect by sequestering carbon dioxide ($6 billion US and $135 billion worldwide). Waste disposal, the breakdown of organic matter by those species within ecosystems known as decomposers, has been estimated to be worth $62 billion per year in the US ($760 billion worldwide). These estimates must be confirmed or corrected by the sort of research described later in this report, but they certainly indicate that such research is warranted, because the replacement of these services by artificial means is either impossible or prohibitively expensive.

Just as we improve and maintain transportation systems to avoid slowing the delivery of goods, we should restore and maintain ecosystems to ensure that the services we derive from them continue to flow. Just as the underlying capital value of human-constructed infrastructures is built into cost-benefit analyses for their maintenance, so the value of natural capital should be incorporated into calculations of the costs and benefits of uses that society proposes for its natural assets.

Aesthetic Values of Biodiversity within Natural Ecosystems

The search for solitude or comfort as well as sustenance from natural surroundings is deeply imbedded in the human spirit. The ethical and religious beliefs of many cultures encompass a stewardship role that encourages protection of and reverence for natural surroundings. Religious texts from many traditions assume that all life on earth is interconnected, and assert that humans have the task of sustaining those connections. For example, Ezekiel 34 entreats: "Is it not enough for you to feed on good pasture? Must you also trample the rest of your pasture with your feet? Is it not enough for you to drink clear water? Must you also muddy the rest with your feet?"

Christians, in Jesus' parables, find rich and plentiful metaphors of the natural world as examples of right behavior. Catholic social teaching holds that "there is an order in the universe that must be respected, and... the human person, endowed with the capability of choosing freely, has a grave responsibility to preserve this order for the well-being of future generations." The Orthodox Church considers humankind to be stewards and not owners of material creation; it is imperative that humans display love and respect towards nature. Judaism affirms life, and with it creation as a whole. Humans are responsible for the active maintenance of all life, being commanded to respect nature and having a special position of responsibility towards it; the rich variety of nature (biodiversity), is to be cherished. The Koran emphasizes that, at the Last Judgment, the ways that people have cared for the Earth will be among the deeds that will determine their fate. Even in the most secular segments of our culture, it is widely recognized that we have an ethical responsibility to prevent extinctions of species.

Throughout history, humans have shown a strong curiosity about, and aesthetic attachment to, other species. That this connection to nature is important to people is revealed by numerous activities involving other species, notably gardening (even on highrise rooftops), petkeeping, wildlife and bird watching, the simple pleasure of walking in a woods, or watching the sun set over native prairie. It is impossible to place an objective economic value on this desire. At the same time, the aesthetic and emotional bond to other species has enormous economic consequences for many people. Worldwide, ecotourism and recreational enjoyment of the natural landscape and the species that inhabit it generates between $0.5 and $ 1 trillion a year. As noted above, within the US alone, these activities generate at least $100 billion per year.

Society and the Biosphere

Biodiversity, and ecosystem services, are worth trillions of dollars annually, but because they are usually not traded in markets, they typically carry no pricetags that could alert society to changes in their supply or to deterioration of the underlying ecological systems that generate them. These circumstances make it easy to take ecosystem services for granted and difficult to imagine that they could be disrupted beyond repair. Yet, escalating human impacts on natural ecosystems, now manifest in even the most remote parts of the planet, imperil the delivery of these services. Unchecked and unmitigated, these impacts will thereby impoverish and endanger our children and grandchildren.

There is a crucial need for policies, generated by government, business, and society at large, that can help prevent biodiversity loss and ecosystem deterioration, and preserve the natural capital that provides our economic prosperity. Such policies must resolve a daunting array of tradeoffs: Where should natural ecosystems be developed for farmland, housing, industry, or other human activities, and where should they be safeguarded for the valuable services that they deliver? What balance will best serve human needs, for present and future generations? Current understanding of ecosystem services is not complete, yet it is substantial, wide-reaching, and policy-relevant. As such, it can inform the resolution of these tradeoffs. The safeguarding of biodiversity and of ecosystem services will require that their economic and ecological value be explicitly incorporated into decision-making frameworks.

Over the long term, we cannot rely on directives and regulations to ensure conservation of America's living capital. Rather, it must be demonstrated to communities living within ecosystems, and to industries that generate their income from the benefits of ecosystem services, that conservation is in their own economic interests. This requires that ecologists, economists, planners and policy-makers devise ways of managing important ecosystems that can yield benefits to the local community while at the same time conserving integrity of the systems. It requires, in short, that economic development and environmental conservation be brought into a sustainable relationship. Investment in the design of new, efficient economic incentives and structures for determining how to safeguard ecosystem services will have tremendous payoffs.

The Challenges Ahead

There are economic, national security, and human physical and mental health consequences that follow from the manner in which our natural capital has been, is, and will be managed from this time forward. We are struggling today with the unfortunate consequences of the management practices of the past and present, which have not been adequate to the task. If we are to continue to benefit from America's abundant natural capital, we need to develop a new framework that integrates greater ecological understanding with a more realistic economic appreciation and societal perception of biodiversity and ecosystem services. Such a framework for sustainable management of natural capital is proposed below.

These challenges include:

- Maintaining sufficient growth in agricultural productivity to meet the projected two to three-fold increase in global demand for food over coming decades;

- Finding means to mitigate the pressures on the waste absorption and detoxification services of natural ecosystems that are generated by use of fossil fuels, chemical fertilizers and pesticides, and other human activities;

- Restoring natural water purification services of ecosystems that are currently degraded by deforestation, draining of wetlands, and other activities that allow pollutants from agricultural, industrial and residential sources to move directly into water supplies;

- Discovering new species and their genetic capabilities to solve environmental problems and improve crops, health, and bioremediation;

- Mitigating the disruption of ecosystems caused by local or global climate change so that disease vectors living in those ecosystems do not threaten human health;

- Discerning the most efficient ways to preserve the Nation's biodiversity and the functioning of its ecosystems;

- Preserving recreational opportunities, including the simple enjoyment of natural areas and relatively undisturbed ecosystems rich in biodiversity that are at present threatened by pollution, urban sprawl, or intensive agriculture;

- Protecting national security from a number of threats that stem directly from effects of environmental degradation in various parts of the world (effects such as deterioration of human nutritional status, lack of safe drinking water, and energy scarcity):

- Well-being within US boundaries can be threatened by increased exposure to infectious diseases, which can rapidly spread from areas outside our borders.

- Resource scarcity and environmental deterioration abroad exacerbate tensions, which may lead to increased (and multiple) pressures for US intervention in violent conflicts.

- Mass migration of peoples away from degraded areas can lead to significant social disruption.

- Achieving necessary cooperation from other nations to deal with Earth’s environmental problems will require concerted efforts to reduce the global impacts of US consumption of products of biodiversity and of ecosystem services. With our prosperity comes an obligation to act responsibly, especially if we expect other nations to do the same.

Sustainable Management of Natural Capital

We offer a vision of a promising new framework for realigning the relationship between the environment and market economics. This framework would devise incentives to encourage the redirection of market forces so that they act to conserve rather than destroy ecosystem services. It would seek to illuminate profitable, efficient strategies for bringing the impacts of myriad human activities into balance with what Earth’s life support systems can sustain. This framework calls for the establishment of new economic instruments and methods, and it will require assigning appropriate economic value to natural capital and the channeling of market forces based on that value.

To achieve this vision and implement the framework, it will be necessary for biologists to gain an appreciation of economics and interact with economists. And, economists will need to work with ecologists and other biologists to develop a new way of thinking about biodiversity and ecosystems. This will involve a concerted policy and funding effort to generate the new and deeply cooperative research effort that is needed. Together, biologists and economists must conduct research of several types:

- identification and characterization of natural capital assets and the processes that generate goods and services from those assets,

- improvement of on-the-ground management of natural capital that balances the ecological needs of the capital assets with the economic needs of society,

- economic assessment and accounting mechanisms for tracking the status of the assets and the supply of goods and services, and

- means for generating market incentives for conservation of capital to promote the flow of goods and services over the long term.

Identification and Characterization of Natural Capital

The safeguarding of vital biodiversity and ecosystem services based on their economic value requires that they first be identified. In comparison to record-keeping involving physical and financial capital, little formal accounting has been taken of the stocks of natural capital. At a variety of scales, from local communities to nations and the entire globe, an explicit cataloging of biodiversity and important ecosystem services is needed. For any given geographic location, it is also important to know which of these services are supplied locally, which are imported from elsewhere, and which are supplied globally.

In addition to knowing what services are delivered, how they are delivered, and how important they are (in economic or other terms), it is critical that society be able to track trends in the quality and rate of supply of goods and services from biodiversity and ecosystems, just as it tracks similar trends in its financial goods and services. Sustainable management of Earth's life support systems requires widespread, systematic monitoring of ecosystem services all over the world, with measurements taken at appropriate scales. Because not everything can be monitored, indicators of various sorts need to be developed, tested, and refined.

We need to develop a sound understanding of the ecosystem processes that yield natural goods and services, such as water-purification or generation of soil fertility, if society is to make a rational evaluation of the tradeoffs it faces as it pursues material prosperity. This includes an understanding of how ecosystem services are generated by biodiversity, how susceptible they are to human disruption, and how amenable they are to repair. A brief outline of some of the important questions that require further research before they can be answered effectively can be found in Box 2.

Box 2:
Some of the important questions about ecosystems and the services they provide:

- What ecosystems provide which life support services?

- What are the relative impacts of alternative human activities upon the supply of services?

- What are the relationships between the quantity or quality of services and the condition (e.g., pristine vs. heavily modified) and spatial extent of the ecosystem supplying them? Where do critical thresholds lie?

- To what degree do ecosystem services depend upon the ecosystem being biodiverse (from the genetic to the landscape level)?

- How interdependent are the services? How does exploiting or damaging one influence the functioning of others?

- To what extent have various services already been impaired? How are impairment and risk of future impairment distributed geographically?

- To what extent, and over what time scale, are ecosystem services amenable to repair?

- How effectively, at how large a scale, and at what cost can existing or foreseeable human technology substitute for ecosystem services?

- Given the current state of technology and scale of the human enterprise, how much natural habitat and biodiversity are required to sustain the delivery of ecosystem services locally, regionally, and globally?

• Can we anticipate all the effects of perturbing a complex system and be alerted while there is still time to prevent serious consequences?

• How can ecosystems best be managed to preserve biodiversity and ecosystem resiliency?

Valuing and Accounting for Natural Capital as an Economic Asset

How can we measure the vital but largely unquantified values of natural capital and the goods and services that flow from it? No general, well-established methodology exists, and this is an area in which cross-disciplinary research is urgently needed. Possible methods of assessing economic value include calculations from:

- Direct Market Value: Sometimes ecosystem services contribute directly to the production of something that does have an established market value, such as timber. Assigning the value of an output to the resources used in producing it requires understanding on two fronts, scientific and economic, and at present this understanding is likely to be missing.
- Indirect Inference: Sometimes it is possible to infer from people's choices in other areas what value they place on an environmental attribute or service, even if there is no market for it or its products. A few approaches have been developed, but more and better ones are needed.
- Contingent Value: Another means of estimating worth of services is to ask people directly what value they place on them (that is, to ask people what they are willing to pay to preserve certain types of environmental assets). There have been many such studies, but their utility is a matter of considerable argument, because of the value-laden nature of the questions.
- Replacement Value: In the New York watershed example (Box 1), there was a well-defined cost to replacing the services of the Catskill ecosystems, namely the cost of engineering an artificial filtration plant, so that cost could be equated with the value of the ecosystem service. However, it is not always possible to apply this method.

We need new accounting systems that track both the biological status of ecosystem services and the measurement of their economic value. In particular, the national accounting system should incorporate both the usual measures of wealth (e.g., Gross National Product or Gross Domestic Product) and the long term environmental costs of unsustainable use of natural capital. Although research has begun to develop the mechanisms by which such a system of accounting could be implemented, we are far from having a satisfactory framework, and much additional research is needed. We also need national (or regional) ecological accounting systems in many respects parallel to our traditional national and regional economic accounting systems. The task of developing ecological accounting systems would be distinct from the task of modifying traditional economic accounting to include long term environmental costs.

Developing and Implementing a New Economic – Ecological Framework

The intelligent management of biological resources, both in the United States and throughout the world, requires a level of coordination that has been difficult to attain. Part of this report is devoted to an examination of some of the mechanisms that should be brought into play to achieve such coordination. Responsibility for the sustainable management of biodiversity in the US is distributed among a number of Federal agencies, and is also an important activity of state and local governments and of the private sector.

Management for the overall good depends on continuing to improve coordination among the activities of these entities. We urge that such coordination be approached as a matter of high national priority.

Mechanisms that will promote rapid information flow from science into sound management decisions are an absolutely essential part of this coordination and the implementation of the recommendations of this Report. Information flow facilitates coordination among different entities. Also, data that are held by government agencies, museums, libraries and other institutions are needed for the various types of research that are recommended. In addition, educational institutions, industries, and the public must have access to available information on biodiversity and ecosystems. Mechanisms to promote this vital information flow include networks, computers, computer programs, data standards, and so on—the components of an information infrastructure. Thus, major portions of this report are concerned with strengthening the current National Biological Information Infrastructure (NBII), which is part of the National Information Infrastructure, and supporting the computing, networking and information science and computer science research that will result in the "next generation" of the NBII. Very modest investments will go far to increase the information content of the NBII as it is currently configured. Larger investments are needed to achieve a significant step forward in information management and manipulation. The "next generation" NBII would be possible very rapidly for an investment of $90 million per year, but can be achieved with $40 million per year for five years, followed by reasonable yearly expenditures for maintenance.

New results from scientific research in several biological fields (taxonomy and systematics, genetics, population biology, ecology and ecosystems), and in the social sciences and especially economics, are needed to provide a sound basis for conservation and sustainable use of the Nation’s natural capital. Much of this research should be interdisciplinary, combining biological and socioeconomic efforts to develop economic incentives for all sectors of society to participate in conserving biodiversity and ecosystems. This report provides guidance as to the sorts of research that are needed and the means by which that research should be supported. Overall, support for research in the several areas discussed in this report (biodiversity cataloging, ecological pattern and process, economics, and the intersection among all of these) should be increased by 36% (a total of $138 million across a number of agencies). This investment will greatly increase knowledge of the biodiversity resources of the US, increase our grasp of ecosystem functioning and the means to restore it, and generate an understanding of the interaction of economics and ecology.

The results of the various research programs we recommend here, and information about environmental issues, should be shared with the American public. This information will be much more valuable if the populace understands the scientific approach to environmental issues. We recommend increasing support for agencies and institutions that provide scientifically centered informal environmental education and professional development for teachers, as well as the exploration (by another PCAST Panel, or a Presidential Commission) of mechanisms for improving the scientific basis for environmental education in the schools.

The approach we recommend weaves together insights from, and builds upon, the strengths of both the natural and the social sciences so that scientific knowledge, economic reality, and policy-making may be better integrated. Implementation of this approach will enable the United States to preserve and enhance its natural wealth, and to make the best use of that wealth in the long-term interests of its citizens. The measures we set out in this report are important for ensuring sustainable prosperity in the United States.

Section I

Make Use of Current Knowledge in

Managing Biodiversity and Ecosystems of the US

"These are our national treasures. When we maintain our national parks, nourish our wildlife refuges, protect our water, and preserve places like the Everglades, we are standing up for our values and our future, and that is something all Americans can be proud of. God created these places but it is up to us to care for them. Now we are and we're doing it the right way, by working together."

William J. Clinton, 12 October 1996

In order to manage the living resources of the United States and the world sustainably, it is necessary to use the scientific information that is currently available to inform conservation strategies at the local, regional, and national levels. It is also necessary to generate new knowledge to fill in gaps in our understanding—which is the topic of succeeding sections of this Report. Our first recommendations, however, concern using knowledge that we do have, organizing it electronically, and providing it to all parties that need it. To accomplish this, we will need to form partnerships among governmental organizations at Federal, state, and local levels, and between them and the private sector. These partnerships, using up-to-date information, can begin the process of developing coordinated local, regional and national strategies by designing best management practices and further sharing information.

Public-Private Partnerships Should Manage, Use, and Conserve Biodiversity and Ecosystems

Develop coordinated strategies for conservation and sustainable management of biodiversity and ecosystems of the United States.

This Panel was charged with recommending actions to improve the Nation's conservation of biological resources in the 21st Century. At present, governmental agencies and other entities that are responsible for managing the Nation's natural capital sometimes do so in an uncoordinated—indeed conflicting—manner, largely because they are operating from differing (and sometimes outmoded) knowledge bases. Also, many confrontations between advocates for the environment and defenders of commercial activities could be avoided or resolved by applying objective, scientific information—ready accessibility would enhance such use. Conservation and management should also be coordinated across all Federal, state, and local agencies and among governments and other managing entities. In fact, the United States should develop a comprehensive national conservation strategy, building from the elements which currently exist.

To formulate such a strategy, we need to develop, through public-private partnerships, an objective, accessible knowledge base. The expansion of the capability of the NBII to deliver, rapidly and accessibly, comprehensive and comprehensible information for devising strategies, making responsible management decisions, and resolving conflicts is an essential part of bringing scientific knowledge into the service of society. The Ecosystem Management Initiative, which attempted to codify information needs in different regions, was a beginning. An agreed-upon knowledge base can then be used to foster local, regional, and national conservation strategies that are biologically and ecologically acceptable and economically sustainable. The goal of these strategies should be net enhancement of natural capital, so that future generations may enjoy the bounties of nature as well as economic prosperity. These strategies should include mechanisms for managing and protecting ecosystems sustainably in the face of global change and guarding our natural capital in all its forms; they should also employ the best, most up-to-date scientific information available, and should evolve to incorporate new information as it is generated. There are already some excellent examples of such strategies that have been developed around the country under the leadership of non-governmental organizations, elements of the private sector, or representatives from local, state, and Federal agencies.

The Science Board of the Department of the Interior recently took a good step toward assuring the use of the best information available in policy decisions. The Science Board is chaired by the Secretary and includes the assistant secretaries and bureau directors. Each bureau has selected a significant management issue that should be informed by science but which may offer room for improvement in this respect. For example, the Bureau of Land Management has chosen to review fire management. A team, including representatives from other agencies in the Department, has been formed to review the inclusion of up-to-date science in the fire management decision-making processes of the Bureau. Following review, a presentation that includes analysis, steps planned for improvement, and recommendations on actions requiring authorization outside of the Bureau will be made to the Board. The review will be designed to answer several questions: Is the scientific information being used actually relevant to the policies and decisions that must be made? Has information been provided in a way that facilitates its use? Is the information timely? Is it credible? Is it understood by decision makers? Is it understood by stakeholders?

The process instituted by the Department of Interior Science Board is commendable, and should be considered for adoption throughout the government.

Any plan for conservation and management should:

- be based on agreed-upon guiding principles,
- incorporate mechanisms for managing ecosystems sustainably in the face of global change,
- protect critical ecosystems and rare and endangered species,
- minimize the introduction of non-native species and mitigate damages caused by invasives already present,
- account for the needs of society and the economy while guarding natural capital in all its forms, and
- provide for ongoing research to continually better our ability to live prosperously and sustainably on the benefits that we derive from natural capital.

The planning, thought, and exploration that would go into the development of these strategies for the sustainable management of biodiversity and ecosystems would be of great benefit to local communities, the Nation, and all levels of organization in between. Once developed, the strategies would guide future management decisions while allowing flexibility to incorporate new knowledge. In addition, the coordination of actions among various agencies would help to eliminate duplication of effort and therefore save funds that could be invested more wisely. Coordination also would illuminate research areas in which agencies and academia could cooperate, and would facilitate the development of information systems that would serve not only management agencies but also the public. The development process should provide forums for discussion, so that lessons learned by one entity can be instructive to many. We should build on and learn from efforts such as the Ecosystem Management Initiative, which attempted to discern the appropriate Federal role in regional management. At present, we are probably not gaining the full value of lessons learned from policy successes and failures. Forums also provide an avenue for input from the public and from the private sector, which in itself can be of great value in time and expense saved, opportunities for understanding gained, and in litigation avoided.

The absence of coordinated strategies for conservation is one factor that allows the continued degradation of our natural capital. If coordination of management and research activities among Federal agencies, and between the Federal government and other public and private stakeholders, is not achieved, many of these agencies will continue to manage inefficiently or to work at cross purposes with each other. This in turn leads to unnecessary expenditures, interagency conflict, public dissatisfaction, and mismanaged natural resources. In the absence of coherent strategies, it will become more and more difficult to bring the results of up-to-date research into management and policy decisions.

Individuals, companies, local communities, state governments, and Federal agencies all have a stake in the development of these strategies. A special role of the Federal government should be to provide a framework for activities at all levels and to provide for the integration and availability of the highest-quality information for these purposes. In doing this, it should facilitate the organization of workshops that would bring together knowledgeable people from government, academia, non-governmental organizations and the private sector to establish agreed-upon best practices for management of ecosystems. Compilation of regional best practices that emerge from the workshops would then enlighten a national strategy for managing Federal lands. Because much research has shown that greater biodiversity improves the services that ecosystems provide, and because of the importance of preserving biodiversity as a capital asset for future generations, the federal government has a special obligation to manage its lands to maximize their biodiversity. Indeed, such management is socially necessary and socially sustainable because both its costs and its benefits are shared equitably by all current and future generations.

The development of nationally coordinated strategies for managing biodiversity and ecosystems would be a natural outgrowth of the concept of "ecosystem management" that has been employed in several agencies in recent years, partly in connection with understanding the effects of global climate change on agriculture, human health, and in other areas. The budgets of these agencies should include funds for cooperating in the development of coordinated strategies for the sustainable management of biodiversity and ecosystems. Trained biologists and other specialists should be recruited by the agencies and promoted to management positions within them to insure that current understanding of the underlying facts and concepts involved in these strategies is represented at policy-making levels. Job descriptions, especially those for management positions, should be **rewritten** when appropriate to facilitate such recruitment and promotion.

All agencies with responsibility for managing biodiversity and ecosystems should be directed to cooperate in developing coordinated management of the nation's biodiversity and ecosystems. Certain elements of appropriate management are already in place or being developed, such as the plan for dealing with invasive alien species (see Box 3). Other topics that should have priority among management actions involve endangered species (see Box 4) and harmful marine algae (see Box 5). Coordinated efforts have already been developed to deal with some local situations. For example, the diverse group of stakeholders that constructed the San Diego Multi-Species Conservation Plan (see Box 6) includes private landowners and other citizens, representatives of conservation groups, universities, industries, and agencies at all levels of government. Similar activities, such as the Northwest Forest Plan and the public-private partnership that is working to save and improve the Everglades ecosystem, are underway throughout the Nation, and should be fully encouraged within a coordinated, national context.

Increase the Information Content of the National Biological Information Infrastructure

Promote and support rapid development of the National Biological Information Infrastructure to bring the most up-do-date scientific research available into local, regional, and national conservation strategies.

The National Biological Information Infrastructure (NBII) is that part of the National Information Infrastructure devoted to providing biodiversity and ecosystem information, and biological information in general. The NBII is not a single facility, but rather a distributed one that includes all institutions or agencies that provide online databases of biological information. However, the amount of information that the NBII can provide at the moment does not reflect even a small percentage of the body of ecological and other biological knowledge. There is much information available in the scientific literature and even in databases that is not part of the NBII and is not readily accessible, but which could be extremely useful in the generation of habitat conservation plans and other biodiversity and ecosystem management strategies. Steps should be taken to increase the online electronic information content of the NBII; these steps are outlined below.

Biological information about biodiversity and ecosystems is among the most complex scientific data to manage electronically, yet it is vitally important that we do so. There are intellectual challenges in the area of biodiversity information analysis, synthesis, presentation, validation and long term storage that require considerable information science and computer science research and infrastructure. In Section V of this report, we call for the research needed to enable the "next generation" NBII that will address these challenges.

In the meantime, however, there are data collection and provision actions that should be taken now to increase the biological information content of the current NBII. These include:

- allocation of a certain percentage of all research funding specifically for the long term management of the data and information generated by that research,

- development and adherence to data and metadata standards and best use protocols,

- provision of new funding for digitizing the data associated with specimens in natural history collections, and conversion of "legacy" ecological datasets, and

- setting of priorities to guide information gathering. For example, data on endangered and invasive species should have a high priority (see Boxes 3, 4, 5).

Other priorities, based on recommendations made in the National Research Council study "A Biological Survey for the Nation" (www.nap.edu/readingroom/books/ bio/contents.html), with which this Panel agrees, are presented in Access America section A04 (www.gits.fed.gov/htm/env.htm).

There are a number of current Federal agency activities that can improve the performance of the NBII if they are recognized by, and budgetarily supported by, upper levels of participating agencies as an important contribution to the NBII. These include the Integrated Taxonomic Information System (ITIS), the National Environmental Data Index (NEDI, [www.nedi.gov]), and CENDI, which was formed by an interagency (NASA, NIH and the Departments of Commerce, Energy, Health and Human Services, Defense, and Interior) Memorandum of Understanding to facilitate information management. Other agencies, notably the Department of Agriculture and its subsidiaries, should be directed to participate in these efforts, which should be coordinated so that duplication of effort is prevented.

Federal government expenditure on research, development, and management that is related to environment is on the order of $5.3 billion per year (including NASA expenditures for the Earth Observing System, and Department of Energy expenditures on global change and energy issues that are inextricably linked with other environmental issues). Of that amount, approximately $600 million is spent on information generation through research, data collection through monitoring, and the storage and analysis of data. Many of these data are measurements of the physical parameters of the environment. The biological data that would be delivered by the NBII can be combined with these data, making both more useful to all public and private sectors, and providing a greater return on these expenditures than would otherwise be the case.

Existing high-quality information is not currently being incorporated into management decisions. There are a number of reasons for this, but two of the most important are: 1) lack of electronic availability of needed biological information, and 2) lack of skill on the part of many resource managers to analyze and interpret that information. The recommendations for the NBII as described here will address the first of these shortcomings. The "next generation" NBII described in Section V will in part address the second by increasing the ease of use of information through software developments, and by providing a system that is driven by user needs. Of course, entities that employ resource managers will need to insist that those persons have appropriate skills.

The NBII is truly national, in that it interlinks datasets held by individuals, museums, governments, industry, and so on. However, the Federal government is a major user and provider of information, and should play a leading role in the development of the NBII, and participate in public-private partnerships to enhance the NBII. All agencies of the Federal government that hold or generate data that are relevant to biodiversity and ecosystems should be directed to:

- Make all data they hold (those in agency databases as well as those generated by the work of both intramural and extramural individual researchers whom they support) fully accessible via the NBII.

- Discover redundancies in data collection routines among agencies, and eliminate duplication of effort and expenditure wherever possible by combining efforts or utilizing data collected by another agency.

- Coordinate software and systems development with other agencies to eliminate duplication of effort and expenditure wherever possible.

- Cooperate with other government agencies, scientists, and the private sector to establish and adopt data and metadata standards, authority files and thesauruses for biodiversity and ecosystem information.

An NBII that is truly functional must be designed from the perspective of the users, and must be adequately funded to achieve the goal of full electronic accessibility to biological information for all citizens. Despite the great economic value of biodiversity and ecosystem services, the biodiversity and ecosystem information domain has not received adequate attention from professional software developers. The building of the NBII is an excellent opportunity to forge public-private partnerships in software development by providing incentives for private-sector developers to become engaged in this information domain. The Nation should harness the intellectual energies of small businesses by providing incentives for them to become involved. These incentives could take several forms:

- Contracts with mission agencies for specific developments, with follow-on agreements that provide a market for those developments;

- Cooperative agreements among several agencies and between them and the private sector for development and technical support of software that serves several agencies.

- Direct grants for exploratory developments in standards and software from the Biological Resources Division of the USGS, and from the Division of Biological Infrastructure of the NSF.

> Current budgets for these activities should be at least doubled over the course of three years, and thereafter maintained against inflation.

The US possesses approximately 750 million biological specimens in its natural history museums and herbaria. The georeferenced data (geographic coordinate data attached to the biological information) from these specimens is urgently needed as a tool to study status and trends of biodiversity and ecosystems, but the vast majority of this information has not been digitized. Also, literature dating back to the time of Linnaeus (mid-1700s) and before is still vital to the study of biodiversity and ecosystems. Therefore, critical Federal and non-Federal information resources (museums, libraries) will require funding to digitize their information and bring it online as a part of the NBII.

Funding for this effort should come in part from a partnership among state and local government, institutional, and private sources, but substantial Federal funding must be provided to leverage support from other partners. Clearly, the priority of the information to be digitized and the scientific merit of data-capture projects must be used as a criterion for allocating funds within a system of merit review. An appropriate mechanism for grants for digitizing data already exists. There is a working relationship between the NSF's Directorate for Biological Sciences and the USGS/BRD, first established by Memorandum of Understanding in 1995 and strengthened by several interagency agreements since. Therefore, USGS/BRD, in partnership with the appropriate NSF/BIO programs, could fund such projects based on the NSF merit review system.

Within NSF/BIO, approximately $3 million is available annually to proposals for museum data digitization. The relevant programs should, over the course of the next several years, make data acquisition a priority for proposals and awards, and the NSF should add significantly to the funds available to museums for information provision projects. Because the USGS/BRD is central to the development of the NBII, the agency's current budget for data acquisition should be increased by an order of magnitude within three years, and maintained against inflation thereafter.

SECTION II

Assess, Monitor, and Study the Biota and Ecosystems of the United States

"To learn more about where we stand in protecting all our biological resources ... and ... to help the agricultural and biotechnical industries of our country identify new sources of food, fiber, and medication."

William J. Clinton, 21 April 1993

"Biological information is the most important information we can discover. ...DNA is like a computer program but far, far more advanced than any software we've ever created."

Bill Gates, *The Road Ahead* (1996), p. 228

Ecosystems, whose properties depend on those of the organisms that occur within them, provide the basis for all human activities everywhere on Earth. Since the invention of agriculture approximately 10,000 years ago, humans have expanded from hunter-gatherer societies comprising no more than several million individuals scattered throughout the world into the overwhelmingly dominant force on the planet. During the second half of the 20th Century, human numbers have increased from approximately 2.5 billion to nearly 6 billion people, most of whom share high aspirations for material well-being. As a direct result of this growth, however, the characteristics of the atmosphere have changed substantially, agricultural lands have decreased by 15 to 20 percent, and a major proportion of the world's forests has been cut without replacement. No wonder that noted conservationist George Schaller has stated, "We cannot afford another century like this one."

To survive and flourish, humans must learn to make sustainable use of the Earth's living resources. To do so, we must deepen our knowledge of living systems and the organisms that comprise them. And we must make that knowledge available and employ it in constructing a world that will continue to support our societies and the needs of our children and grandchildren. Societies that master this knowledge and use it effectively will have a major competitive advantage. Understanding and managing ecosystem services, including individual organisms and their genes, will provide the key to sustainability.

In the following pages and sections, we lay out plans for a multifaceted, interdependent program of research and education that we are convinced, if implemented properly, will provide the United States with the knowledge it needs to sustain the Nation's prosperity for succeeding generations. Economics research, informatics research and infrastructure, and education are treated in sections three through five. The biological portion of this research program is addressed here, and has three major, intertwined components:

· Expansion of our knowledge of the biological resources of the Nation,

· Expansion of our system of environmental observatories so that we may know how we are impacting the life support systems of the Earth, and

· Expansion of our knowledge of the functioning of ecosystems so that we may better manage them.

Any of these three components could contribute to the knowledge needed for solving the environmental problems that our Nation faces. However, a real solution, and a truly sustainable future, can be gained only if the interdependence of the three branches is recognized and a multifaceted program of research carried out.

Assess the Biotic Resources of the United States

Discover and document the biotic resources of the United States, including species, their genetic diversity, and their distribution into habitats and ecosystems.

America is a nation of explorers and catalogers of diversity. Beginning with the request of President Thomas Jefferson to the Lewis and Clark expedition to explore the West and search for "minerals, soils, climate, peoples, and animals in their diverse kinds, as well as ...the dates at which particular plants put forth or lose their flowers or leaf, times of appearance of particular birds, reptiles or insects, " the Federal government has supported biodiversity research and exploration that has contributed to the development of our Nation’s economy. As need for sustainability increases, so should support for exploration and research that will meet the need. We are in a new age of discovery, equipped with newly developed tools unimaginable to explorers of the 19th Century, the last great age of biodiversity discovery in this country. We are also facing unprecedented needs for that discovery. There are willing partners in the private and academic sectors, but the Federal government must focus and provide consistent impetus for the intense discovery effort that is needed as we enter the 21st Century. This should be accomplished by strengthening systematic biology research programs, particularly for biodiversity inventory, as described below.

The United States, on the basis of its proportional representation of relatively well-known groups of organisms, harbors perhaps 500,000 or more species, or at least 5 percent of the world total. Of these, we have named fewer than 150,000, and even for most of those we know very little beyond the names. No wonder the management of our natural systems seems at present so difficult—without knowledge of the players, their roles and interactions in ecosystems can hardly be predicted. A recent study coordinated by the National Center for Ecological Analysis and Synthesis found that the factor that most hampers the success of Habitat Conservation Plans (HCPs) in preserving and restoring species and their habitats is lack of scientific information about the species involved. When there is scientific information about the species, it is well employed within the HCPs. The research discussed here will contribute to the body of knowledge needed for this and other purposes.

Research to document America’s species more completely is needed if we are to achieve full benefit from the economic and other opportunities that will inevitably follow from knowing the properties and interactions of species. In this discovery process, emphasis should be placed on those groups of organisms that are important for managing our habitats and ecosystems, enhancing the sustainable use and economic importance of these ecosystems, improving human health, and maintaining the productivity, sustainability, and stability of our agricultural lands, forests, streams and lakes, and coastal marine waters. Many organisms of substantial ecological and economic importance are among the least well known species in the US—fungi, nematodes (roundworms), mites, insects, and bacteria.

As our knowledge of genomes and genetics of individual organisms increases, it will be increasingly possible to locate and utilize the genes of individual organisms to improve the characteristics of other species used in agriculture, forestry, the chemical industry, and other economic enterprises. Knowledge of the nature and occurrence of individual species will provide the basis for such exploration. This program of research will significantly increase the supply of new genetic material for pharmaceutical and biotechnology industries, improve our ability to control harmful invasive species and prevent the demise of endangered native ones, and provide a scientifically sound baseline of knowledge for monitoring, assessing, and predicting the consequences of global change.

We suggest embarking on a ten-year mission to understand what biodiversity we have, where it is, how it came to be there and how it interacts with its habitats. This discovery project should include all kinds of organisms and all types of habitats (terrestrial, freshwater, marine).

There are several ways to survey biological diversity, and each has merit. One is to collect all the members of a particular major category of organisms, such as plants, in a particular geographic area (such as is being done by the Flora of North America project for the US and Canada). Another is to seek out all the species that belong to a particular group of organisms, such as a family of beetles, wherever in the world they might occur (as is done by monographic taxonomists). Yet another is to conduct an All Taxa Biological

Inventory (ATBI) of a circumscribed region. A project of this sort allows researchers to determine not only the identity and morphological characteristics of the organisms but also to accumulate information about their ecological interrelationships. Detailed inventories of small areas, perhaps as little as a hundred hectares, would reveal much about the interrelationships of organisms that are fundamental to the functioning of ecosystems. ATBI projects dealing with larger areas should also be conducted with an eye to establishing baselines for monitoring ecological changes and gathering information for educational programs and bioprospecting. An ATBI project in Great Smoky Mountains National Park is in the planning stages, and should be supported as one arm of the effort to document the biodiversity of the United States.

An inventory of the plants, animals, fungi and microorganisms of the US is such a large task that choices need to be made to maximize the efficiency of the activity and the utility of the results. We have deliberated about appropriate choices, and recommend some groups for intensive initial attention:

- Plants (vascular plants and "bryophytes") are fundamental to the structure and functioning of ecosystems, and are responsible for much of their productivity. Along with approximately 50,000 species of algae worldwide and up to a few hundred species of photosynthetic bacteria, plants are the only organisms on Earth capable of transforming light energy to chemical bonds in the process of photosynthesis, which ultimately is the basis of all life. Plants are relatively well known, with perhaps 90 percent of the estimated 260,000 species (worldwide) having been discovered. Because they are key elements in agriculture, forestry, and other productive systems, and because it is critical to make wiser use of them in the course of achieving sustainable development, plants should be explored in depth throughout the world and conserved to the extent possible. The Flora of North America project is providing the first complete synthesis of the estimated 20,000 species of plants in the United States and Canada, which will provide an indispensable basis for improved management, conservation, and use of our plant resources. It should be supported on an ongoing basis.

- Fungi, along with bacteria, are the decomposers of the biosphere and play a role indispensable to the continued existence of life on Earth by breaking down the organic materials accumulated by photosynthetic organisms. Fungi growing in symbiotic relationships with the roots of most kinds of plants (mycorrhizae), including all of the tree species native to the US, are indispensable to the healthy growth of those plants. Other fungi, such as lichens, harboring cyanobacteria or green algae, are major contributors to the biological productivity of many natural communities and to the input of nitrogen in these areas. Fungi are also major disease-causing organisms of plants and animals, including domesticated crops and livestock, and cause serious economic impacts by destroying organic materials such as wood, paper, stored food, and the like. Fungi also play a central role in many industrial processes, including baking and brewing. And, more than 3,000 antibiotics have been patented from fungi and bacteria. Despite their overwhelming economic and ecological importance, little attention is being paid to fungi on a broad scale, and only about 20,000 species of an estimated total of perhaps 115,000 in the US (70,000 of an estimated 1.5 million worldwide) have been discovered. Because of their significance and the fact that perhaps only a small fraction of the species in the US have been discovered, we recommend strongly that fungi be targeted for intensive inventory effort.

- Bacteria — The fundamental importance of bacteria in every living system on Earth is beyond question. They are also important as disease-causing organisms. Nonetheless, our efforts to date to learn about bacteria have been inadequate. Only about 3,000 species of bacteria have been characterized and named by being grown in culture and studied in detail, as required by current laws of naming them. However, the use of DNA sequencing methods to detect individual species regularly reveals the presence of 5,000 or more species, almost all unknown, in a single gram of soil. Bacteria exhibit metabolic diversity far greater than that of any other group of organisms, and occur in extreme habitats such as deep in the soil, under vast ice caps, in near-boiling hot springs, and in highly saline environments where no other known life forms can survive. The genes and enzymes that make these modes of existence possible have an obvious and direct commercial importance (see Box 7). Perhaps fewer than one in a hundred species of bacteria can be cultured using currently available techniques, but an improved inventory would lead to the discovery of many species of bacteria with properties that are economically useful (including novel genes) or ecologically significant.

• Insects and Other Arthropods—

Hymenoptera—Bees, wasps, and ants are among the most beneficial insects. Bees are the foremost insect pollinators of flowering plants. Wasps are important parasites in natural systems and are essential biocontrol agents for pests such as the gypsy moth, worms, flies, and scales that attack food crops and forest ecosystems. Ants play a major role in terrestrial ecosystems by influencing soil fertility and acting as predators and decomposers. About 17,500 species have been characterized in the United States, with thousands more awaiting discovery. Increased knowledge of the estimated 36,000 US species will significantly improve our ability to manage agricultural ecosystems.

Hemiptera—As many as a third of the true bugs found in the United States have yet to be discovered and described. This is an important gap in our knowledge of the insect fauna because true bugs are major plant pests of forest ecosystems, corn, rice, soybeans, fruit trees, and numerous horticultural crops and ornamentals. They are also the source of dyes and lacquers, and are of potential importance for new biotechnology products. Further, some have been used in weed and insect biocontrol.

Coleoptera—Beetles are the most diverse of all groups of insects (a conservative estimate is 25,000 species known from the US, with another 7,000 undescribed), and thus are critical components of all terrestrial ecosystems. Beetles are also economically important. In the United States, bark beetles are the most economically devastating forest insect pests, causing the annual loss of well over 8 billion board feet of standing timber worth about $2 billion. Another group of beetles, the weevils, is highly diverse (over 2,600 are known, but hundreds of additional species remain to be discovered and described for North America north of Mexico). They are pests of fruit, ornamentals, and field crops, and effective control programs will require much more taxonomic knowledge of the group. Some other beetles, in contrast, are beneficial, yet we have insufficient understanding of their diversity. Among the estimated 3,200 or so US species of rove beetles, for example, are numerous species with potential biocontrol importance.

Lepidoptera (butterflies and moths) are among the most widely appreciated insects, yet most species are small and nondescript, and the majority of these have not been discovered or described. Many moths are agricultural pests. As noted above, butterflies are useful index organisms for understanding the fate and function of natural communities. Yet even in these economically and ecologically important groups, our understanding of their diversity remains incomplete: there are about 14,000 US species, with up to an estimated 3,000 remaining to be described.

Aphids are well known to the public as pests of plants and cause millions if not billions of dollars of damage each year. They also serve as important vectors of a wide diversity of plant diseases. They are diverse, but about 66% of the fauna is undescribed.

Gall midges are cryptic little flies that form galls on various parts of crop plants; an example is the Hessian fly, which is a major pest of wheat. Gall midges are very diverse but about 80% of the species are undescribed. It is highly probable that many species could be used as indicators of the status of various natural ecosystems.

Spiders have a high profile because they are encountered by the public on a daily basis, a few are medically important, and they are one of the most abundant and influential components of agricultural ecosystems, thanks to the fact that they prey on many different kinds of insects. They are diverse, but about 20% of the fauna remains undescribed.

• Soil and Sediment Microorganisms—

Soils and sediments are a critically dynamic center of global ecosystem processes. Microorganisms control many soil and sediment functions including, among others, nutrient cycling, formation and decomposition of organic matter, transport and degradation of pollutants, and provision of clean water. Knowledge of soil organisms and their contributions to ecological processes is essential if we are to maintain and manage ecosystems properly and secure the Nation’s food supply. Yet, soil and sediment microorganisms (bacteria, protozoa, annelids, nematodes, oligochaetes, polychaetes, termites, ants, mites, fungi, and others) are severely understudied. One group that is particularly poorly known is the nematode worms. There are approximately 20,000 named species, but conservative estimates place the actual number closer to one million. Likewise, mites (including chiggers and ticks) have a high profile because they are important plant pests and are vectors of diseases. Yet, with fewer than 40,000 mite species discovered and described, it is estimated that the global total may approach 1 million species.

• Marine Invertebrates—

The marine biota is very poorly known compared to the terrestrial biota. An increase in our understanding of the components of marine ecosystems will be essential if these systems are to be saved. There is a need to explore and improve the taxonomy of virtually all groups of marine invertebrates. This is fundamentally important because of the vital contribution invertebrate animals make to all marine communities. In addition, the widespread introduction of many species of marine invertebrates throughout the world is having an important negative impact on fisheries and other industries. An improved understanding of these introduced organisms is fundamental to managing them properly. Such a program, however, presupposes that the basic taxonomy of these groups exists. It does not.

Biological Surveys

These surveys will require coordination of concerned governmental agencies at Federal, state, and local levels; museums, universities, and other institutions that contain systematics collections; and other stakeholders. This partnership would appropriately be led by the Department of Interior’s US Geological Survey Biological Resources Division (USGS/BRD) and the Department of Commerce’s National Marine Fisheries Service (NMFS), which is part of the National Oceanic and Atmospheric Administration. The survey should be funded through the USGS/BRD; NMFS; the Divisions of Environmental Biology, and Molecular and Cellular Biology, of the National Science Foundation (NSF); and the Department of Agriculture, particularly its Agricultural Research Service. The Smithsonian Institutions’ National Museum of Natural History would logically play a major role in an invigorated national biological survey, as would many other public and private organizations. In this mix, universities have a unique importance because of their educational role. Collectively, the taxonomic and systematic activities of these agencies and organizations are funded at approximately $55 million per year. Over a period of three years, this level of support should be raised to at least $88 million per year, and maintained against inflation thereafter. Other organizational and programmatic aspects of this program of discovery-oriented research and the partnership that would support and guide it are described in greater depth in the National Research Council’s report, "A Biological Survey for the Nation."

As this ten-year effort continues, it must be evaluated and fine-tuned, based on the ecological and systematic insights obtained. The knowledge will contribute to the formulation of plans for sustainable development. The research will also produce new understanding of the roles of species within ecosystems, and new products, including genetic material for the agricultural and pharmaceutical industries. In short, the U.S. must organize an effort to understand its own biodiversity and ecosystems, a substantial source of national wealth, that equals the scale and intensity of similar efforts that have been underway for some years in countries such as Costa Rica (INBio) and Mexico (CONABIO). Just as these efforts have produced benefits for their countries, so a similar project in the United States will yield direct, measurable benefits for Americans.

Benefits derived from this program of research would include:

- Sustainable agriculture. Throughout the world, advanced agricultural systems are in the process of reducing the amount of pesticide, fertilizer, and herbicide usage by emphasizing practices such as biological control, integrated pest management, and sustainable agriculture. These technologies rely heavily on our knowledge of pest groups, their plant hosts, and the natural enemies that keep them in check. Taxonomic information is the language and predictive basis for this enlightened agricultural management and improvement. We can expect, for example, that thousands of potentially useful biological control agents exist that are currently unknown to science. Before they can be economically useful, however, these organisms must be discovered, described, and integrated into classification and information systems. If organisms that can enhance productive and environmentally sound agroecosystems remain unknown or confused with other organisms, progress in agriculture will be hindered. In addition, the search for new crops, and the improvement of existing crops through biotechnology, depend on the exploration and understanding of biodiversity in the United States and beyond.

- Human health. Protection of human health depends in part upon documentation of disease-causing organisms and disease vectors. Even the most innocuous bacterium or virus can be life-threatening to persons who become immunocompromised by diseases such as AIDS or by drug therapies for cancer, burns or transplants. Many diseases are undergoing a resurgence (example: tuberculosis) because they are evolving drug resistance. Other, previously unknown diseases are emerging. The process of discovering, describing, and understanding disease-causing agents is essential for developing new antibiotics and vaccines, as well as protocols for better sanitation and diet aimed at maintaining and improving human health.

- New pharmaceuticals. Drugs derived from the world’s species save countless lives and generate many billions of dollars in sales worldwide. Most of the species within those groups of organisms that have the greatest potential to provide new sources of medicines have yet to be discovered or described. For example, bacteria are diverse and constitute a major source of new pharmaceuticals and other biotechnology products. The better their diversity, and that of many other groups of organisms, is understood, the more likely it is that we will discover useful genes and gene products, and their functioning and interactions.

- Resource management. Products derived from the fisheries industry provide a primary source of high-quality protein for many people. Differentiating among species of fish and other commercial seafood is of obvious importance for managing these natural resources and selecting species for aquaculture. Invasive species are a major problem within marine ecosystems and threaten to disrupt some of the Nation’s most productive fishing grounds such as the Gulf of Mexico; these species also need to be identified and understood.

- Biotechnology. Our rapidly growing knowledge of the relationship between genes and an organism’s chemical and physical characteristics is the key to many vital advances in the future. In particular, our newfound ability to transfer genes between distantly related species of organisms will play an increasingly important role in the improved biological productivity of the future. Transgenic organisms will become increasingly important as components of agricultural, health, pharmaceutical, and resource management activities. For example, it is possible in principle to alter the nutritional value of crop plants according to the specific health needs of particular individuals or groups of individuals, or to intensify integrated pest management with the introduction of readily-produced transgenic organisms. Taxonomic knowledge of organisms will serve as the route map in our search for appropriate genes to produce desired characteristics.

Economic losses suffered by the United States every year because of lack of species knowledge include but are not limited to:

- Loss of Agricultural Productivity.
  - The Office of Technology Assessment estimated in 1993 that the Nation spends $3.6 to 5.4 billion annually to mitigate the effects of invasive species. Without knowledge of those species, a predictive long-term control program is more difficult and costly.
  - Fungal and insect damage to agricultural crops in the US costs more than $7 billion annually. The lack of accurate descriptions and identification of these pests greatly hinders the discovery of natural biological control agents.
  - The US annually imports billions of dollars worth of agricultural commodities; with these may come exotic pests and pathogens that damage domestic production. Taxonomic studies of these organisms are essential for controlling them.
- *Soil Function and Depletion.* Soils act as living systems whose properties are determined by interactions among the fungi, bacteria, and other small organisms that occur within them. These organisms also form symbiotic relationships with the roots of plants, enhancing plant productivity. Although soil organisms provide many obvious benefits to agriculture, water quality, and ecosystem resilience, the identity and function of those organisms is very poorly understood. This understanding is needed to improve management of agricultural and other ecosystems.
- *Loss of Timber to Forest Pests.* Insect and fungal pathogens, of which bark beetles and their mutualistic fungi are the most economically important, cause domestic economic losses of timber more than 8 billion board feet, estimated at $2 billion annually. Many of these organisms remain uncharacterized.

Increase the workforce capable of carrying out these tasks by creating jobs in both the public and private sectors, and by supporting training and education of taxonomists.

Numerous national and international organizations, including the United States National Science Board, the National Academy of Sciences, and the Subsidiary Body on Scientific, Technological and Technical Advice to the Conference of Parties of the Convention on Biological Diversity, have recognized the urgent need for taxonomists with expertise in organismal groups other than large vertebrates. Evidence for this need includes:

- the importance of biodiversity and ecosystems to human life,
- current understanding of how little we know about biodiversity,
- a species extinction rate estimated to be some 10,000 times greater than the normal rate across geological time,

- mismatch between the numbers of species in a group and the number of taxonomists trained to work on that group, and

- the diminished employment opportunities for taxonomists and systematists compared to previous decades, particularly in universities.

The numbers of trained taxonomists and systematists who have jobs devoted to the great task of mapping the diversity of life locally or globally is woefully inadequate to the task. This is true particularly for specialists who focus on organisms such as fungi, bacteria, nematodes, mites, and many groups of insects. Nevertheless, knowledge of these organisms, because of their ecological and economic roles, is of critical importance to the US and world economies. A sustained dedication to the establishment and maintenance of adequately paid jobs available to experts on such groups of organisms will facilitate commercially-important progress in agriculture, health, and biotechnology.

New employment lines (FTEs) for taxonomists and systematists of United States biota should be added to the systematics laboratories of the Agricultural Research Service, and in other agencies that are stewards of the country's natural capital (particularly the Department of Agriculture's Forest and Natural Resource Conservation Services, the Department of Interior 's Bureau of Land Management and National Park and Fish and Wildlife Services, and the Department of Commerce's National Marine Fisheries Service). The taxonomists that are already on staff and those that should be hired could all be more productive if each were provided with a technician. These positions, at GS-5 level, would represent a very modest investment in the greater productivity of highly trained Ph.D. scientists (usually GS-13 or higher). In recent years, positions for support staff have eroded so much that GS-15s are now forced to spend time on GS-5 level work rather than their own. This is a clear misuse of training, talent, and salaries, and should be rectified as rapidly as possible.

In addition, support for natural history institutions (museums, herbaria, arboreta, botanical gardens) of the Nation should be bolstered so that they also can add staff positions (see next section). The existence of these jobs will entice many more bright young people into systematics than are currently entering the field. Many students are interested in the discipline, and do well in courses in taxonomy in college, but ultimately turn to other majors because they do not perceive an employment future in systematics.

Moreover, we need to foster partnerships between taxonomists, ecosystem ecologists, and applied biologists because of the contribution that taxonomists can make to the discovery of organisms that may help to solve agricultural, medicinal, and environmental problems. This could be done, for instance, by awarding career credit (promotion, pay increases, etc.) to the participants in such collaborations.

The Partnerships for Enhancing Expertise in Taxonomy (PEET) program of the National Science Foundation's Division of Environmental Biology has gained worldwide recognition as a visionary effort to redress the "taxonomic impediment" that has been perceived by the governments of almost every other nation on Earth. To provide training that results in scientific expertise in taxonomy, systematic biology and collections management, the United States should increase and sustain its investment in this program.

The total investment in PEET to date (3/98) has been $10 million, for the funding of 31 research projects that are each training at least two new taxonomists (in some cases three or four). As impressive as these numbers are, much more needs to be done. We recommend that the PEET competition for funding be conducted every year rather than every other year, and that the awards total $10 million per year, beginning with the next NSF funding cycle and continuing for at least ten years. At present, only the NSF is funding the PEET program. We recommend participation and contribution to the funding by all of the Federal agencies that have biodiversity management responsibilities. The NSF should retain the lead in proposal review. The measure of success will be a workforce of taxonomists engaged in discovering biodiversity and the economic benefits that can be derived from it.

By hiring professionals to do systematics and surveys, and by consistently supporting the PEET initiative, the United States will begin to build the body of trained personnel needed to help provide the scientific basis for managing our biodiversity resources. We cannot understand ecosystems, or their productivity and functioning, if we do not even know the identities of the organisms that live in them.

Lack of taxonomic expertise also leads, for example, to missed opportunities to capitalize on understanding the characteristics of close relatives of newly discovered organisms, and to learn more about the mechanisms by which organisms defend themselves, adapt to changing conditions, and maintain their integrity in the face of environmental challenges. Such knowledge of other organisms could easily and immediately become critical to our own survival and well-being.

Expand the capacity of the nation's biodiversity research collections of all types (extracted genetic, living, and preserved), and support the electronic capture and distribution of the information associated with their specimens.

The natural history collections of the United States (found in natural history museums, herbaria, university facilities, and in governmental agencies such as the Department of Agriculture and Department of the Interior) contain at least three-quarters of a billion specimens of plants, animals, fungi, and microorganisms. These collections document the existence of species now extinct, allow us to track expansion of the ranges of invasive species, and make it possible to answer all manner of other questions about species and organisms. The specialized libraries and databases associated with these collections comprise a record of the history of the Nation's natural capital. Systematic collections of living organisms are maintained in aviaries, aquaria, arboreta, botanical gardens, seed banks, and zoos or in specialized repositories of germplasm, frozen tissues, and cultures of microorganisms (see Box 7).

Collections are essential resources for many areas of applied biology, including the health sciences (parasitology, epidemiology, diagnostics), agriculture, resource management, and biotechnology. Studies of specimens preserved in collections, for example, were central to documenting the presence of DDT in the environment and the historical pattern of mercury contamination in the Nation's rivers. Collections also provide extensive support for informal and formal education programs, as well as professional development for K-12 teachers. Through exhibits, collections provide entertainment and promote public awareness of nature and biodiversity.

The research program to inventory the biota of the US will generate many specimens that must be placed in collections as a record of our discoveries. These specimens will be a baseline against which to measure and monitor environmental change, and serve many other functions in scientific research. However, US systematic collections are underfunded, and are highly challenged to properly care for the specimens they already have, much less to absorb those that will result from the biotic survey that must be done.

Moreover, the vast majority of the information about our natural resources that is already contained in natural history collections and their libraries is not readily accessible online in databases and Web pages. To meet societal needs, this information must be made available as part of the National Biological Information Infrastructure.

Biodiversity research collections have immediate and pressing needs for:

- expansion and upgrade of the infrastructure for collections (new space and equipment), and

- trained people to bring collections data online and care for the specimens that voucher those data.

These needs must be addressed as a part of the research program to search out new species.

Current funding for federally supported collections (those of the Agricultural Research Service, the National Park Service, and the National Natural History Museum of the Smithsonian Institution) totals approximately $5 million per year, and Federal grant funds for collections managed by other institutions total approximately $14 million per year (from the National Science Foundation's Research Collections and Living Stocks programs in the Division of Biological Infrastructure, and the Institute for Museum and Library Services). Over the next three years, these amounts should be raised by at least 70%, and maintained against inflation thereafter.

The benefits of supporting and strengthening the nation's biodiversity research collections will be measured by the benefits gained from a more thorough knowledge and record of the actual biotic resources (genes, gene products, and species) that form America's living capital, and by a significant increase in the biodiversity information content of the NBII. In addition, having the data from the Nation's collections in electronic format will facilitate a rapid tally of what is known and is not known and what localities have and have not been explored for their biodiversity. This will help prevent duplication of research effort and facilitate focusing attention on sites that are either completely unknown or likely to host significant diversity.

These increases in funding for biodiversity research collections infrastructure will ensure that the collections will be available to contribute to our understanding of the nation's natural resources and therefore to our continued economic prosperity. Improvement in collections care is a continuous process, because collections must be maintained indefinitely. Enhancing the infrastructure, with substantial investments over the next several years, will be a necessary ingredient for achieving the economic objectives outlined in this report.

Measure the Status of the United States' Biotic Communities and Ecosystems

Continue interagency participation in and support for the Environmental Monitoring and Research Initiative, especially in promoting public - private partnerships.

A certain level of interagency coordination in management of biodiversity and ecosystems by the Federal government has been achieved through the Committee on Environment and Natural Resources (CENR) of the National Science and Technology Council (NSTC). This coordinated effort has focused on the Environmental Monitoring and Research Initiative and the call for an "Environmental Report Card" on the status of the Nation's ecosystems. The Report Card promises to make possible better application of both new and currently available knowledge to a wide variety of management decisions at Federal, state, and local levels. By involving academia, the private sector, and agencies of state and local governments, this effort will help us devise the most suitable solutions to environmental problems. The Report Card process represents an important model for national decision-making, and we recommend strongly that public-private partnerships such as those formed during the Report Card process be pursued actively and consistently.

The data that will be used in the Report Card on the status of ecosystems, and the research that will elucidate ecosystem trends, will come from three tiers of data collection. The first of these tiers is remote sensing (such as by Landsat); the second is systematic, national on-the-ground sampling; and the third is a system of index sites at which cause-effect relationships can be examined through experimentation and monitoring. The Federal government has the strongest need to develop and synthesize a national picture, but there are many excellent opportunities for public-private partnerships in the process. To maximize the usefulness of the results of these activities, they must be coordinated while remaining distributed across the country.

The CENR can and should function as the coordinating body that keeps agencies working together and cooperating with other entities. Without this coordination, there will be a tendency for agencies to move in separate directions, for the level of communication between agencies and academia or between agency researchers and managers to decline, and for the critical mass of scientists needed to advance ecosystem management research to disperse. As a result, management actions might become less coherent than they are today.

The Administration will need to ensure that all of the agencies under the aegis of the CENR invest the time and expertise of appropriate personnel in the Environmental Research and Monitoring Initiative so that an environmental baseline (the initial Report Card), against which changes and trends can be compared, can be established as rapidly as possible. The lifetime of the "initiative" should only be long enough to establish the processes by which environmental research and monitoring should be conducted on a constant and continuing basis, and at that time it should become the Environmental Research and Monitoring Process (or Project) and have no "sunset" on the horizon. The need for the process will be unending, as will the need for the cooperation of many agencies and entities in the conduct of the process. There should be a self-evaluation component to the process that will constantly improve the output.

Evaluate existing ecological observing systems, and identify and implement any needed improvements.

A prototype Report Card will be developed by the spring of 1999, and will cover three major ecosystem types (forest, crop lands, and coastal/marine). The first complete Report Card, in 2001, will be expanded to include rangeland, fresh water, and urban ecosystems. For each ecosystem type, the status of goods, services and other valued attributes (e.g., extent, productivity, ecosystem condition, recreation and aesthetics) will be compiled. The Report Card will provide a summary of the status and trends of our Nation’s ecosystems that is easily accessible to the general public and firmly based on the sorts of scientific information used by researchers and resource managers.

To be able to proceed from the current status report and investigate trends and directions of ecosystem change, researchers will need data that are appropriate to the kinds of questions they will be asking, taken on a scale appropriate to the size of the ecological region and/or the dimensions of the ecological process being considered. For instance, the sorts of data needed to investigate the relationship between ecosystem structure and biogeochemical cycling differ in scale and type from those needed to study the relationship between biological community functions and species-level biodiversity. To enlighten management practice, data amenable to research at all scales will be required.

The data on which the first Report Card will be based have been collected by a number of agencies, for a number of purposes, using several different methods. It may be that the same kinds of data are being collected by more than one agency (unnecessary duplication of effort), or that the data being collected are inadequate to the tasks for which they are needed, or that data on one environmental parameter cannot be combined with or compared to data on another environmental parameter for any one of a variety of reasons (different data structures, scales of measurement, region of coverage, times at which the data were collected, etc.), or that there are flaws in the systems that accumulate data from a variety of sources.

Once the Report Card process has identified what kinds of data we do have, it can be used to elucidate the information that we need but are not at present collecting. Or, it may demonstrate that data collected for another purpose may in fact be taken "off the shelf" and put to new uses. The utility of the data we are currently collecting should be evaluated, and means of improving and streamlining data capture should be devised and tested. This evaluation of the quality of the data and the outputs of data-collection activities should be conducted on a regional basis. A pilot evaluation project of this type is currently underway in the Federal Mid-Atlantic region.

Certain outcomes of these regional evaluations can be predicted with reasonable certainty. For instance, the current land-cover map of the US generated using remote sensing is at a scale (1 km) that is acceptable for low-resolution landscape analyses but is not meaningful for many biological studies. The 30-meter land-cover data set, generated from Landsat data and processed for Federal regions using a consistent protocol by the Multi-Resolution Land Characterization (MRLC) consortium of Federal agencies, will be much more useful in biodiversity and ecosystem studies. The MRLC consortium plans to produce from this dataset a 30-m resolution land-cover map of the conterminous US. The planned completion date is the year

2000. This Panel recommends that efforts be concentrated on completing this map on time or ahead of schedule.

Another outcome of the evaluations will very likely be the recognition that the degree of integration among the three tiers of data collection (remote sensing, systematic sampling, and indexing) is insufficient. Effort must be invested in making it possible, for instance, to address a question such as "what is the relationship between the ecosystem size needed to maintain biogeochemical integrity and the size needed to maintain the naturally occurring species diversity of that ecosystem?" Such a question requires that data from all three tiers be compiled and validated, the correlations among them identified, and analyses performed. Grappling with this type of question will be easier as coordination of data collection and information management methods are improved. This coordination will be challenging to achieve, but the effort must be made in order to enable the kinds of analyses of multiple factors that are required to develop sustainable management strategies.

An ongoing evaluation process that points out means of improving the effectiveness of data will raise the quality of the research that depends on those data, and this in turn will improve the ecosystem management strategies that are based on that research. In its role as coordinator of the nation's environmental research and monitoring effort, the Federal government should be vigilant that its agencies are consistently evaluating, validating, upgrading their data-gathering and environmental observation activities on the basis of those evaluations, and ensuring that they are relevant and useful to research, policy, and management decisions by government and by citizens.

Expand the nation's system of "environmental observatories" and bolster the research and modeling that are conducted at these sites.

In order to answer the sorts of societally and economically important questions exemplified in the Introduction to this report, we will need a great deal of experimental and synthetic ecological and ecosystem research. This research should address:

- fundamental questions about the effects of land use and management practices, patterns, and intensities on biodiversity and on the sustainability and stability of both ecosystem processes and biodiversity;

- the amounts and kinds of biodiversity needed to sustain the services provided to humanity by both natural and managed ecosystems;

- the amounts, sizes, and geographic distributions of reserves required to preserve the critical levels and compositions of biodiversity needed to sustain functioning of ecosystems;

- the factors that influence the assembly of ecological communities and ecosystems, including those that control invasions by exotic species and the impacts of such invasions on ecosystem processes and biodiversity.

There are several components of ecosystems that must be accounted for in this research, including:

- Chemical cycles: Organisms are a dominant factor in chemical element cycling and storage and therefore regulate many aspects of global processes; yet, these cycles remain insufficiently understood. For instance, different forms of nitrogen, and apparently the chemical transitions between these forms, affect both organisms and water quality differently. Very little is known about the underlying processes that make this so.

• Community characteristics: Basic information on the number and distribution of species is limited, as is our understanding of the connection between species and the factors that enable species to become established, thrive or decline.

• Spatial structure and temporal change: Relationships between biological communities and the physical structural elements of the environment, their evolution over time, and their relationship to diversity are insufficiently understood.

• Scaling: Process research has generally been limited to small areas. Management-scale experiments have been limited and extrapolation may not be simple; conversely, present modeling efforts often cannot be brought down to the scale of decisions about specific locations.

In addition, increasingly sophisticated modeling paradigms and algorithms will be important tools, not only for the conduct of the theoretical research to understand our living resources, but also for translating the research results into useful and usable tools for ecosystem management. In current practice, geographic information systems (GIS) are often used to integrate data and aid in decision making based on what is currently known. What is needed in addition to GIS are predictive models based on understanding of process that are capable of incorporating various land use and management strategies. Such models should reflect fundamental ecological principles, including natural variability and the non-steady-state nature of disturbed as well as non-disturbed ecosystems. The software for these modeling exercises should be accessible through the "next generation" National Biological Information Infrastructure (NBII-2) that is described in the next Section of this Report.

To make these advances possible, it will be necessary to expand support for ecological and ecosystem research in academic and other institutions. It will also be necessary to increase the size of the nation’s system of permanent research sites at which the environment is observed; experimental, comparative and synthetic research is conducted; and predictive models are generated and tested. The Long Term Ecological Research network of sites, currently incorporating 20 research areas, should be increased to more thoroughly cover the range of America’s ecosystems (especially important to add are the full range of marine ecosystems from coral reefs and major fisheries to the open oceans). Additional areas, for example national parks or Man and the Biosphere reserves, should be established as centers for the types of research described here. The nature of this research will also require an increase in the number of monitoring and research sites maintained by agencies such as the EPA, NOAA, the Department of Energy, the US Forest Service, and the USGS/BRD. Also, assurance of access for researchers to Mission to Planet Earth and Landsat data and data processing are important to this effort. A number of agencies already have a stake in the support facilities needed for this research, including NOAA, the Forest Service, the USGS, the EPA, the Department of Energy, and the NSF. Current investments (approximately $300 million per year, spread across the several listed agencies) should be enhanced by approximately $55 million per year in order to increase the return on this investment, with the greatest additions made to programs that use rigorous peer review. Infrastructure capacity and performance by Federal agencies that already have research and monitoring sites in place should be increased immediately; the remainder of the increases should be accomplished within three to five years.

Clearly, the manner in which America's living capital is currently being managed and used is not sustainable. The research strengths of all Federal agencies, academia, and the private sector should be mobilized as rapidly as possible to protect the ecosystems that generate goods and services while providing the benefits of those goods and services to the American public. The urgency of the need to bring the economy and the environment into a sustainable relationship (see Introduction and Section 3) compels urgency in this research agenda as well. Many researchers must be engaged as rapidly as possible in order to meet the challenge, and therefore a significant investment is required. However, the investment will be well justified if we gain an ability to shift toward sustainable management of America's living capital.

Augment the Scientific Basis for Ecosystem Management

Conduct a concerted program of research, designed to discover fundamental principles, on the functioning, structure, and sustainability of natural and managed ecosystems.

The ongoing discovery and monitoring of pattern, and the correlation of pattern and process, have already provided us with a certain level of understanding of the structure of ecological systems. However, our current understanding is inadequate for predicting the long-term costs and benefits to society that may be associated with alternative ecosystem management practices or environmental policies. The stated goals of the annual performance plan (required by the Government Performance and Results Act) of the Bureau of Land Management include "restore and maintain the health of the land"; those of the National Park Service include "natural resources...are protected, restored and maintained..."; and those of the Forest Service include "restore and protect ecosystems." Restoration implies an understanding of appropriate manipulations—and yet if we do not have the results of the research described in this section, the non-linear surprises of ecosystems will confound any manipulations that we institute. These agencies and others will not achieve their performance goals, and the Nation will not benefit from the improvement in ecosystem goods and services that is implied in their goal statements.

At the present time, it is difficult to clearly identify an optimal management practice. This is because the relationships between structure and function and those between cause and effect are not yet fully understood in either the temporal or geospatial dimensions of ecosystems. These relationships are non-linear, and therefore full of surprises. Or, to put it in the words of the author G. Harry Stine, "You can't fool mother nature (but she can fool you)."

If we are to gain fundamental insights that will enable clearer decisions among alternatives, new research must be conducted to show us the ecosystem parameters needed to maintain biogeochemical integrity, those required for the maintenance of species diversity, and the relationship between these two sets of parameters. We also need to know what processes control the functioning of natural and managed ecosystems and influence the assembly of ecological communities and ecosystems, which factors promote or repel invasions by exotic species, and what impacts species invasions and extinctions (separately or in combination) have on ecosystem processes.

Case studies of how ecosystems are being managed, or of the suite of ecological research projects that are being conducted in various regions of the country, show that both management and research tend to differ among ecosystems. Ecologists working in one ecosystem have tended to focus on one set of questions while those working in another ecosystem have focused on another. Ecosystem management efforts are hampered by lack of knowledge of the broad framework of the fundamental organizing principles of ecosystem function and ecological process. There is a critical need for research directed at discovering a framework of fundamental ecological principles and at testing the utility of that framework.

The Federal government is itself the steward of fully one-quarter of the nation's natural capital (as measured in land area). Often, the decisions made about the management of one ecosystem differ from those made about another (even within a single agency), in part because of the absence of an an objective, accessible knowledge base and a common understanding of fundamental principles. Therefore, this Panel calls for a concerted effort to enable both intramural and extramural experimental and theoretical research. Research results from studies of the kind described here would 1) facilitate more consistent decision-making and the attendant efficiencies of scale, and 2) lead to better means of improving the status of perturbed ecosystems.

Theoretical research is essential in order to make proper use of all the data that are collected by empirical research and monitoring efforts. Theoretical science involves the formulation and testing, against real data, of hypotheses, some of which may turn out to be general principles. It also involves construction and study of models and simulations. Sometimes these models and simulations are relatively simple, abstract ones exemplified by a few mathematical equations. These may share only a few critically important features with real systems. Or, models may be complicated ones that contain a great many characteristics of real systems. The former often have the virtue of transparency, making it fairly easy to see why certain fundamental principles apply both within the model and within the real world. The latter, while usually less transparent, may be more suitable for direct comparison with actual data.

The principles to be elucidated in the course of theoretical research on ecosystems will relate, for example, to:

- interactions among different kinds of organisms,
- the collective properties that emerge from those interactions,
- relations among different spatial and temporal scales, and/or
- the reaction of the system to various external influences—including human activities.

Also, there is need for theoretical research that speaks to the whole "pure to applied" spectrum of science.

In addition, interdisciplinary comparisons—for instance with the structure and function of human organizations and institutions (such as the market economy, or the interdependencies of individual, family, community, and society)—are very likely to be highly valuable in the development of understandable and usable ecological and ecosystems theory.

The vast stores of data accumulated by all the ecological and ecosystems research that has been conducted to date is available *now* for use in the sorts of analyses required by this research. The country has scientists highly qualified to do the research, both within the government and in the private sector, including academia. Synthetic research must become a priority. What is needed is focus on and funding for research to achieve the level of understanding described here. The need to begin improving the status of perturbed ecosystems is immediate. We recommend that appropriate reallocations both of budget and effort within agencies be implemented within the next budgetary cycle, and that calls for and funding of extramural research be included in the earliest possible proposal cycle of all the agencies. It should be recognized that this sort of research is long-term in nature and must be ongoing. The funding allocations and reallocations made to it should minimally be for five years and preferably be indefinite. Milestones for evaluating the results of this investment include improvement in predictions of the effects of ecosystem manipulations, productivity of ecosystems, and the status of the habitats that are managed according to the principles that are discovered by the research.

Develop and provide the computational tools needed to synthesize and use all available ecological data to advance scientific understanding and guide policies and decisions.

All of the data manipulation, hypothesis testing, contingency modeling, and interdisciplinary comparisons that are so necessary to the elucidation of principles and theoretical frameworks discussed here require intensive computation, massive data delivery across networks, and advanced analytical algorithms—in short, a thoroughly mature, high-caliber information management environment. The "next generation" NBII, mentioned above and described in the next section, will provide this environment.

In parallel with the development of a unifying framework of underlying ecological theory and ecosystem principles, the adaptation of theory for use in management and policy must also occur. Mechanisms for interpreting new data in the light of a body of theory and applying those interpretations in the solutions to everyday problems must be devised and delivered to on-the-ground managers; rationales for high-level policy actions must be generated from accumulations of ecological data integrated with other societal concerns. Again, the delivery of easily understood results of theoretical and applied research requires an informatics environment that can provide tools to readily interpret research results for use in the real world. The NBII-2 is needed to provide this environment as well.

One institution that will be very much a part of the NBII-2 network of institutions and computers is the newly-established National Center for Ecological Analysis and Synthesis at the University of California, Santa Barbara. The NCEAS is perfectly situated to carry out the development of the special software and to conduct the complex analyses required by the theoretical research described above. A failure to fully exploit the capabilities of this facility would represent the loss of an opportunity to capitalize on investments that have already been made. As pointed out above, government agencies very much need the results of theoretical ecological and ecosystems research, which in turn needs a unique sort of informatics infrastructure both for the conduct of the research and for the delivery of the results.

The need for theoretical ecosystem research is immediate and ongoing, and the research cannot be conducted without the informatics developments. Therefore, the establishment in 1996 of the NCEAS, with an initial lifespan of five years, was particularly fortuitous. The NCEAS should be supported for an additional five years (and probably more) at higher level than it is at present, so that full advantage may be taken of the huge body of data that is being assembled. Approximately one-third of its funds should be competitively dispersed to researchers at institutions other than the NCEAS itself, for use in developing the software applications that are central to the conduct of theoretical ecosystem research. This increase in funding should be provided by entities (management agencies and industries, in partnership) that would benefit from the results of the research and the delivery system for those results that will be provided by the NBII-2.

SECTION III

Encourage a Sustainable Relationship between the Economy and the Environment

"...what we need is an understanding that we can grow the economy and still preserve the environment."

William J. Clinton, 8 January 1998

" ...the new economy is more like an ecosystem, which depends for its health on diversity, nutrients, and its ability to change and evolve and learn and grow."

Albert Gore, Jr., 21 March 1994

Economic development must operate within the environment in a way that will allow us to live sustainably and provide our children with both prosperity and the intact natural heritage on which prosperity is founded. Much of America's prosperity can be traced to its abundant endowment of natural wealth, a form of capital that the country is now drawing upon without replenishment. This depletion of natural capital, if continued, will have serious repercussions in terms of economic and environmental security that could jeopardize the well-being of current and future generations. As explained in the Introduction to this Report, natural capital in the form of ecosystems that provide services must be safeguarded. To achieve this, economic development and environmental conservation must be reconciled so that the people living within an ecosystem recognize the economic benefits it provides and take an active role in guarding it.

To gain the needed insights, research must be conducted at the intersection of sociology, economics, and ecology. We gave examples of some mechanisms by which a better relationship between the economy and the environment might be forged in the Introduction to this Report. Yet, there is still a great deal to learn about the manner in which sociological, economic and political behaviors can be redirected toward protecting natural capital without requiring a major shift in American lifestyle or philosophy. The research we recommend will enhance the Nation's ability to manage the ecosystems that provide critical services, and thus help to alleviate economic losses currently resulting from mismanagement based on inadequate knowledge.

The economic losses caused by the degradation of ecosystem services already amount to billions of dollars per year, and are likely to grow exponentially in the absence of greatly improved tools for managing these systems. The research program recommended here will provide the understanding needed to stem these losses, and to improve our ability to sustainably manage America's living capital. Failure to do the research needed to develop new economic and social mechanisms to promote stewardship will allow continuation of past practices that have led to loss of agricultural soils, public health problems of increasing severity, decline in the recreational value of the environment, and so on.

The research that we recommend here is novel and fundamental. It focuses on resources and services that are of immense social and economic value yet are hard to commercialize. This is also an area in which it is difficult to readily establish intellectual property rights, yet it is of great significance to all sectors of society. Therefore, the Federal government should provide the impetus and funding for such research, while forming public-private partnerships at every opportunity.

This topic is so fundamental to our society that almost every department of the Federal government and each of their agencies should be involved in conducting and contributing to the funding of this research. Many of these departments might not ordinarily be involved in "environmental" research, but in this case they are directly socially relevant. For example, the Departments of Housing and Urban Development, Education, Health and Human Services, Labor, Commerce, and State should all be included because of the social, economic, national security, and international implications of the realignment of economics and environment. These players in the social and economic arena should work together with those departments and agencies that have long cooperated in interagency activities concerning the environment (Agriculture, Interior, the Environmental Protection Agency, the National Aeronautics and Space Administration, and others) within the National Science and Technology Council framework. The matter of ecosystem services is so encompassing as to rightfully be of concern to the entire Administration.

The National Science and Technology Council should immediately focus on research to discover economic incentives for conservation, and remain committed to overseeing

- the conduct of socio-economic / environmental research by the government's intramural researchers,

- the funding of an extramural grants program to involve academia, non-governmental organizations, and the private sector,

- intragovernmental shifts in policies and attitudes that will help to institute new modes of economic thinking, and

- the establishment of public-private partnerships that will ultimately enable changes in such areas as banking, stock markets, and securities as research indicates that these are needed.

The NSTC should establish an Interagency Working Group that would coordinate various agency contributions to a single funding source for extramural research, generate guidelines for proposals for funding from academic investigators, and participate in the merit review process. It should also ensure that extramural research take into account the extensive work Federal "trustee" agencies have already done on evaluation of damages caused to ecosystems by releases of hazardous substances and use of this information in claims against polluters. This Working Group should be inclusive of agencies in all the current Committees of the NSTC, and should be led by the National Science Foundation, which would be in charge of the handling and review of extramural proposals. The first competition for these research funds should occur within two years, and the program should be continued for at least five years but preferably indefinitely. The Working Group should assure that the guidelines for proposals for extramural research on society and biosphere contain a call for both types of research described in this section of this Report: the development of techniques for economic assessment of biodiversity and ecosystem goods and services, and the development of social and economic incentives for stewardship of natural capital. The two go hand-in-hand, but each is a distinct area of research.

The total amount of funding needed for the research recommended here is $24 million per year over a minimum of five years. This is a vanishingly small percentage of the Gross Domestic Product ($6.9 trillion in 1996), almost all of which has its origins in one way or another in our country's natural wealth. The amount is likewise minuscule in comparison to the $112 billion of GDP generated by agriculture alone; it is tiny relative to the total science and technology R&D expenditures of the Federal government (currently approximately $76 billion). And yet, this modest investment will generate understanding of means by which we can sustain America's productivity, while safeguarding the store of natural capital that makes this productivity possible.

Improve characterization and economic assessment of biodiversity and ecosystem services.

Research that will enable us to mobilize the full potential of market forces to conserve natural capital must include efforts to discover the best ways to estimate the social value of ecosystem services. The next step must be to devise means to convert that social value into economic (cash) value. To do that, we will have to understand more fully the processes through which ecosystem goods and services are produced, and how human activity impinges on these production processes. Key research issues are:

- What ecosystems provide which life support services?
- What are the relative impacts of alternative human activities upon the supply of services?
- What are the relationships between the quantity or quality of services and the condition (e.g., pristine vs. heavily modified) and spatial extent of the ecosystem supplying them? Where do critical thresholds lie?
- To what degree do ecosystem services depend upon the ecosystem being biodiverse (from the genetic to the landscape level)?
- How interdependent are the services? How does exploiting or damaging one influence the functioning of others?
- To what extent have various services already been impaired? How are impairment and risk of future impairment distributed geographically?
- To what extent, and over what time scale, are ecosystem services amenable to repair?
- How effectively, at how large a scale, and at what cost can existing or foreseeable human technologies substitute for ecosystem services?
- Given the current state of technology and scale of the human enterprise, how much natural habitat and biodiversity are required to sustain the delivery of ecosystem services locally, regionally, and globally?
- Can we cope with the "surprises" that are virtually guaranteed to occur when any complex system is heavily perturbed and be alerted while there is still time to prevent serious consequences?
- How can ecosystems best be managed to preserve biodiversity?

If there were adequate methods of placing dollar values on ecosystem goods and services, it would be possible to alleviate much debate, delay and uncertainty within and among government agencies, between Federal resource managers and the public, and in society in general. And, progress toward sustainable development could proceed more rapidly if techniques of economic assessment enabled the redirection of market forces toward stewardship of natural capital. One of the sources of distrust between the public and private sectors regarding natural resource use is our current inability to address questions of societal and economic value of ecosystem goods and services using hard-headed, realistic figures that can be incorporated into reasonable business agreements. If methods of economic assessment that take multiple factors into account are not developed, this distrust (and the resulting lack of stewardship) will continue, as will mismanagement of the nation’s natural capital.

Discover workable economic incentives for conservation of natural capital.

There are currently some offices within Federal agencies that deal to a certain extent with economic assessment and incentives for conservation, but only in a tangential way. For instance, the EPA Office of Policy Planning and Evaluation is collaborating with the World Resources Institute to work on natural resource accounting, and with The Nature Conservancy to develop Compatible Economic Development Centers through the Community-Based Environmental Protection program. The International Cooperative Biodiversity Groups program of the National Institutes of Health and the NSF is involved in the creation of mechanisms for putting a monetary value on natural resources for purposes of reimbursing people in areas from which those resources were derived. The NSF and EPA together have a grants program in Decision-Making and Valuation for Environmental Research, the Water and Watersheds program, which requires investigators to include sociological components within their ecological research, and the two new Urban Long-Term Ecological Research sites that will incorporate studies of demographic shifts and the effects of urban centers on ecosystems. None of these efforts is specifically geared toward the discovery of realistic methods of economic assessment of the value of ecosystem goods and services and the development of new economic incentives for conservation, which is why the program we recommend here is sorely needed.

We need to understand the kinds of investments that will be required to preserve or restore the functioning of ecosystems. We then need to discover mechanisms to make these investments attractive financially. This will involve realizing as a cash flow to the investors a part of the economic and societal value of the services of the ecosystems conserved. If the social value of the ecosystem services can be transformed into cash, part of which can be paid to those who conserve, then market forces can be harnessed to the goal of conserving our natural capital. The extent to which this is possible depends on the particular ecosystems involved and the characteristics of the goods and services supplied, in particular whether these are public or private goods—i.e., whether they are goods or services for which markets can readily yield to the seller a significant fraction of the social value of their product.

Many ecosystems provide several different goods and services to society. For example, a growing forest may purify water as a watershed, control floods, sustain biodiversity, sequester carbon, provide timber, or afford recreational opportunities. Its overall economic value is the sum of the values of all of these services, each of which could be rewarded through a separate market. As an illustration of this approach, the government of Costa Rica has recently initiated a system under which the agencies managing certain forests are compensated for the watershed and carbon sequestration roles of the forests on a per hectare basis, and the government plans to extend the compensation to cover other functions.

Where markets can be used to manage the provision of ecosystem goods and services, they will automatically indicate a value for these via market prices. These prices may not fully reflect the social values of the services, but will usually provide a good starting point in calculating social values. There will always remain some situations in which markets cannot be used and market prices for ecosystem services are not available. For such cases, we need ways of appraising the value of the services that are not based on market prices. Some such methods were mentioned in the Introduction, and need to be developed further.

As noted above, the National Science and Technology Council should stimulate intramural and extramural research in these two areas immediately. The first competition for extramural research should occur as soon as the guidelines can be formalized, and the program should be continued for at least five years but preferably indefinitely.

Successes of the research program can be measured by

- the impact it has on our understanding of the relationship between biosphere and society,

- the lessening of distrust between government and the private sector over living resource issues,

- the increased ability of Federal and other agencies to complete tasks such as generating indicators of sustainable development,

- the application of the results in economic and social institutions as they adopt strategies that are sustainable over the long term, and

- an enhanced appreciation by the public of the value of America's living capital and the services it provides.

SECTION IV

Build a "Next Generation"

National Biological Information Infrastructure

"... more and more people realize that information is a treasure that must be shared to be valuable...our Administration will soon propose using ... technology to create a global network of environmental information."

Albert Gore, Jr., 21 March 1994

"With all of everyone's work online, we will have the opportunity ... to let everyone use everyone else's intellectual effort. ... The challenge for librarians and computer scientists is to let us find the information we want in other people's work..."

Michael E. Lesk (1997), http://community.bellcore.com/lesk/ksg97/ksg.html

The economic prosperity and, indeed, the fate of human societies are inextricably linked to the natural world. Because of this, information about biodiversity and ecosystems is vital to a wide range of scientific, educational, commercial, and governmental uses. Unfortunately, most of this information exists in forms that are not easily used. From traditional, paper-based libraries to scattered databases and physical specimens preserved in natural history collections throughout the world, our record of biodiversity and ecosystem resources is uncoordinated and isolated. It is, de facto, inaccessible. There exists no comprehensive technological or organizational framework that allows this information to be readily accessed or used effectively by scientists, resource managers, policy makers, or other potential client communities. "We have ... vast mountains of data that never enter a single human mind as a thought. ... Perhaps this sort of data should be called 'exformation' instead of information ... " (Albert Gore, Jr. [1993], *Earth in the Balance*, pp. 200-201).

However, significant increases in computation and communications capabilities in recent years have opened up previously unimagined possibilities in the field of information technology, and these trends will continue for the foreseeable future. It is clear that abundant, easily-accessible, analyzed and synthesized information that can and does "enter the human mind as a thought" will be essential for managing our biodiversity and ecosystem resources. Thus, research and development is needed in order to harness new information technologies that can help turn ecological "exformation" to "information."

We need computer science, library and information science, and communications technology research (hereafter abbreviated as CS/IT) to produce mechanisms that can, for example, efficiently search through terabytes of Mission to Planet Earth satellite data and other biodiversity and ecosystems datasets, make correlations among data from disparate sources, compile those data in new ways, analyze and synthesize them, and present the resulting information in an understandable and usable manner. At present, we are far from being able to perform these actions on any but the most minor scale. However, the technology exists to make very rapid progress in these areas, if the attention of the CS/IT community is focused on the biodiversity and ecosystems information domain.

Focus research on biodiversity and ecosystems information to promote use of that information in management decisions, in education and research, and by the public.

Knowledge about biodiversity and ecosystems, even though incomplete, is a vast and complex information domain. The complexity arises from two sources. The first of these is the underlying biological complexity of the organisms and ecosystems themselves. There are millions of species, each of which is highly variable across individual organisms and populations. These species each have complex chemistries, physiologies, developmental cycles and behaviors, all resulting from more than three billion years of evolution. There are hundreds if not thousands of ecosystems, each comprising complex interactions among large numbers of species, and between those species and multiple abiotic factors.

The second source of complexity in biodiversity and ecosystems information is sociologically generated. The sociological complexity includes problems of communication and coordination—between agencies, between divergent interests, and across groups of people from different regions, different backgrounds (academia, industry, government), and different views and requirements. The kinds of data humans have collected about organisms and their relationships vary in precision, accuracy, and in numerous other ways. Biodiversity data types include not only text and numerical measurements, but also images, sound, and video. The range of other data types with which scientists and other users will want to mesh their biodiversity databases is also very broad: geographical, meteorological, geological, chemical, physical, etc. Further, the manner and mechanisms that have been employed in biodiversity data collection and storage are almost as varied as the natural world the datasets document. Therefore, analysis of the work practices involved in building these datasets is one among several CS/IT research priorities.

All this variability constitutes a unique set of challenges to information management. These challenges greatly exceed those of managing gene or protein sequence data (and that domain is challenging in its own right). In addition to the complexity of the data, the sheer mass of data accumulated by satellite imagery of the Earth (terabytes per year are captured by Landsat alone) presents additional information management challenges. These challenges must be met so that we can exploit what we do know, and expand that knowledge in appropriate and planned directions through research, to increase our ability to live sustainably in this biological world.

Various research activities are being conducted that are increasing our ability to manage biological information:

- The Human Genome project is spawning not only new medical therapies but also developments in CS/IT areas as well.

- Geographic Information Systems (GIS) are expanding the ability of some agencies to conduct their activities more responsibly and making it possible for industry to choose sites for new installations more intelligently.

- The National Spatial Data Infrastructure has contributed to progress in dealing with geographic, geological, and satellite datasets.

- Research conducted as part of the Digital Libraries projects has begun to benefit certain information domains.

- The High-Performance Computing and Communications initiative has greatly benefited certain computation-intensive engineering and science areas.

- All of science has benefited from the Internet; those benefits will increase with the development of the "next generation" Internet, or Internet-2.

But, to date, there has been insufficient attention paid to the need for CS/IT research on biodiversity and ecosystems information.

Given the importance of and need for biodiversity and ecosystems data to be turned into information so that it can be comprehended and applied to achieve a sustainable future, this Panel recommends that the attention of a number of governmental research and research funding activities be directed toward the special needs of biodiversity and ecosystems data:

- The Federal Geographic Data Committee should immediately include biodiversity and ecosystems data in its work to produce standard descriptors for Federal geospatial data.

- The Digital Libraries Initiative of the NSF, DARPA, and NASA should call for research specifically focused on the biodiversity and ecosystems information domain in all future Requests for Proposals. Current Digital Libraries projects are working on some of the techniques needed (automatic indexing, sophisticated mapping, brokering routines, etc.), but the developments are not focused on biodiversity and ecosystems information, which have their own unique characteristics.

- The Knowledge and Distributed Intelligence and the Life in Earth's Environment initiatives of the NSF should call for CS/IT and appropriate associated biological and sociological research specifically focused on the biodiversity and ecosystems information domain in all future Requests for Proposals.

- The NSTC Committee on Technology should focus on the biodiversity and ecosystems information domain within a number of its stated R&D areas, particularly: 1) addressing problems of greater complexity (in the High End Computing and Computation Program Area); 2) advanced network architectures for disseminating environmental data (Large Scale Networking Program Area); 3) extraction and analytical tools for correlating and manipulating distributed information, advanced group authoring tools, and scaleable infrastructures to enable collaborative environments (Human Centered Systems Program Area); and 4) graduate and postdoctoral training and R&D grants (Education, Training and Human Resources Program Area).

The biodiversity and ecosystems information domain is not at present as amenable to correlation, analysis, synthesis and presentation across networks as are other domains because of the problems of complexity pointed out above and because the CS/IT community has, to date, more or less ignored these sorts of data and the associated challenges. A concerted research effort, by government, business, and academia is needed, and needed soon, so that the masses of data and information that are stored in the museums, libraries, and government agencies of this country, and that are generated daily by Mission to Planet Earth and other activities, can be put to good use.

The problem of excess data will get steadily worse if means are not devised to analyze and synthesize those data quickly and effectively to turn them into usable and useful information that can be brought to bear in decision-making, policy formulation, directing future research, and so on. Computers were invented to assist humans in tedious computational tasks, which the conversion of satellite data into useful information surely is. One reason that we have unused data is because we are collecting it while we still do not have efficient means to convert it into comprehensible information. What person could be expected to absorb and "understand" terabytes of satellite data by brainpower alone, without the assistance of computers? The CS/IT research endeavor advocated here will reap great rewards by inventing better means to make the conversion from data to useful information. Much of the talent needed for this work is employed in the private sector, and so public-private partnerships that involve software and hardware designers and biologists will be needed to accomplish the task.

The investments that have been made in acquiring data are large ($1 billion per year on Mission to Planet Earth is only one example). The full potential of those investments will not be realized if new tools for putting the data to use are not devised. Unused data are not worth the initial investment made in gathering them. Failure to develop the technologies to manipulate, combine, and correlate the biodiversity and ecosystems data we have available from all sources will have adverse effects on our ability to predict and prevent degradation of our natural capital.

Federal computing, information, and communications programs invest in critical, long-term R&D that advances computing, information, and communications in the United States. These investments to date have enabled government agencies to fulfill their missions more effectively and better understand and manage the physical environment. They have also contributed much to US economic competitiveness. It is our contention that future investments by the government's computing, information, and communications programs that are overseen by the NSTC Committee on Technology should be concentrated in the area of biodiversity and ecosystems information. As has happened in other areas, this Federal investment will enable agencies to manage the biological environment in better ways, and will very likely spin off new technologies that can be exploited by the private sector to benefit the US economy.

The first of these investments should be made in the next round of competition for research awards. Progress in the development of the needed technologies can be measured by increases in the ability of agencies to utilize data they already have or are now collecting, in the creation of private sector jobs and businesses that are directly related to biodiversity and ecosystems information management, and in research that is more clearly focused because proper data management has illuminated both what is already known and what remains to be discovered.

Design and construct the "next generation"

National Biological Information Infrastructure (NBII-2).

The CS/IT research described above will contribute to progress in managing biodiversity and ecosystems information. The productivity of individual research groups, driven by their own curiosity, ingenuity, and creativity has served this country well in myriad fields of science and the development of technology. Yet, there are important issues in the management and processing of biodiversity and ecosystems information that must be addressed in a much more coordinated and concerted way than has been attempted to date.

The value of raw data is typically predicated on our ability to extract higher-order understanding from those data. Traditionally, humans have done the task of analysis: one or more analysts become familiar with the data and with the help of statistical or other techniques provide summaries and generate results. Scientists, in effect, generate the "correct" queries to ask and even act as sophisticated query processors. Such an approach, however, rapidly breaks down as the volume and dimensionality (depth and complexity) of the data increase. What person could be expected to "understand" millions of cases, each having hundreds of attributes? This is the same question asked about satellite data above—human brainpower requires sophisticated assistance from computers to complete these sorts of tasks. The current National Biological Information Infrastructure (NBII) is in its infancy, and cannot provide the sophisticated services that will enable the simultaneous querying and analysis of multiple, huge datasets. Yet, it will become more and more necessary to manipulate data in this way as good stewardship of biodiversity and ecosystems grows increasingly important.

The overarching goal of the "next generation" National Biological Information Infrastructure, or NBII-2, would be to become, in effect, a fully digitally accessible, distributed, interactive research library system. The NBII-2 would provide an organizing framework from which scientists could extract useful information —new knowledge—from the aggregate mass of information generated by various data gathering activities. It would do this by harnessing the power of computers to do the underlying queries, correlation, and other processing activities that at present require a human mind. It would make analysis and synthesis of vast amounts of data from multiple datasets much more accessible to a variety of users. It would also serve management and policy, education, recreation, and the needs of industry by presenting data to each user in a manner tailored to that user's needs and skill level.

We envision the NBII-2 as a distributed facility that would be something considerably different than a "data center," something considerably more functional than a traditional library, something considerably more encompassing than a typical research institute. It would be all of these things, and at the same time none of them. Unlike a data center, the objective would not be the collection of all datasets on a given topic into one storage facility, but rather the automatic discovery, indexing, and linking of those datasets. Unlike a traditional library, which stores and preserves information in its original form, this special library would not only keep the original form but also update the form of storage and upgrade information content. Unlike a typical research institute, this facility would provide services to research going on elsewhere; its own staff would conduct both CS/IT and biodiversity and ecosystems research; and the facility would offer "library" storage and access to diverse constituencies.

The core of the NBII would be a "research library system" that would comprise five regional nodes, sited at appropriate institutions (national laboratories, universities, etc.) and connected to each other and to the nearest telecommunications providers by the highest bandwidth network available. In addition, the NBII-2 would comprise every desktop PC or minicomputer that stores and serves biodiversity and ecosystems data via the Internet. The providers of information would have complete control over their own data, but at the same time have the opportunity to benefit from (and the right to refuse) the data indexing, cleansing, and long-term storage services of the system as a whole.

- The framework to support knowledge discovery for the nation's biodiversity and ecosystems enterprise that involves many client and potential-client groups;

- A common focus for independent research efforts, and a global, neutral context for sharing information among those efforts;

- An accrete-only, no-delete facility from which all information would be available online, twenty-four hours a day, seven days a week in a variety of formats appropriate to a given user;

- A facility that would serve the needs of (and eventually be supported by partnership among) government, the private sector, education, and individuals;

- An organized framework for collaboration among Federal, regional, state, and local organizations in the public and private sectors that would provide improved programmatic efficiencies and economies of scale through better coordination of efforts;

- A commodity-based infrastructure that utilizes readily available, off-the-shelf hardware and software and the research outputs of the Digital Libraries initiative where possible;

- An electronic facility where scientists could "publish" biodiversity and ecosystems information for cataloging, automatic indexing, access, analysis, and dissemination;

- A place where intensive work is conducted on how people use these large databases, and how they might better use them, including improvement of interface design (human-computer interaction);

- A mechanism for development of organizational and educational infrastructure that will support sharing, use and coordination of these massive data sets;

- A mirroring and/or backup facility that would provide content storage resources, registration of datasets, and "curation" of datasets (including migration, cleansing, indexing, etc.);

- An applied biodiversity and ecosystems informatics research facility that would develop new technologies and offer training in informatics;

- A facility that would provide high end computation and communications to researchers at diverse institutions.

To be effective, the NBII-2 that we propose must be a system designed more for information users than for data providers, although the system would supply services to the latter as well. Research is necessary to better characterize the needs and requirements of different classes of users of digital library systems, and to gain insight into how to adapt systems to specific user needs and behaviors. The linkage of personal and work-group information management systems to a digital library system is an issue of particular importance. A great deal of design research is needed to construct the system, which must be a constantly evolving entity.

This facility would not be a purely technical and technological construct, but rather would also encompass complex sociological, legal, and economic issues in its research purview . These might include intellectual property rights management, public access to the scholarly and cultural record, and the characteristics of evolving systems of scholarly and mass communications in the networked information environment. The human dimensions of the interaction with computers, networks, and information will be a particularly important area of research as systems are designed for the greatest flexibility and usefulness to people.

The needs that the research nodes of the NBII-2 must address are many. A small subset of those needs includes:

- New statistical pattern recognition and modeling techniques that can work with high dimensional, large-volume data;

- Workable data-cleaning methods that automatically correct input and other types of errors in databases;

- Strategies for sampling and selecting data;

- Algorithms for classification, clustering, dependency analysis, and change and deviation detection that scale to large databases;

- Visualization techniques that scale to large and multiple databases;

- Metadata encoding routines that will make data mining meaningful when multiple, distributed sources are searched;

- Methods for improving connectivity of databases, integrating data mining tools, and developing ever better synthetic technologies;

- Ongoing, formative evaluation, detailed user studies, and quick feedback between domain experts, users, developers and researchers.

In order to comprehend and utilize our biodiversity and ecosystem resources, we must learn how to exploit massive data sets, learn how to store and access them for analytic purposes, and develop methods to cope with growth and change in data. The NBII-2 that we recommend here will be an enabling framework that could unlock the knowledge and economic power lying dormant in the masses of biodiversity and ecosystems data that we have on hand.

Box 8: Why do we need an NBII-2?

Biodiversity is complex; ecosystems are complex. The questions we need to ask in order to manage and conserve biodiversity and ecosystems therefore require answers comprised of information from many sources. As described in the text, our current ability to combine data from many sources is not very good, or very rapid—a human being usually has to perform the tasks of correlation, analysis, and synthesis of data drawn painstakingly from individual datasets, one at a time. The NBII of today only has the capability to point a user toward single data sets, one at a time, that might (or might not) contain data that are relevant to the user’s question. If the dataset does appear useful, the human must construct a query in a manner structured by the requirements of the particular application that manages the dataset (which likely as not is somewhat arcane). The human must then collate results of this query with those of other queries (which may be very difficult because of differences in structures among datasets), perform the analyses, and prepare the results for presentation. What we need is an organizing framework that will allow that same human being to construct a query in everyday language, and *automatically* obtain exactly the information needed from all datasets available on the Internet. These data would be *automatically* filtered, tested for quality, and presented in correlated, combined and analyzed form, ready for the human mind to perform only higher-order interpretation. With tools such as these, we will begin to be able to "mine" the information we already have to generate new insights and understanding. At present, the task of "data mining" in the biodiversity and ecosystems information domain is so tedious as to be unrewarding, despite our very great need for the insights it has the potential to yield.

Box 9: Why do we need an NBII-2? Scenario 1

An agricultural researcher has just isolated and characterized a gene in a species of *Chenopodium* that enables the plant to tolerate high-salt soil. To find out about other characteristics of the habitat within which that gene evolved, the researcher uses NBII-2 to link to physical data on the habitat (temperature and rainfall regimes, range of soil salinity, acidity, texture and other characteristics, elevation and degree of slope and exposure to sunlight, etc.), biological information about other plants with which this *Chenopodium* occurs in nature, data on animals that are associated with it, and its phylogenetic relationship to other species of *Chenopodium*, about which the same details are gathered. Linkages among these ecological and systematic databases and between them and others that contain gene sequence information enable the researcher to determine that the gene she has isolated tolerates a wider range of environmental variables than do equivalents in other species that have been tested (although this analysis also points out additional species that it would be worthwhile to test). The gene from this species is selected as a primary candidate for insertion by transgenic techniques into forage and browse plants to generate strains that will tolerate high-salt soils in regions that currently support sheep and cattle but which are becoming more and more arid (and their soils saltier) because of global climate change.

Box 10: Why do we need an NBII-2? Scenario 2

On an inspection of a watershed area, a resource manager finds larval fish of a type with which he is unfamiliar. Returning to the office, the manager accesses an online fish-identification program. Quickly finding that there are several alien species represented in the sample he took, he then obtains information on the native ranges of these species, their life history characteristics, reproductive requirements and rates, physiological tolerances, ecological preferences, and natural predators and parasites from databases held by natural history museums around the world. He is able to ascertain that only one of the alien species is likely to survive and spread in this particular watershed. Online, he is also able to access data sets that describe measures taken against this species in other resource management areas, and the results of those measures. By asking the system to correlate and combine data on the environmental characteristics of the fish's native range that have been measured by satellite passes for the past 20 years, as well as the environmental characteristics of the other areas into which it had been introduced, he is able to ascertain which of the management strategies is most likely to work in the situation he faces. Not only does the manager obtain this information in a single afternoon, but he is able to put the results to work immediately, before populations of the invading fish species can grow out of control. The form and results of the manager's queries are also stored to enable an even faster response time when the same or a related species is discovered in another watershed.

Box 11: Why do we need an NBII-2? Scenario 3

A community is in conflict over selection of areas for preservation as wild lands in the face of intense pressures for development. The areas available have differing characteristics and differing sets of endangered species that they support. The NBII-2 is used to access information about each area that includes vegetation types, spatial area required to support the species that occur there, optimal habitat for the most endangered species, and the physical parameters of the habitats in each of the areas. In addition, information on the characteristics and needs of each of the species is drawn from natural history museums around the world. Maps of the area are downloaded from the US Geological Survey, and other geographic information data layers are obtained from an archive across the country. Also, the NBII-2 even provides access to software developed in other countries specifically for the purpose of analyzing these multiple data types. The analyses conducted on these datasets using this software provide visually understandable maps of the areas that, if preserved, would conserve the greatest biodiversity, and of those areas that would be less desirable as preserves. Conservation biologists then make information-based predictions about success of species maintenance given differing decisions. On the basis of the sound scientific information and analysis delivered by the NBII-2, the conflict is resolved and the community enjoys the benefits of being stewards of natural capital as well as the benefits of economic growth.

If all the species of the world were discovered, cataloged, and described in books with one specimen per page, they would take up nearly six kilometers of shelving. This is about what you would find in a medium-size public library. The total volume of biodiversity and ecosystems data that exist in this country has not been calculated, probably because it is so extensive as to be extremely difficult to measure.

Of course, the complete record of biodiversity and ecosystems is orders of magnitude greater than this and exists in media types far more complex than paper. Biodiversity and ecosystem information exists in scores of institutional and individual databases and in hundreds of laboratory and personal field journals scattered throughout the country. In addition, the use of satellite data, spatial information, geographic information, simulation, and visualization techniques is proliferating (NASA currently holds at least 36 terabytes of data that are directly relevant to biodiversity and ecosystems), along with an increasing use of two- and three-dimensional images, full-motion video, and sound.

The natural history museums of this country contain at least 750 million specimens that comprise a 150- to 200-year historical record of biodiversity. Some of the information associated with these collections has been translated into electronic form, but most remains to be captured digitally. There are many datasets that have been digitized, but are in outdated formats that need to be ported into newer systems. There are also datasets that are accessible but of questionable, or at least undescribed, quality. There are researchers generating valuable data who do not know how to make those data available to a wide variety of users. And data once available online can still be lost to the community when their originator dies or retires (our society has yet to create a system that will keep data alive and usable once the originator is no longer able to do so). For these reasons, we lose the results of a great deal of biodiversity and ecological research that more than likely cannot be repeated.

Potentially useful and critically important information abounds, but it is virtually impossible to use it in practical ways. The sheer quantity and diversity of information require an organizing framework on a national scale. This national framework must also contribute to the Global Information Infrastructure, by making possible the full and open sharing of information among nations.

The term "data mining" has been used in the database community to describe large-scale, synthetic activities that attempt to derive new knowledge from old information. In fact, data mining is only part of a larger process of knowledge discovery that includes the large-scale, interactive storage of information (known by the unintentionally uninspiring term "data warehousing"), cataloging, cleaning, preprocessing, transformation and reduction of data, as well as the generation and use of models, evaluation and interpretation, and finally consolidation and use of the newly extracted knowledge. Data mining is only one step in an iterative and interactive process that will become ever more critical if we are to derive full benefit from our biodiversity and ecosystems resources.

New approaches, techniques, and solutions must be developed in order to translate data from outmoded media into usable formats, and to enable the analysis of large biodiversity and ecosystems databases. Faced with massive datasets, traditional approaches in database management, statistics, pattern recognition, and visualization collapse. For example, a statistical analysis package assumes that all the data to be analyzed can be loaded into memory and then manipulated. What happens when the dataset does not fit into main memory? What happens if the database is on a remote server and will never permit a naive scan of the data? What happens if queries for stratified samples are impossible because data fields in the database being accessed are not indexed so the appropriate data can be located? What if the database is structured with only sparse relations among tables, or if the dataset can only be accessed through a hierarchical set of fields?

Furthermore, problems often are not restricted to issues of scalability of storage or access. For example, what if a user of a large data repository does not know how to specify the desired query? It is not clear that a Structured Query Language statement (or even a program) can be written to retrieve the information needed to answer such a query as "show me the list of gene sequences for which voucher specimens exist in natural history collections and for which we also know the physiology and ecological associates of those species." Many of the interesting questions that users of biodiversity and ecosystems information would like to ask are of this type; the data needed to answer them must come from multiple sources that will be inherently different in structure. Software applications that provide more natural interfaces between humans and databases than are currently available are also needed. For example, data mining algorithms could be devised that "learn" by matching user-constructed models so that the algorithm would identify and retrieve database records by matching a model rather than a structured query. This would eliminate the current requirement that the user adapt to the machine's needs rather than the other way around.

The major research and infrastructure requirements of the digitally accessible, distributed, interactive, research library are several:

- **Networking:**

  The library will of necessity place extensive and challenging demands on network hardware infrastructure services, as well as those services relating to authentication, integrity, and security, including determining characteristics and rights associated with users. We need both a fuller implementation of current technologies—such as digital signatures and public-key infrastructure for managing cryptographic key distribution—and a consideration of tools and services in a broader context related to library use. For example, the library system may have to identify whether a user is a member of an organization that has some set of access rights to an information resource. As a national and international enterprise that serves a very large range of users, the library must be designed to detect and adapt to variable degrees of connectivity of individual resources that are accessible through networks.

- **Computation:**

  A fully digital, interactive library system requires substantial computational and storage resources both in servers and in a distributed computational environment. Little is known about the precise scope of the necessary resources, and so experimentation will be needed to determine it. Many existing information retrieval techniques are extremely intensive in both their computational and their input-output demands as they evaluate, structure, and compare large databases that exist within a distributed environment. In many areas that are critical to digital libraries, such as knowledge representation and resource description, or summarization and navigation, even the basic algorithms and approaches are not yet well defined, which makes it difficult to project computational requirements. It does appear likely, however, that many operations of digital libraries will be computationally intensive—for example, distributed database searching, resource discovery, automatic classification and summarization, and graphical approaches to presenting large amounts of information—because digital library applications call for the aggregation of large numbers of autonomously managed resources and their presentation to the user as a coherent whole.

- **Storage:**

  Even though the library system we are proposing here would not set out to accrue datasets or to become a repository for all biodiversity data (after all, NASA and other agencies have their own storage facilities, and various data providers will want to retain control over their own data), massive storage capabilities on disc, tape, optical or other future technology (e.g., holography) will still be required. As research is conducted to devise new ways to manipulate huge datasets, such datasets will have to be sought out, copied from their original source, and stored for use in the research. And, in serving its long-term curation function, the library will accumulate substantial amounts of data for which it will be responsible. The nodes will need to mirror datasets (for redundancy to ensure data persistence) of other nodes or other sites, and this function will also require storage capacity.

• Software:

Information management: Major advances are needed in methods for knowledge representation and interchange, database management and federation, navigation, modeling, and data-driven simulation; in effective approaches to describing large complex networked information resources; and in techniques to support networked information discovery and retrieval in extremely large scale distributed systems. In addition to near-term operational solutions, new approaches are also needed to longer-term issues such as the preservation of digital information across generations of storage, processing, and representation technology. Traditional information science skills such as thesaurus construction and complex indexing are currently being transformed by the challenge of making sense of the data on the World Wide Web and other large information sources. We need to preserve and support the knowledge of library and information science researchers, and help scale up the skills of knowledge organization and information retrieval.

Data mining, indexing, statistical and visualization tools: The library system will use as well as develop tools for its various functions. Wherever possible, tools will be adopted and adapted from other arenas, such as defense, intelligence, and industry. A reciprocal relationship among partners in these developments will provide the most rapid progress and best results.

• Research Issues:

Many of the research issues to be taken up by the researchers who work at the virtual library system have been mentioned in the discussion above. Among the most important issues are content-based analysis, data integration, automatic indexing on multiple levels (of content within databases, of content and quality of databases across disciplines and networks, of compilations of data made in the process of research, etc.), and data cleansing. The latter is a process that at present is extremely tedious, time- and human labor-intensive, and inefficient and often ineffectual. Much of the current expenditure on databases is consumed by the salaries of people who do data entry and data verification. Automatic means of carrying out these tasks are a priority if we are to be able to utilize our biodiversity and ecosystems information to protect our natural capital.

We have laid out the case for building a fully digital, interactive, research library system for biodiversity and ecosystems information, and the basic requirements of and goals for the library and its research and service. In the 21st Century, work will be increasingly dependent on rapid, coordinated access to shared information. Through the NBII-2, a shared digital library system, scientists and policy makers will be able to collaborate with colleagues across geographic and temporal distances. They will be able to use these libraries to catalog and organize information, perform analyses, test hypotheses, make decisions, and discover new ideas. Educators will be able to use these systems to read, write, teach, and learn. In traditional fashion, intellectual work will be shared with others through the medium of the library—but these contributions and interactions will be elements of a global and universally accessible library that can be used by many different people and many different communities. By increasing the effectiveness and speed with which information is communicated and used, the NBII-2 is likely to lead to major scientific discoveries, promote interdisciplinary synergism, advance existing areas of study, and enable entirely new areas of inquiry.

As Vice President Gore said, we have excess data that are unused. Yet we have paid substantial sums to collect those data, and, if they are analyzed and synthesized properly, they can contribute much to our understanding of biodiversity and ecosystems. Our national natural capital is too critically important for us to fail to devote the time and energy required to learn to use it sustainably. To develop the means to do that, we need to have knowledge and understanding of biodiversity and ecosystems; to develop that knowledge and understanding, we must mine the data that we have and that we are generating for correlations that will identify pattern and process. We must prevent what Mr. Gore referred to as "data rot" and "information pollution" by putting the data to use. To do that effectively, we must employ the tools and technologies that are making data mining possible. If we do not build the fully digitally accessible, interactive, research library of biodiversity and ecosystems information, we will lose the opportunity to realize the fullest returns on our data-gathering investments and also to optimize returns from our natural capital.

We recommend that an appropriate avenue be found for further planning and implementation of the library system. The planning panel should include knowledgeable individuals from government, the private sector, and academia. It should further develop the interactive research library concept, and design a plan whereby sites would be proposed and chosen and the work carried out. A request for proposals will be needed, and a means of selecting the most meritorious among these. Many government agencies will of necessity be involved in this process, and all should contribute expertise where needed, but we recommend that the NSF take the overall lead in the process, supported by the NSTC Committee on Technology (CIT), with participation from agencies that hold biodiversity and ecosystems information but which are not members of the CIT.

Each of the regional nodes that will form the core of the digitally accessible, interactive, research library system will require an annual operating budget of at least $8 million. Supporting five or six such nodes (the number we regard as adequate to the task) and the high-speed connections among them will therefore require a minimum of $40 million per year, an amount that represents a mere fraction of the funds spent government-wide each year to collect data (conservatively estimated at $500 million)—data that may or may not be used or useful because the techniques and tools to put it to optimal use have yet to be developed. As with the Internet itself, and other computer and information technologies, the Federal government plays a "kickoff" or "jumpstart" role in the institution of a new infrastructure. Gradually, support and operation of that infrastructure should shift to other partners, just as has happened with the Internet, although in this case there will have to be at least a modicum of permanent Federal support (for the maintenance of its own data, for instance).

The planning and request-for-proposals process should be conducted within one year. Merit review and selection of sites should be complete within the following six months. The staffing of the sites and initial coordination of research and outreach activities should take no more than a year after initial funding is provided. The "lifetime" of any one facility should probably not be guaranteed for any more than five years, but the system must be considered a long-term activity, so that data access is guaranteed in perpetuity. Evaluation of the sites and of the system should be regular and rigorous, although the milestones whereby success can be measured will be the incremental improvements in ease of use of the system by policy-makers, scientists, householders and even shool children. In addition, an increasing number of public-private partnerships that fund the research and other operations will indicate the usefulness of accessible, integrated information to commercial as well as governmental concerns.

SECTION V

Assure that Environmental Education is Centered on Science

"...science and education are important allies in preserving the environment. ...a solid grasp of science and ecology is indeed the first step toward a cleaner world." **William J. Clinton**, 18 October 1997

"We will propose [that] the schools and students of the world ... study environmental information on a daily basis..."

Albert Gore, Jr., 21 March 1994

The natural world provides a host of goods and services that are used every day by every human being, and yet there is an alarming lack of understanding among the public that this is so. An electorate that does not understand the natural world or the nature of the tradeoffs that must be made in managing it wisely and sustainably cannot make informed decisions. Communities that do not have an understanding of the workings of the ecosystems within which they live will be unable to function as responsible stewards, and will thereby too often cause and suffer from losses of biodiversity and ecosystem services. The National Biological Information Infrastructure described in the previous section will make all manner of biodiversity and ecosystems information available to the voting populace as well as to governments. The recipients of that information, however, will need some fundamental knowledge in order to apply the information wisely and effectively. This knowledge must come from both formal classroom and informal education.

There are many benefits that come from investments in education: a more informed populace, high cost-effectiveness, and more scientifically literate citizens. Informal education is very cost effective, and people enjoy learning informally because they have control over the timing and topics (without tests and grades). When people enjoy educational experiences, they value the lessons more and remember them longer, and they are more motivated to seek further learning.

Increase opportunities for informal and participatory education about biodiversity and ecosystems, for student-scientist interactions, and for continuing education for K-12 teachers.

Student-scientist partnerships such as those engendered by the school-based Global Learning and Observations to Benefit the Environment (GLOBE) program are an extremely valuable activity that benefits not only the students' educational experience but also the scientific projects themselves. There are many organizations that promote this sort of interaction both within government agencies and in the private sector. Some partnerships of this type have expanded to include the participation of community groups, museums, Federal agencies, and city, state and county governments. An example is the two-year-old "Chicago Wilderness" project. This community effort to document and restore the wild areas in and around the city of Chicago is coordinated by the Field Museum of Natural History, US Forest Service, and US Fish & Wildlife Service, but also involves 50 or more non-governmental organizations and more than 5,000 individuals. Persons of all ages work side by side with scientists from the Museum and the agencies, learning about and contributing to the welfare of the environment at the same time.

Similar projects should be started around the country in cities that have natural history museums or botanic gardens to provide the scientists; offices of the Forest Service, Fish & Wildlife Service, Bureau of Land Management, or National Park Service to provide initial funding; and concerned citizens to provide the leadership and organization. There are many Americans who stand ready to improve the environment that they will leave to their children and grandchildren. The efforts of the Federal offices in Chicago should be commended and also emulated wherever possible. Scientists should be commended for interacting with the public. And, grant programs to support such partnership activities would go far to encourage more scientists to participate.

Informal education in museums, science centers, zoos, aquaria, botanical gardens and like institutions has long been recognized as one of the most effective means for helping people of all ages understand and learn about science. This is because the informal context allows individuals to find something of personal value that they wish to learn about, and then provides them with an entry into the information on that topic. The learning that takes place in informal settings is extremely cost effective. Each year, 130 million people gain new insights in natural settings in US national parks. The pricetag is less than $1.00 per visit to visitor center displays, walks and campfire talks provided by the National Park Service. The National Museum of Natural History is one of the most popular visitor sites on the National Mall in Washington , DC, but it (and all other natural history institutions in the country) are underfunded in comparison to their needs and to their popularity.

The expenditures of the government on informal education are very modest, and should be increased to meet demand. For instance, many people are turned away from National Park Service and other interpretive programs every year because there is insufficient space to accomodate all of those who are interested. Museums require additional funding to maintain interactive exhibits, which often wear out before their planned expiration because the positive response of visitors to the exhibits exceeds the capacity to maintain them. Nature centers and exhibits on public lands are all in need of maintenance and expansion to serve the public's desire to know about nature. There are various mechanisms that the Federal government can use to increase support of informal education, such as increasing budget lines in agencies that have programs in these areas and providing grants to state and private institutions to increase their efforts in these areas.

Teacher-training opportunities in settings other than colleges of education can provide K-12 teachers with skills that they can use in the formal classroom. Science and Technology Centers, Long-Term Ecological Research sites, the National Park Service, natural history museums, and botanical gardens, etc., all offer teacher training opportunities in between school semesters that provide teachers with skills and lesson plans that they can take into their classrooms. These are most effective when facilitators from the training institution follow up with the teachers, observing them when they present these new lessons for the first time and providing feedback. One such project conducted by a Science and Technology Center over the course of two years reached 55 teachers, and through them 1,500 students, at a cost of approximately $150,000. The project was co-funded by a grant to the center and by the schools that employed the teachers, and its success was demonstrated when these teachers' students achieved higher exam scores over the period of the project. The apparent cost of $100 per student is actually less over the long term, as the same teachers re-use the skills they have acquired.

Increasing investments in professional development for teachers of the type described above will quickly reach students with scientifically sound environmental education (see next section), and can be done in partnership between governmental levels (Federal and local). The Eisenhower Professional Development Federal Activities program for math and science is already in place, and is developing certification frameworks for 25 teaching fields. One of these should be specifically directed at environmental education as an interdisciplinary area that integrates the social and behavioral sciences with mathematics and the natural sciences. The Eisenhower Professional Development State Grants funnel $250 million per year to the states to improve education in science and mathematics. Environment, as a field of integrative science, should be a focus for the improvements made with these funds.

Funding for continuing teacher development in content and skills for environmental education is fully justifiable, and should be increased sufficiently to reach at least 10,000 teachers per year (and through them 250,000 to 300,000 students in any given year). This can be done by restoring funds within the Eisenhower Professional Development Federal Activities Program for grants in this area to 1995 levels, and by increasing National Science Foundation (NSF) teacher enhancement funding in the area of environmental education. Also, grant funds from the Environmental Protection Agency and the Informal Science Education program of the NSF should be elevated to increase capacity and number of sites (museums, botanical gardens and the like) that provide professional development opportunities for teachers, in conjunction with the Department of Education's Eisenhower Mathematics and Science Regional Consortia. Investments in education are generally rewarding, and are always needed as new students enter school, new teachers enter the workforce, and as individuals discover new interests. The success of the sorts of programs we are recommending here can be measured only in part by increasing student test scores. It is more likely that informal educational experiences will generate an increased understanding of environmental principles by the public. For students, such lessons from informal education will be reinforced by school-based instruction. We believe that greater environmental science literacy will lead to more informed voting, and ultimately to better stewardship of our nation's living capital.

Take steps to establish an "Environmental Science Curriculum Study" to produce texts, other learning tools, and teacher preparation materials for the Nation's schools and colleges.

Environmental education must be based in science. Unfortunately, in the past some instruction and instructors have not adhered to this principle. Instead, some single-interest groups have widely advertised biased views, and some communities have become polarized by conflict between the need for jobs and the needs of species. Environmental education has devolved all too often into emotional environmentalism (or emotional anti-environmentalism).

Education to understand the relationship between society and the biosphere should draw from the sociological, geological, geographic, meteorological, chemical, physical, ecological, taxonomic, and economic sciences. Unfortunately, as has been noted in recent reports by groups from both the political right and the political left, much of the curricular and textual material available for use in America's schools does not include such a balance. Many of America's teachers are not themselves equipped with the knowledge and skills to work beyond the limitations of the materials at hand, or to choose the best from among the materials that are available. And, making matters worse, many school districts in this country completely exclude environmental education of any sort from the curricula for their K-12 students.

There are several publications that peripherally address the issue of curricular development for environmental education. The North American Association for Environmental Education has published "Environmental Education Materials: Guidelines for Excellence" (1996). This document encourages teachers to look for fairness and accuracy, depth, emphasis on skills building, instructional soundness and logic in teaching materials. However, the document is written from an activist perspective rather than the empirically driven perspective of science. The National Science Teachers Association, in conjunction with the Environmental Protection Agency, is developing a "Global Environmental Change Series" which begins with a unit on "Biodiversity." This booklet brings biology together with economic realities and expresses these in a manner that can be understood by and builds the skills of students. But it is one study unit for a workshop or high-school classroom, not a curriculum. The National Academy of Sciences has produced (1995) a set of National Science Education Standards. These cover the breadth of the teaching of science, the training of teachers, and the assessment of science education, but do not address curricula specific to environmental education.

This Panel believes that America's schools should provide future voters with a logical basis and scientific skills for making choices among alternative ways to manage the Nation's natural capital. Further, this education should be incorporated throughout a student's years in school, including college, and should be taught according to a balanced scientific curriculum. However, because it is beyond the scope of this Panel's charge to develop such a curriculum, we recommend that the Administration take steps to establish an "Environmental Sciences Curriculum Study," or ESCS.

The ESCS of our vision would be patterned on and parallel to the highly successful BSCS (Biological Sciences Curriculum Study), which has been the source of high-quality teaching materials and teacher-instruction materials for the biological sciences in America's schools since 1958. The BSCS is constantly updating and upgrading the texts it produces, which it publishes in several versions to allow teachers and school districts a choice among alternative methods and perspectives. Application of the curriculum- and materials-development methods used by the BSCS would enable the ESCS to bring a much needed scientific rigor to environmental education, allow inclusion of the many scientific disciplines that must be integrated when considering environmental questions, and enable presentation of an equitably balanced view of biodiversity, ecosystems and society.

The availability of such curricula and materials would mitigate the resistance to environmental education that occurs in a great many school districts. This resistance probably occurs for a number of reasons, but two of the main ones are lack of teachers prepared to teach scientific principles in this context, and the tendency toward emotionalism and activism found in so many texts that are not grounded in real data and clear thinking. In the absence of the text and curriculum development that we recommend here, a very large percentage of America's future voters will be deprived of the tools they will need to fully participate in choices about how the Nation's natural capital will be managed. As has been said so succinctly by Presidential Science Adviser Dr. John Gibbons, "Since when is ignorance a promising route to deliverance?"

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