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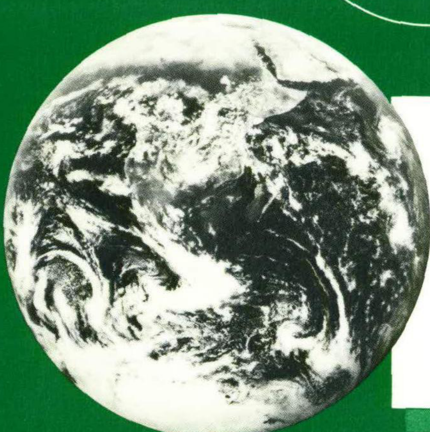

Loss of Biological Diversity: A Global Crisis Requiring International Solutions

A Report to the National Science Board

Committee on International Science's
Task Force on Global Biodiversity

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Craig C. Black
Chair
NSB Task Force on Global Biodiversity

PREFACE

The Committee began work on this report in October 1987. Over the course of two years' deliberations, we heard from numerous individuals—practitioners of systematic biology and ecology, resource economists, and information scientists to mention a few. We heard from researchers from the Smithsonian, several universities, USDA, USAID, and the National Library of Medicine. We heard about issues in the tropics, the temperate zone, the marine environment, in the lakes and rivers and in the soils—literally every corner of the Earth. The overriding theme that has come through to us, and which we sought to convey in our recommendations, is that to investigate biological diversity and to understand biological diversity we must realize that we are dealing with a transdisciplinary problem.

When considering biological diversity—the loss of species, and the environmental degradation and changes taking place on the planet—we have been too quick to settle on the biological and environmental sciences as sole sources for answers. However, the economics of development, as well as sociological and cultural factors are central to understanding both the basis of the biodiversity crisis and its eventual solutions. Information science and computational science will play a significant role in any program designed to understand and to track environmental and biological changes. The amounts of data to be collected, analyzed and archived are staggering. In fact, the eventual solutions to many of the data issues are likely dependent on technologies yet to be developed in the computational sciences.

Overarching all of this is the undeniable fact that any approach to an understanding of biological diversity—what it is now, how it is being affected through human activities as well as natural changes in the environment—has to be done on an international basis. Biological diversity is not a research project that is limited to a laboratory or a university campus in this country. It is a research program that has to be carried out on an international scale with the full cooperation and participation of scientists from a variety of countries around the world.

When discussing the international dimensions of biological diversity, we are speaking of the need to develop structures and cooperative agreements, and cooperative research programs with individuals in the developing countries of the world. When we speak of the European Common Market and Japan, we are seeking a partnership with our developed world counterparts. Because to understand biological diversity and develop workable means to manage, preserve and restore biological diversity, we are going to have to invest cooperatively with countries in Central America, South America, Southeast Asia and in Africa to develop within their own boundaries the research capabilities to understand and to continue to pursue research programs in areas related to ecological change, species loss, ecological restoration, and eventually sustainable natural resource development.

The biological diversity crisis is indeed that; there is but one Earth, one biota, and our actions in the developed and developing world alike are destroying that which is irreplaceable. There are no quick solutions—even the full dimensions of the resource are elusive—nor is there a second chance. The actions needed are clear to us and are set forth in the report recommendations. Biological diversity has been recognized for at least the past 15 years. Yet progress to mount a reasonable research program to get not only the information that is being lost but to develop the basis with which to counteract that loss has been slow to develop. Our choice of the word "crisis" is a very deliberate one because we are rapidly running out of time where we can hope to understand and preserve the diversity of life on this planet. It is with this motivation and conviction that we submit our findings.

Craig C. Black, Chair
September 1989

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I. PROLOGUE: GLOBAL BIODIVERSITY—A VANISHING RESOURCE

We are at a critical juncture for the conservation and study of biological diversity: such an opportunity will never occur again. Understanding and maintaining that diversity is the key to humanity's continued prosperous and stable existence on Earth.

The extinction event that we are witnessing is the most catastrophic loss of species in the last 65 million years. Most importantly, it is the first major extinction event that has been caused by a single species, one that we hope will act in its own self interest to stem the tide.

Unless the international community can, indeed, reverse the trend, the rate of extinction over the next few decades is likely to rise to at least 1000 times the normal background rate of extinction, and will ultimately result in the loss of a quarter or more of the species on earth.

II. EXECUTIVE SUMMARY

Biological diversity refers to the variety and variability among living organisms and the ecological complexes in which they occur. Diversity can be defined as the number of different items and their relative frequency. For biological diversity, these items are organized at many levels, ranging from complete ecosystems to the chemical structures that are the molecular basis of heredity. Thus, the term encompasses different ecosystems, species, genes, and their relative abundance (OTA, 1987).

There is an ongoing, unprecedented loss of the variety as well as absolute numbers of organisms—from the smallest microorganism to the largest and most spectacular of mammals. Loss of tropical moist forests, which contain over half the total species of organisms, has been well documented by scientists and is now widely reported in the media. Many other ecosystems are also threatened; as human populations and their support systems expand, natural ecosystems at all latitudes are altered or converted.

At its meeting on October 15, 1987, the National Science Board concluded that the world's decreasing biological diversity is a critical scientific issue requiring immediate attention. The National Science Board's Committee on International Science was asked to study the scientific and international aspects of the decline of biological diversity and to recommend a course of action. This report describes what the National Science Foundation (NSF) can do to influence the U.S. science and education base, articulates where international scientific cooperation is needed, and suggests roles for other agencies and organizations (both national and international) which have scientific, educational, and management responsibilities.

The current disappearance of biota has several causes: the destruction or degradation of entire ecosystems; the accelerating loss of individual species from communities or ecosystems as a result of human disturbance; and the loss of genetically distinct parts of populations due to human-induced selective pressures. Although not all parts of the planet are equally affected, the problem is global, and human activities are the primary cause.

The loss of biological diversity is important because human existence depends on the biological resources of the earth. Human prosperity is based very largely on the ability to utilize biological diversity: to take advantage of the properties of plants, animals, fungi, and microorganisms for food, clothing, medicine, and shelter.

Scientific knowledge about the earth's biological diversity has huge gaps. This lack of information hampers society's ability either to estimate the magnitude of the problem or to prevent further losses. It is impossible to identify all the biological resources at risk, since there is no complete inventory of all the life forms on earth. Approximately 1.4 million species have been given scientific names, but estimates of actual numbers range from 5 million to 80 million species. Although knowledge of some taxa is extensive, the vast majority of groups are largely unknown. The current wave of extinction is destroying both known biotic resources and those still undiscovered.

As is proving to be the case with most environmental problems, neither the loss of biological diversity nor its solution is the exclusive province of any one nation. International cooperation is necessary to develop both scientific knowledge and successful mitigation and management strategies. The root causes of the problem include sociological and economic processes which operate on an global scale; a thorough understanding will require investigation and elucidation of both biological and non-biological components.

There are several reasons for increasing National Science Foundation (NSF) involvement in biodiversity studies: the economic and social importance of biodiversity (and the risk of opportunity lost due to accelerating extinction); the contributions such leadership can make toward to conservation of biological diversity; the important role of such studies in the international growth of science, especially in tropical countries; the potential impact of such studies on the future course of biology as a whole; and enhancing public awareness of the issues.

NSF should assume a scientific leadership position with respect to agencies in the U.S. and throughout the world. By insisting on the central importance of biodiversity, the NSF could encourage collaborative support for the actions recommended below.

The Committee's five recommendations are outlined below.

1. **The Committee believes that the role of the NSF is clear—NSF should, as a matter of National Science Board Policy, provide leadership to undertake the inventory of the world's biodiversity.**

   We recommend that support of biotic inventories be significantly expanded within the Division of Biotic Systems and Resources, with initial funding of $5 million annually, climbing to about $20 million.

   We specifically recommend significant expansion of support of microbial systematics and ecology, with an initial funding of $8 million and a growth to approximately $20 million annually. Although microorganisms are the basis for numerous advances in molecular biology and genetics and are one of the bases for the rapidly emerging field of biotechnology, microbiology is poorly known from the standpoint of ecology, species diversity, and systematics. The study and classification of these organisms is both difficult and costly, because the methods used are primarily molecular and require expensive technologies.

   We additionally propose that the Biological Research Resources Program be enhanced. Support for those institutions most active in the inventory should be funded at the rate of $5 million annually. This will supply funding necessary to handle the increased numbers of specimens generated by the inventory. A comparable sum will be needed for information management, e.g. data banks, Geographic Information Systems (GIS), to handle and disseminate the data generated by the inventory.

2. **The scientific basis for conservation biology, restoration ecology, and environmental management must be strengthened.**

   We recommend increased support across the Federal government to develop the scientific base underlying the emerging fields of conservation biology, restoration ecology, and environmental management. Effective preservation and restoration must include social and economic considerations. This will involve multidisciplinary research in ecosystem restoration, creation and enhancement, in development of environmental planning and management methods, and in development of environmentally compatible technology. These programs should be funded at a level of $3.5 million the first year, building to a level of $10 million per year.

3. **Educational and public awareness programs related to biodiversity need increased support.**

   We recommend special emphasis on biological diversity education, including K-12 and informal science education.

   Specifically needed are opportunities for predoctoral and postdoctoral training in the fields such as systematics, ecology, conservation biology, and environmental management. Support of international students studying these disciplines in U.S. institutions should be included. NSF has virtually the full responsibility for the health of these fields of biology in the U.S.

   Although predoctoral and postdoctoral opportunities are vital at this time, primary and secondary education should not be ignored. The present mode of primary support for the K-12 level should include the development of materials pertinent to systematics and ecology. These subjects are of interest to most students, and it is increasingly important that all citizens be educated about the global biodiversity crisis. Early education in these subjects is now as important to the national interest as early education in mathematics and other sciences.

4. **The economic and social aspects of the biodiversity crisis need additional study.**

   We recommend additional funding, initially at the level of $1 million annually, for theoretical and empirical studies of the economic and social causes, consequences, and remedies of the biodiversity crisis. These funds would be added to the budgets of the appropriate programs in the Division of Social and Economic Sciences.

5. **Enhance support for developing country scientists and institutions for biodiversity research and conservation.**

   We recommend that NSF, in concert with bilateral and multilateral development assistance agencies, devise new mechanisms to fund scientists and institutions in developing countries working on biodiversity. NSF leadership is critical, because NSF is in a key position to mobilize the resources of the scientific community. These activities will involve U.S. scientific collaboration, but their primary focus must be directed to improving institutional infrastructure, educational opportunities, and employment of systematists, ecologists, and environmental management specialists in the developing countries. Initial funding should be at the level of approximately $2 million.

   This recommendation recognizes that the planet's biodiversity is heavily concentrated in the humid tropics; that new forms of international funding partnerships are essential to the advance of science; and that NSF's future leadership role in biodiversity depends upon its securing an expanded international operating mandate. In the absence of this mandate and increased funding, NSF's capacity to provide international scientific leadership (especially collaborative initiatives) is likely to remain unrealized.

III. PURPOSE OF THE REPORT

Biological diversity is a multi-disciplinary, multi-agency, multi-government issue. At its meeting on October 15, 1987, the National Science Board (NSB) concluded that the world's decreasing biological diversity is a critical scientific issue which requires immediate attention. National and international cooperation are needed to develop both knowledge about and solutions to the problem. The knowledge generated and the solutions undertaken will, in turn, lead to important new opportunities in economic development.

Because of the global scope of the issue, the NSB's Committee on International Science, augmented by other NSB members and scientists at-large, was asked to undertake a study of the scientific and international aspects of the decline of biological diversity. To respond to that charge, this report assesses the issues and sets forth a course of action. The report describes what the National Science Foundation (NSF) can do to influence the U.S. science and education base, articulates where international scientific cooperation is needed, and suggests roles for other agencies and organizations (both national and international) which have scientific, educational, and management responsibilities.

IV. SCOPE OF THE ISSUE

Biological diversity refers to the variety and variability among living organisms and the ecological complexes in which they occur. Diversity can be defined as the number of different items and their relative frequency. For biological diversity, these items are organized at many levels, ranging from complete ecosystems to the chemical structures that are the molecular basis of heredity. Thus, the term encompasses different ecosystems, species, genes, and their relative abundance (OTA, 1987).

The destruction of ecosystems throughout the world, but especially in the warmer regions, has been well documented by scientists and is now widely reported in print and on television. For example, tropical moist lowland forests, the biologically richest, most poorly known, and, until recently, least disturbed of tropical communities, are being decimated at a rapidly accelerating rate. Large areas of the tropics potentially are affected. Left unchecked, most of the forests will be entirely lost or reduced to small fragments by early in the next century.

Brazil has recently taken a positive step to combat the problem by issuing a management plan for Amazonian tropical moist forest and establishing a new institute to study the issue (Secretaria de Assessoramento da Defesa Nacional, 1989).

The loss of tropical moist forests can have profound and far-reaching effects, including: changes in climate, especially rainfall patterns; changes in biological productivity; soil erosion; and an increase in emissions of "greenhouse" gases, which further affects global climate. Destruction of such biologically rich ecosystems also causes extinctions of vast numbers of species. Most of the lost species are unknown; their potential agricultural, pharmaceutical, or silvicultural values vanish with them.

Although habitat loss in tropical regions has drawn the most attention and are the most immediately threatened, losses of natural ecosystems are occurring in nearly every part of the globe as human populations and their support systems expand.

CURRENT KNOWLEDGE ABOUT THE BIODIVERSITY CRISIS

There is an ongoing, unprecedented loss of variety as well as absolute numbers of organisms—from the smallest microorganism to the largest mammal. Loss of tropical moist forest is only one example. Other ecosystems are also threatened, including coral reefs, inland and coastal wetlands, and other tropical forest types. Although not all regions of the planet are equally affected, the problem is global, and human activities are the primary cause.

The decline in biological diversity is important not only for reasons of aesthetics or scientific curiosity, but because human existence depends on the biological resources of the earth. The current wave of extinction is destroying both known biotic resources and those still undiscovered.

The current loss of biota has several causes. One is the destruction, conversion, or degradation of entire ecosystems, with the consequent loss of entire assemblages of species. Another is the accelerating loss of individual species within communities or ecosystems as a result of habitat disturbance, pollution, and over-exploitation. Third, and more subtle, is the loss of genetic variability. Selective pressures such as habitat alteration, presence of chemical toxins, or regional climate change may eliminate some genetically distinct parts of the population, yet not cause extinction of the entire species.

Estimates of species loss rates suggest that, unless current trends are reversed, from one quarter to one half of the earth's species will become extinct in the next 30 years (Lovejoy, 1980; Ehrlich and Ehrlich, 1981; Norton, 1986).

GAPS IN SCIENTIFIC UNDERSTANDING OF BIODIVERSITY

Our knowledge about the earth's biological diversity has significant gaps. The lack of information hampers society's ability either to understand the magnitude of the problem or to prevent further losses.

It is impossible to even identify all the biological resources at risk, since there is no complete inventory of all the life forms on earth. Current estimates range from 5 million to 80 million species (Erwin, 1983; Stork, 1988; Wilson, 1988). Thus, incredibly, the amount of diversity on the planet is not known even to within the nearest order of magnitude.

Scientists have collected and named only 1.4 million species so far (Wilson, 1988). Although knowledge of some taxa is extensive, the identity and natural history of other groups are largely unknown. A more adequate knowledge base is needed to support the relatively new sciences of conservation biology, restoration ecology, and environmental management. Better information will help develop the means to slow or reverse the losses.

THE PROBLEM IS GLOBAL AND THE SOLUTION INTERNATIONAL

As is proving to be the case with most environmental problems, neither the loss of biological diversity nor its solution is the exclusive province of any one nation. Loss of species is taking place in both the North and the South, primarily as a result of the economic exploitation of species' habitats. Natural resource exploitation is in part a function of international markets and financial practices. Trade in elephant ivory (mostly illegal) and tropical timber (legal) has important consequences for biodiversity maintenance. Similarly, development agency policies to fund (for example) dams, frontier roads, even agriculture, lead directly to the demise of species. Moreover, developing country debt undoubtedly drives these countries to higher levels of natural resource exploitation (and consumption) than would otherwise be the case.

If the causes of biodiversity loss are a part of the international financial fabric, so, too, are the solutions. International cooperation and funding are necessary to develop both scientific knowledge and successful mitigation and management strategies. At the most elementary level, biodiversity funding needs are greatest—both in terms of scientific inquiry and in terms of conservation—in poorer, developing countries. If global and scientific objectives are to be served, more effective mechanisms for North-South transfers of funding must be found; more productive mechanisms for scientific collaboration must be invented.

V. GLOBAL PRESSURES ON BIODIVERSITY

This is a time of unprecedented extinction—the permanent loss of many of the kinds of organisms that inhabit Earth. Several factors contribute to this crisis. They include the explosive growth of a record human population; the existence of widespread and extreme poverty and malnutrition; and a notable lack of sustainable, productive agricultural and forestry systems in many regions where such systems are needed. The resulting economic pressures force many people in developing countries to overexploit natural resources, leading to ecosystem degradation and destruction. This is exacerbated by written and unwritten policies, both of developed and developing countries, which encourage such exploitation.

GLOBAL POPULATION AND ECONOMIC PRESSURES

The global human population, now 5.2 billion, has doubled in size since the early 1950's. This record number of people puts increasing pressure on the earth's biological resources.

The global distribution of people has been changing drastically. For every person who lived in an industrial country like the U.S. in 1950, there were two people living elsewhere; by 2020 (just 70 years later), there will be five. At that time, approximately four times as many people will live in countries that are partly tropical (excluding China[1]) as did in 1950 (World Resources Institute et al., 1988).

In addition, the world population will not stabilize for at least two or three more generations. A high proportion of the people in developing countries have yet to reach childbearing age (typically, 38% to 45% are less than fifteen years old) (World Resources Institute et al., 1988). United Nations' projections from the early 1980's suggested that, even if countries' current family-planning objectives were continued, a stable world population of 9 to 12 billion people would be achieved only in the latter portion of the next century (World Resources Institute et al., 1988). However, that projection assumed a greater increase in worldwide family planning than has occurred. The most recent projections from the United Nations Population Fund (UNFPA), based on the current rate of birth control use, indicate that the world's human population will reach 14 billion by the year 2100. Unless birth control use increases significantly, the world population will reach 10 billion by the year 2025 (UNFPA, 1989).

Although a smaller and smaller percentage (currently about 25%) of the world's population lives in industrialized countries, they control most of the world's wealth. The people in developing nations base their standard of living on no more than 15% of the world's total resources, although they represent 75% of the global population. This unequal distribution of resources is true regardless of what statistic is measured: money, industrial energy, metals, or industrial production (World Resources Institute, 1988).

Developing countries have more agrarian economies and are more directly dependent on natural resources. At present, humans are using between 20% and 40% of the

[1] Because of the unavailability or unreliability of data for China (PRC), these data are not included.

net terrestrial primary productivity (Vitousek et al., 1986; Wright, 1987). Larger populations will require even greater use of natural resources.

More than one billion of the roughly 2.8 billion people now living in the developing world, exclusive of China, are living in a substandard condition that the World Bank defines as absolute poverty. This widespread poverty drives the overexploitation of natural resources, such as clearing tropical forest for agricultural uses.

For these reasons, political and economic instability are widespread, and the scientific and technological infrastructure of developing countries is tragically inadequate. Unless changes are made, prospects for stable development in the tropics in the near future are poor.

HABITAT DEGRADATION CAUSES LOSS OF BIODIVERSITY

Habitat destruction throughout the world, especially tropical regions, is directly related to the population and economic factors described above. Humans have always altered their habitat. However, as human numbers and human technological abilities increase, anthropogenic changes in ecosystems cause environmental degradation and species extinctions.

Much discussion has centered on tropical terrestrial habitats because of the immediate threat and direct connection to human causative factors. Over half the world's species are associated with tropical forests. These forests are being cut at an increasing rate. Ten years ago, the United Nation's Food and Agriculture Organization (FAO) estimated that 70,000 square kilometers of tropical moist forest were destroyed per year: a loss rate of 100 acres every three minutes. The current rate of loss is estimated at 100 acres of forest per minute—the equivalent of losing an area the size of a football field every second. In addition to outright destruction, estimates are that at least another 100,000 square kilometers are significantly disturbed annually (Myers, 1988).

The theory of island biogeography states that when natural communities have been reduced to less than 10% of their original area, half of the original species are at risk (MacArthur and Wilson, 1967). For example, when forests in Central and South America are reduced to patches of twenty square miles or less—a common occurrence—10% or more of the bird species are lost within 10 years (Terborgh, 1974; Willis, 1979; Simberloff, 1984; Wilson, 1988)

A 90% reduction in habitat area has already occurred in several regions of the world, including western Ecuador, Madagascar, and the Atlantic forests of Brazil. In these regions, the surviving biota clings to life in islands of vegetation. These small populations are subject to climatic change associated with edge effects; frequent human-induced disturbance; and inbreeding effects. In these cases, local environmental disasters can easily extinguish entire species.

Such species extinctions may not have immediate effects on human well-being. However, as forests are removed, profound effects on regional and global climates result. For example, at least half of the rainfall in the Amazon is associated with the forest cover (Salati et al., 1983; Salati and Vose, 1984). By stripping the Amazon Forest (an action that, until very recently, was heavily subsidized by the Brazilian government) Brazil may be ruining its own productive agriculture. Clear-cutting the Amazon may cause regional temperatures to rise more than 5°C in the agricultural lands of southern Brazil (Salati et al., 1983; Salati and Vose, 1984).

Destruction of tropical moist forest is a dramatic example of how human activities are causing species loss and other undesirable environmental effects. However, such habitat degradation and concommitant species loss is not limited to the tropics or to terrestrial environments.

Terrestrial ecosystems in every latitude are being destroyed, degraded or converted. In addition, virtually any perturbation of the terrestrial environment has a corresponding effect on aquatic habitats, though the effect may be separated in time and space. Destruction or degradation of aquatic habitat causes both changes in species abundances and outright extinctions. Consider the following examples.

—Emissions from power plants in the midwestern United States cause acid rain in Canada and in the northern United States. Acid rain has been linked to forest dieback and to the reduction or loss of many aquatic species in northern lakes and ponds. Similar observations have been made in Europe.

—Almost 35% of all rare and endangered species in the United States are either located in or dependent on wetlands, although wetlands constitute only about 5% of the nation's lands (Kusler, 1983). However, wetlands are often converted to other uses. The current rate of wetlands loss in the United States is probably greater than 275,000 acres per year (Conservation Foundation, 1988).

—In the United States' Pacific Northwest, logging practices have been linked to reductions in the salmon runs. Logjams have blocked streams, preventing salmon from traveling upstream to spawning grounds. In addition, soil erosion from clear-cutting forests has caused siltation of salmon spawning grounds, either preventing salmon from spawning or killing eggs already laid.

—Catastrophic flooding in Thailand has been linked to the logging and conversion of forests.

Freshwater ecosystems are not the only aquatic habitats affected by alteration of terrestrial habitat. Marine and coastal environments are also affected by changes made on land.

A large proportion of the world's people live in coastal regions. In many areas, the ocean biological resources are a significant economic resource for the region's inhabitants. Therefore, reduction or destruction of the marine coastal habitat may have severe economic impact on local people.

Coastal bays and estuaries serve many important functions. For example, estuarine systems are sites of high denitrification and are important in reducing eutrophication. In addition, these regions are nursery areas for many marine species. Such "ecosystem services" may be lost as the system is overstressed. Degradation of coastal areas may reduce populations or even eliminate some species of fish, crustaceans, and mollusks.

Human-induced eutrophication can reduce species diversity in coastal regions. For example, eutrophication of Chesapeake Bay from agricultural runoff and sewage has probably increased the production of algal biomass and altered algal species abundances. Increased algal blooms may cause the increased frequency and duration of the seasonal anoxia in the Bay. These changes probably have reduced numbers of benthic organisms and thereby contributed to reducing the productivity of the Bay (Officer et al., 1984).

Biological diversity in other marine systems can also be affected by human activity. For example, coral reefs are among the most diverse, biologically, of any assemblage of organisms and are often a significant source of protein for the people of the region. However, coral reef ecosystems are fragile and extremely vulnerable to disturbance. Eutrophication and sedimentation affect coral reefs. In Hawaii's Kaneohe Bay, sewage effluent and siltation from terrestrial runoff had devastating effects on the coral reefs (Smith et al., 1981).

VI. THE SCIENCE OF BIODIVERSITY

Scientists who collect, describe, and classify organisms and evaluate their phylogenetic relationships are traditionally called taxonomists or systematists. Such scientists study a group, or groups, of related species, often on a regional basis, and may attempt to determine the phylogeny (pattern of evolutionary descent) of the members of that group. To determine phylogenetic relationships, systematists use characteristics ranging from gross morphology to gene sequences. Systematists also study other aspects of the group's natural history (for example, the pollination and dispersal biology of plants).

Systematists prepare monographs of particular groups of organisms, e.g., the palms of the world or the mammals of North America. In a complementary fashion, they also conduct biotic surveys of a variety of organisms in a particular area, for example, the flora of Puerto Rico. Studies of both kinds—monographic treatments of particular groups of organisms and the faunistic or floristic accounts of the organisms that occur in a particular region—are important elements in building up a more complete account of the world's biodiversity.

Systematic studies provide the necessary underpinnings for further biological research. Such basic biological knowledge is essential for productive investigation into the organisms' natural history, ecology, and genetics: the scientific information needed to formulate scientifically-based policies for environmental management.

Biologists are still very far from a complete inventory of all the species of animals, plants, and microorganisms, although Swedish naturalist Carolus Linnaeus founded the science of plant and animal taxonomy over two hundred years ago. In most cases, answers are unavailable for the seemingly simple but important questions, such as: How many species are there? Where do they occur? What is their ecological role? What is their status: common, rare, endangered, extinct?

Of the estimated 1.4 million kinds of organisms which have been assigned names, only about 400,000 occur in the tropics and subtropics; yet scientists agree that no fewer than three million species actually occur in these regions, and the eventual total may be as much as ten times greater (Erwin, 1983). Even for the named species, detailed descriptions of their biology is known for very few species. In other words, current scientific knowledge is inadequate for estimating even the most general characteristics of the abundance and distribution of the plants, animals, and microorganisms.

An NSF-sponsored study on research priorities in tropical biology, completed a decade ago and published in 1980, advocated a worldwide survey of plants, vertebrates, butterflies, mosquitoes, and a few other relatively well-known groups of organisms (NRC, 1980). The report argued that such information would provide an index to patterns of distribution and the nature of communities throughout the tropics. To identify valuable biological resources before they are irretrievably lost, such a survey should be conducted soon; the population, economic, and political factors outlined previously are generating increasing pressures on the world's remaining biodiversity.

In addition, there are other groups of organisms which deserve special attention—ecologically significant groups such as free-living nematodes, ciliates, mites, filamentous fungi, and bacteria. Present knowledge of these groups is very limited, both from a systematic and from an ecological point of view. Current specialists, younger scientists, and students must be encouraged to pursue this area of science.

BIODIVERSITY OF SIGNIFICANT TARGET GROUPS

Biologists have targeted certain major groups of organisms—microorganisms, plants, terrestrial and aquatic invertebrates, and marine biota—as ecologically significant and consequently deserving special attention. In some cases, even the most basic natural history of these organisms is poorly known.

Microorganisms

Although the basis for numerous scientific advances in molecular biology and genetics, microbiology is poorly known from the standpoint of species diversity and systematics, because of the inherent difficulties in classification. This lack of knowledge about the types and abundance of microorganisms is a major limitation for microbial ecology.

Microorganisms constitute "biological bridges" between trophic levels, between abiotic and biotic factors, and between the biogeosphere and the level of gaseous atmospheric constituents. These linkages assume importance far beyond the microscopic realm in which they operate. For example, mycorrhizal hyphae mediate interactions in plant communities by transferring nutrients between plant species (Chiariello et al., 1982). Other microorganisms are an important source of the greenhouse gases which have a crucial effect on earth's climate—but little is known about that aspect of their ecology.

Many types of microorganisms cause disease in plants and animals. Although diseases are usually considered in light of their economic and medical consequences for humans, microbial and parasitic diseases may play a significant role in population regulation within natural communities. Human-induced changes in ecosystems and the resulting alteration in host species abundances may have unforeseen and undesirable effects on the epidemiology of those diseases.

The current tendency in microbial ecology is to focus on function, rather than on specific species. Because chemical methods for studying microorganisms are more advanced than taxonomic methods, it is easier to study the reactions that microorganisms catalyze, rather than a specific species of microorganism. For example, sulfur deposition in rainfall enhances microorganisms which can reduce inorganic sulfur. This, in turn, stimulates the methylation of inorganic mercury and results in toxicity in aquatic food chains. Yet, surprisingly, the precise taxonomy and community ecology of these microorganisms is unknown. Improving scientific understanding of microbial ecology will require increased knowledge of microbial systematics.

Humans have derived many benefits from scientific knowledge about microorganisms. Actinomycetes alone have been the source of 3000 antibiotics since 1950 (Demain and Solomon, 1981). Biotechnology promises to increase the utilization of microorganisms in solving medical, agricultural, and environmental problems. The two foundations for this "biological revolution" are the techniques and fundamental understanding of molecular biology and genetics, and the diversity of naturally occurring organisms. For biotechnology to fulfill its promise, more knowledge is needed about the microorganisms which will form one of the bases for this new technology.

In the past, there has been little funding for microbial systematics and microbial ecology. However, money alone is not the answer. Like other areas of systematic biology, the human resource base is thin. Rectifying this situation will require education at all levels and attention to training and retraining opportunities.

Plants

In this report, "plants" refers to vascular plants (ferns, conifers, and flowering plants) plus bryophytes (mosses, liverworts, and hornworts). Because of their capacity to convert radiant energy into chemical energy through the process of photosynthesis, plants, along with algae and photosynthetic bacteria, are the basis for all food chains.

There may be as many as 250,000 species of vascular plants, approximately two-thirds of which are found in the tropics. The New World tropics are particularly species-rich; for example, one-sixth of the global diversity of plants, 45,000 species, is found in just three Latin American countries: Ecuador, Peru, and Colombia. Although estimates of the number of plant species are available, more specific biological knowledge is lacking.

Much of the diversity of life is threatened by the destruction of plant diversity, because plants provide both food and habitat for other organisms. One-half of the biological diversity of the earth is associated with tropical forests and is, therefore, threatened by their degradation or destruction. Many as yet unknown plant species will probably become extinct by the year 2000, since all forests will be severely damaged or entirely removed within the next 25 years (Raven, 1988).

Plants provide food, clothing, medicine, and shelter for humans. Tropical regions of the world probably harbor many as yet undiscovered plant species which have benefical uses for humans. For example, the legume family, a plant family with about 18,000 species, contains many well known foods, forage plants, and a large number of important tropical timber trees. Both the winged bean (*Psophocarpus tetragonolobus*), a new food plant whose use has spread widely through the moist tropics over the past 15 years, and the "wonder tree" (*Leucana leucocephala*), hailed as the solution to problems of soil erosion and firewood shortages, are legumes (NRC 1975, 1979). Legumes are, obviously, of great economic importance and have significant potential as genetic raw material for agricultural biotechnology. However, most of the legumes now utilized in productive human systems were discovered quite by chance. Little is being done to investigate the enormous numbers of legume species that exist in the tropics. Six thousand legume species are found in Latin America alone—and 3,000 to 4,000 of those are in danger of extinction.

Although there are ongoing efforts, at this time there is no comprehensive survey of plant distribution. The dearth of scientists trained for systematic studies in tropical countries and the lack of financing means progress is slow. As is the case with microorganisms, insufficient numbers of adequately trained scientists makes the preparation of even simple inventories very difficult.

Terrestrial/Aquatic Invertebrates

After microorganisms, invertebrates are, numerically and functionally, the dominant group of organisms on earth. They are slso by far the most diverse in numbers of species. However, again like microorganisms, most invertebrate groups in most parts of the world are poorly known; overall, far fewer than 50% are actually described. The same processes which cause extinction of higher plants and vertebrates also operate on invertebrates. Many species are highly specialized with respect to food, habitat, or other environmental requirements.

The statistics about invertebrates are impressive. For example, ants comprise 5% to 15% of the biomass of the entire fauna of most terrestrial ecosystems. Approximately two-thirds of the 1.4 million described species are invertebrates (Wilson, 1988). Estimates of the total number of species on earth have been revised sharply upward based largely on recent collections of arthropods from tropical forest canopies (Erwin 1982, 1983).

Invertebrates have key functions in ecosystems, including pollination, decomposition, disease tranmission, and population regulation of other species. For example, the interactions of soil mesofauna (e.g. nematodes, collembola, and mites) and soil microorganisms are crucial in maintaining the plant-soil system. Nematodes both feed on and act as dispersal agents for soil bacteria. In turn, predaceous fungi capture live nematodes for use as energy sources.

The activities of invertebrates can have major economic impacts on humans. For example, agriculture depends on crop pollination by bees, yet can suffer greatly from herbivory by other insects. As another example, consider some of the major human diseases mediated by invertebrates: malaria, schistosomiasis, bubonic plague, encephalitis. The recent spread of Lyme disease in the United States has been linked to ticks of deer and mice.

However, invertebrates are not studied in proportion to their number or importance in ecosystems. For example, there are perhaps 20 ant taxonomists worldwide, and fewer who can identify tropical species. For animals like nematodes, collembola, and mites, the number of specialists is even smaller (Wilson, 1985). Knowledge of invertebrate systematics is crucial for productive scientific investigation into other aspects of invertebrate biology.

Marine Biota

Over two-thirds of the Earth's surface is ocean. The biota of Earth's oceans are essential to the structure and function of the global ecosystem. For example, marine phytoplankton play an important role in the maintenance of the atmosphere. Much of the Earth's human population depends on the oceans, especially marine coastal systems, for food. Approximately 80% of the marine species of commercial importance occur within 200 miles of a coast.

Very little is actually known about the marine biota. Fish, molluscs, and corals are the best-known groups. However, major groups of organisms and new habitats are still being discovered. The phylum Loricifera was described only in 1983 (Kristensen, 1983), and an entirely new habitat was revealed by the discovery of ocean vent systems. The bottom of the ocean is still largely unexplored; assaying and understanding its biological diversity requires a commitment of resources like that committed for exploring the Moon. Funding for ships and associated sampling tools is the limiting factor; such research requires costly and specialized equipment.

Current estimates of the total number of species on the planet assume that approximately 80% of species are terrestrial. However, some research suggests that deep sea fauna may rival tropical forests in species diversity (Grassle, pers. comm. in Ray, 1988). The processes maintaining biological diversity in oceans are similar to those seen in terrestrial ecosystems: gap formation and patch dynamics. However, exactly how these processes operate in marine ecosystems remains largely unknown, because few long-term studies have been undertaken.

Inventories and ecological studies are needed in all oceans, with special emphasis on those habitats most immediately threatened. So little is known about the marine biota that rates of extinction are difficult to estimate; however, Ray (1988) suggests that disturbance and degradation of coastal zones is occurring as rapidly as tropical forest destruction. Just as with terrestrial systems, marine biological diversity is highest in the tropics—and those are also the regions at risk. For example, coral reefs are both highly diverse and extremely fragile.

FUTURE BIODIVERSITY STUDIES

For all groups of organisms, sampling those that occur in threatened regions is of special importance now, because natural communities are being destroyed so rapidly. Large numbers of endemic species are being lost in specific areas that Norman Myers has called "hot spots" (NRC, 1980; Myers, 1988). Particularly in these areas, but increasingly throughout the tropics, inventory work and preservation are crucial. The fine details of classification can be left until later.

Nonetheless, in practice it is often impossible even to recognize the numbers of species present in a given sample without having a specialist's knowledge of that particular group. For that reason, both monographic studies, which constitute the principal activity of many systematic biologists, and regional inventories are of primary importance.

To achieve an acceptable standard of knowledge about the world's biota, the following actions are needed:

(1) Complete a global biological inventory. This is urgent; without a reversal in current rates of habitat destruction and species extinction, a comprehensive

systematic survey will be possible only for the next 10 to 20 years. To ensure the protection of natural resources before they are irretrievably lost, creation and maintenance of protected natural areas is essential.

Whereas some environmental problems are on the horizon, species extinction is here and now. It is not reversible. In systematics research, there must be a balance between hypothesis testing, description, and stewardship.

(2) Obtain comprehensive knowledge of representative and threatened regions. For example, study 200 locations in great depth; concentrate resources of time and of expertise, to avoid dilution of effort. Study locations need to be chosen carefully, in order to devote sufficient effort to poorly known areas, those which are being rapidly destroyed, and those with a high level of endemism, e.g. Madagascar (see NRC, 1980; Myers, 1988). Even 200 sites reflects only a portion of the locations currently under some type of protection. The number of locations at risk is much higher.

(3) Conservation is extremely important. Providing an improved scientific basis for conservation of species and habitats requires nvestigations into organisms' natural history, ecology, and genetics. In addition, there should be more emphasis on the application of technology to seed banks and other types of genetic reservoirs.

(4) Develop comprehensive databases on biological diversity. Computerized data banks are the most effective means of disseminating the data collected and making it available for scientific and societal purposes.

(5) Human resource development is critical. Several factors have contributed to the paucity of trained personnel, including the lack of research and/or teaching positions for systematists, lack of training grants, and competition from other areas of biology.

The forthcoming Higher Education Survey on Systematic Biology Training and Personnel reports that, although the surveyed institutions listed 55 faculty vacancies in systematics, only 20 new hires were likely to be in systematics (Higher Education Panel, 1989). If systematics faculty are not replaced, how will new systematists be trained?

In 1987-88, only 3% of the biology PhD's granted were in systematic biology (Edwards et al., 1985; NSF, 1989). The number of systematics graduate students has declined substantially within the past 10 years. An NSF-commissioned survey done in 1985 reported 1298 doctoral students in systematics (Edwards et al., 1985). In contrast, the forthcoming Higher Education Survey on Systematic Biology Training and Personnel reports that, doctoral and master's students combined, there were only 1,154 systematics graduate students in 1987-88 (Higher Education Panel, 1989). Anectodal evidence suggests that although college students are interested in natural history studies, lack of professional opportunities discourage students from pursuing systematics in graduate school.

A "climate of opportunity," consisting of training funds for aspiring systematists, tenure track slots in colleges and universities and support for research grants, is needed to attract scientists to these fields.

(6) International programs of research cooperation need more attention. The focus should be the rejuvenation of cooperation with developing countries.

Ten years ago, it was estimated that as few as 1,500 (NRC, 1980) systematists worldwide were competent to deal with even one group of tropical organisms. The situation has scarcely improved in the 1980's. The lack of scientists in developing countries makes the overall personnel problem particularly acute, since the vast majority of species inhabit precisely these regions, and they are by far the most poorly known on earth.

Systematists are indispensible for advances in all fields of biology, including ecology, agriculture, and conservation biology. These areas of research are especially important for developing countries.

VII. WHY SHOULD NSF BE INVOLVED IN THE BIODIVERSITY CRISIS?

There are several reasons for increasing National Science Foundation (NSF) involvement in biodiversity studies: the economic and social importance of biodiversity (and the risk of opportunity lost due to accelerating extinction); the important role of such studies in the international growth of science, especially in tropical countries; and the potential impact of such studies on the future course of biology as a whole. NSF leadership in this area can make significant contributions by providing the scientific bases for conservation and enhancing public awareness of the issues.

THE ECONOMIC AND SOCIAL IMPORTANCE OF BIODIVERSITY

Human prosperity is based very largely on the ability to utilize biological diversity: to take advantage of the properties of plants, animals, fungi, and

microorganisms as sources of food, clothing, medicine, and shelter.

Human beings are placing increasing demands on global natural resources. Therefore, it is especially important to understand how to build sustainable systems, and ecologically sound sustainable development requires knowledge. Surprisingly few kinds of organisms are either domesticated or harvested from the wild.

For example, forestry and agriculture are two productive systems based on individual kinds of plants and animals. Undisturbed tropical moist lowland forest is characterized by a moderately high primary productivity. Yet the agricultural and forestry systems with which people have replaced it often fail after only a few years of productivity. Understanding the forest depends directly on both ecological and systematic knowledge: how many kinds of organisms are there, what are their characteristics, and how do they interact?

The changes correlated with forest clearing have generated a collective interest in re-vegetating major portions of the world. Restoration ecologists attempt to return degraded or destroyed ecosystems to many of the economic and aesthetic purposes originally served. Replanting and reforesting tropical areas would slow global warming. It would also supply food and fuel for many people who live in the tropics, thus reducing the economic pressures to cut intact forests. Conservation of the uncut areas will lead to watershed and soil protection, a slowdown in regional climate change, and the preservation of a substantial amount of biodiversity. Detailed knowledge of the plants and the ecological systems of those regions is needed to successfully accomplish the goals of restoration and reforestation.

Scientists estimate that there may be tens of thousands (Meyers, 1983; Plotkin, 1988) of plant species that could be used as food, yet little effort is being made to identify and cultivate them. The few plants now used for agriculture were selected by our Stone Age ancestors as particularly easy to gather and to harvest by hand; nearly all of them have been in cultivation for 2,000 years or more. Methods of selecting new crops have not evolved as human needs and capabilities have changed.

Many of the world's important crop species originated in the tropics. As much as 98% of U.S. crop production is based on species which originated elsewhere (Caufield, 1982). Therefore, wild relatives and regional varieties of current crops are important sources of genetic diversity. Such genetic resources are being lost as wild relatives become extinct and as the use of regional varieties is discontinued. For example, maize is the world's third most important crop. The recent discovery of *Zea diploperennis*, a perennial, virus-resistant, wild relative of maize, has significant agricultural implications. However, this new species of *Zea* could easily have been one of the many plant species lost to extinction; it is known only from a single six hectare site in the Mexican state of Jalisco (Iltis et al., 1979; Vietmeyer, 1979).

Basic biological information is needed to protect current systems against destructive organisms and to develop sustainable systems based on wise use of natural resources. Often, very little is known about pest species. For instance, despite the economic threat posed by leafhoppers as plant pests, there are no more than a handful of specialists worldwide capable of identifying them or describing them scientifically. As a result, when the brown rice leafhopper (*Niloparvata lugens*) suddenly became an agricultural pest and ravaged rice crops throughout the warmer parts of Asia in the late 1970's, it was virtually unknown. Although its biology became the subject of crash programs, almost nothing was known initially. Lack of basic biological knowledge about the brown rice leafhopper impeded the development of methods to combat the new pest (Yanchinski, 1978).

Nearly half of the drugs now in use were developed from substances initially found in nature; these substances were the products of plants, fungi, and microoganisms. At present, no more than 1% of all plant species have been examined in laboratories for their chemical properties; even less is known about bacteria and fungi, especially those found in the world's oceans. These organisms, often natural biocontrol factories, have untapped pharmacological potential. For example, vincristine and vinblastine, drugs used in treating childhood leukemia and Hodgkin's disease, were derived from the Madagascan periwinkle plant (*Catharanthus roseus*). The tropical regions of the earth harbor tens of thousands of unnamed plants and microorganisms. When surveyed, such plants and microorganisms are likely to be sources of new products useful for industry, such as gums, latex, resins, dyes, waxes, oils, sweeteners, and new sources of energy.

Modern methods of genetic technology offer bright possibilities for agriculture, pharmacology, and medicine. These methods depend on the discovery and utilization of particular genes. Each organism represents a collection of tens or even hundreds of thousands of genes, some of them unique; extinction is not only the loss of an unique kind of organism, but also the permanent loss of a collection of genes.

Finally, and of fundamental importance in a world of depleted energy potential, many products can be produced in low-energy-input systems simply by allowing organisms to grow: yet little effort is being made to improve knowledge of these systems or to encourage the studies on which such an improvement could be based.

BIODIVERSITY STUDIES IN INTERNATIONAL SCIENCE

Current international cooperation in science is heavily directed toward the European Community and Japan, and to a lesser extent other developed countries such as the Soviet Union. This current emphasis neglects the decisive future role of developing countries in the economy and environmental health of the world as a whole. The effects of destroying tropical forests in enhancing the greenhouse effect have begun to make the interconnections between environment and economics clear, as have ill-advised efforts to dispose of toxic and radioactive waste products in countries that desperately need foreign currency. The sustainable management of the global ecosystem for common benefit must involve the people of all nations.

Because the great bulk of biodiversity occurs in tropical countries, especially those with forests and fringing reefs, tropical regions are the highest priority for both protection and research. Studies of diversity are labor-intensive and require less expensive apparatus and materials than most other scientific research. It follows that such research can and should be a major part of the scientific agenda in developing countries. Tropical countries will gain increasing benefit from their biological resources in the improvement of agriculture, the development of new pharmaceuticals and industrial products, and the promotion of tourism.

Working in isolation, scientists in industrial countries will not be able to adequately address the problems of biological diversity in the tropics and subtropics: these goals can be achieved only with major participation from scientists living in those countries.

Therefore, the Committee holds the preoccupation with scientific and technical interchange between advanced, industrial countries to be ill advised. We strongly recommend that the National Science Foundation, for reasons of national and international interest, embark on a reinvigorated program of scientific and technical interchange with developing countries throughout the world. To be successful in such a leadership role, the National Science Board must recognize this essential international role and assume its broader responsibilities.

BIODIVERSITY AND FUTURE TRENDS IN BIOLOGICAL RESEARCH

Classical biology contained a large component of systematics: biologists named species, tried to establish the relationships between them, and described their natural history. During the 1950's, the revolution of molecular and cellular biology forced a thematic shift in the study of biology—with enormous benefit. At present, the principal disciplinary orientation stresses levels of organization, such as cellular and molecular, rather than taxonomic groups of organisms.

However, investigations in cellular, developmental, and even molecular biology reveal phenomena which often concern only particular species or, at most, limited groups of species. To determine degrees of generality, investigators map these phenomena onto phylogenetic groups. There is an informal rule in the conduct of biological research that, for every problem, there exists a species ideal for its solution. Enteric bacteria are valuable for genetic mapping, but inappropriate for studies of meiosis. Langurs and lions were the key to understanding infanticide, but would have been an unsatisfactory choice for genetic mapping.

Extinction of species will thus constrain the discovery of unifying biological principles. Furthermore, new emphasis is being placed on the uniqueness of each species. While biologists will continue to think in terms of levels of organization and chains of causation, more and more will commit themselves to studying a particular group of organisms across all the levels of organization. This trend promises a new and productive pluralization of biology, with systematics returning to prominence in biological research. The current biological revolution has helped unite the two approaches: systematists now routinely compare proteins, while molecular biologists construct phylogenetic trees.

The future of basic biological research lies substantially in the exploration of diversity. The surest path to discovery will be systematics of a new kind, in which expanded knowledge of organisms is promoted by research which shuttles between all levels of organization, with an emphasis on diversity and its uses.

VIII. THE ROLE OF THE NATIONAL SCIENCE FOUNDATION

NSF is the dominant Federal agency responsible for research and training in organismal biology. For example, the Foundation currently provides 90% of the Federal support for systematics work at colleges and universities and 75% of the support for ecolgical sciences. Research and education are the "stock in trade" of the Foundation. Given NSF's prominent role nationally and globally in support of organismal biology, it is now entirely appropriate that the Foundation, in its leadership position, stimulate the study of biodiversity.

NSF should take the initiative with respect to similar agencies throughout the world. By insisting on the central importance of biodiversity in meetings with corresponding bodies in such industrialized countries as West Germany, Japan, and Switzerland, the NSF could develop partnerships to support the actions recommended here.

The National Science Foundation can, indeed, must act in three interconnected spheres to address the scientific and educational issues at stake in the biodiversity crisis: within NSF; among Federal agencies; and in the international community of scientific and educational organizations.

WITHIN NSF

NSF must increase funding to support research and training in systematics and ecology, focusing specifically on: biotic inventory; phylogenetic analysis; physiological and genetic mechanisms; and ecological structure and function. Biological inventories and systematic studies are necessary underpinnings for investigations into more complex aspects of organisms' natural history, physiology, ecology, and genetics. Support for natural history museum operations and for education and training are necessary components of this activity.

Conservation biology, restoration ecology and environmental management, although applied disciplines, depend on basic biological knowledge. By funding more research in systematics, ecology, and other disciplines that contribute to the underlying scientific base, NSF can broaden the knowledge base for these applied fields.

In addition, some recent research by resource economists highlight the imperative of increasing interaction between and among economists and biologists. Prices for non-timber tropical forest products have only recently been compared (favorably, it turns out) to timber harvest prices. National tax and credit policies have, in the recent past, contributed directly to and extraordinary amount of rainforest conversion in Brazilian Amazonia and to forest conversion in the United States (Repetto, 1988). United Nation economic growth indicators such as Gross Domestic Product (GDP)—indicators used by planners, bankers, and economists throughout the world—do not include information on reductions in stocks (e.g., timber, soil, fisheries, etc.). Natural resource balance sheets do not exist, nor are there other clear indicators to encourage policymakers to invest in a country's natural resource base through (e.g.) reforestation. Further, there are troubling questions as to whether neoclassical economic theory, as understood and practiced at the close of the 20th Century, adequately addresses natural resource depletion (hence biodiversity loss) issues.

Because public policy land-use decisions which directly affect biodiversity conservation are often made in the idiom of economics (based on the evaluation of costs and benefits), the Committee urges that NSF initiate the development of research agendas which necessitate increased collaboration among economists and biologists.

AMONG FEDERAL AGENCIES

The NSF should promote awareness of biological resource issues in the policy deliberations of Federal organizations. The mission of all natural resource agencies touches on the preservation of biological diversity, both nationally and internationally. The Department of Agriculture, for example, currently concerns itself with crops and their improvement. All productivity in agriculture and forestry is ultimately based on biodiversity. The Department of Interior's land management agencies are charged with managing land for multiple use, which includes harvesting both mineral and biotic resources, all the while maintaining those natural resources for future generations.

In this environment of multiple needs and demands, there is a clear need for leadership to provide a forum and to coordinate scientific consensus on the issue of biodiversity. The Federal Coordinating Council for Science, Engineering, and Technology (FCCSET) could provide such a forum for the various federal agencies by establishing a committee, similar to the Committee on Earth Sciences, on the global loss of biodiversity.

Among development-oriented agencies in particular, concern over biotic impoverishment must be transformed into active stewardship of species and community resources. Better knowledge of those resources would enhance the effectiveness of such stewardship. For example, the U.S. Agency for International Development (AID) mission should enable NSF to forge partnerships with AID to develop the scientific and technical infrastructure in many countries. AID, with now very limited resources, is now devoting considerable attention to the preservation of biodiversity and to other environmental problems in its client countries. Establishment of protected areas is increasingly an integral part of regional development schemes. AID and similar development agencies could assist materially in supporting national museums and similar institutions, in the establishment of regional and national data banks, in education, and in the development of more effective environmental planning and management.

Science must form the basis for identifying policies and actions which will most effectively preserve biodiversity. The single most effective step would be the creation and international funding of an extensive system of international parks and reserves. However, in many parts of the world, natural systems are becomingly increasingly fragmented, simplified, and perturbed; the preservation of pristine ecosystems is becoming less and less possible. In addition, park boundaries are insufficient barriers to many sources of environmental degradation, e.g. acid rain, greenhouse warming, and air and water pollution. Therefore, developing methods to maintain biodiversity in "altered" habitats is critically important; it will not be sufficient only to maintain biodiversity in "untouched" reserves. More research is needed to develop effective methods to restore and enhance damaged ecosystems.

Creation of global networks of seed banks, botanical gardens, zoos, and microorganism culture collections would preserve biotic resources on another level. An additional part of the solution is development of an international convention (similar to that on the protection of the ozone layer) which treats biodiversity as a common property resource and funds its preservation internationally. In response to the World Commission on Environment and Development (the Brundtland Commission), the United Nations Environment Programme (UNEP) is taking the lead in the development of such a convention, with substantial assistance from non-governmental organizations such as the International Union for the Conservation of Nature (IUCN) and World Resources Institute (WRI) (World Commission on Environment and Development, 1987).

In all cases, the NSF, by demonstrating the importance of biodiversity for science and for economic development, could help strengthen the positions of its sister agencies. The cooperation of other agencies would greatly increase the available funding for the solutions proposed here.

WITH INTERNATIONAL SCIENTIFIC AND EDUCATIONAL ORGANIZATIONS

International collaboration is required to solve the problems of biotic degradation and loss. NSF, by expanding the activities of its International Programs (INT), can assume a leadership role in promoting bilateral and multilateral research in systematics and ecology, environmental planning and management, museum development, and educational training.

What can the NSF do to lead the U.S. scientific community into productive interactions with institutions and individuals in developing countries? Resources in these countries are usually inadequate for the kinds of partnership agreements envisioned in NSF-INT for Japan and the European Community countries. Consider that the budget of the University of California is larger than the national budgets of many Latin American and most tropical African countries. No amount of discussion about the necessity of full financial participation in binational research schemes will alter that.

Therefore, new formulas must be found for NSF to help maintain the developing countries' museums and universities which provide education in the ecological sciences and systematic biology. These sciences form the basis for sound conservation and environmental management. For these reasons, such institutions are clearly a resource for American science and are bound to become increasingly important to international science and developing countries' economic well-being in the years to come.

NSF should collaborate with AID, the World Bank and their international counterparts to support these key institutions. The Committee emphasizes the need to stabilize the financial and physical condition of museums and other institutions which house collections. In addition, education in systematic biology, ecology, and environmental planning and management in developing countries, and the provision of adequate, permanent positions for those educated, are essential. Sustainable development requires sound natural resource planning and utilization. Development agencies can make contributions to biodiversity maintenance in many ways: through training programs, support for research, projects to establish and maintain biological reserves, funding for policy analysis, and through their own conditions for economic assistance.

IX. DISCUSSION AND RECOMMENDATIONS

The Committee's recommendations fall into five categories:

(1) the global inventory of biodiversity, including the management of related information and specimens;

(2) the scientific basis for conservation biology, restoration ecology, and environmental planning and management;

(3) support for related educational programs;

(4) support for selected socio-economic research;

(5) enhanced support for foreign institutions active in this area.

These recommendations are discussed in detail below.

1. The Committee believes that the role of the NSF is clear—NSF should, as a matter of National Science Board Policy, provide leadership to undertake the inventory of the world's biodiversity.

Traditionally, support has been focused on a limited number of groups and on the development of whatever hypotheses were fashionable at a given time. Implicit in this strategy is the notion that all species will be around indefinitely. Given the current staggering loss of species, there is pressing need to chart the contours of biological diversity, both as a matter of scientific importance and one of human necessity. NSF has been the prime source of funding for systematic and ecological research in the U.S., and even on a world scale. The dimensions of the problem demand a new kind of thinking about funding patterns for the Foundation.

The biotic inventory program recommended would conduct surveys of the plants, animals, and microorganisms of the world. The criteria for funding should go beyond the scholarship and productivity of the principal investigator(s) (which are already operational criteria for NSF), but also consider: the importance of the region or group proposed for study; the degree of threat to that particular region; and the potential of the project to contribute to meaningful international interactions and to education.

For many groups of organisms, and especially groups (such as microorganisms and many invertebrate groups) which are very rich in species but the object of few studies, the training and recruitment of additional specialists will be necessary. Much of this recruitment can and should occur in developing countries. A new partnership is needed between NSF and the international development donor agencies; scientific leadership, support of specialized training and research, and long-term funding commitment to continued employment are critical to both early success and sustained progress.

We recommend that support of biotic inventories be significantly expanded within the Division of

Biological Systems and Resources, with initial funding of $5 million annually, climbing to about $20 million.

The total cost of a global survey of biodiversity conducted over a ten year period (presuming the availability of a sufficient number of trained people) can be estimated, very approximately, as follows.

—Detailed investigation, over several years, of perhaps 100 major sites in Latin America (which is more poorly known biologically and richer in species) and at least another 100 in Africa and Asia together, would be necessary to gain a sufficiently detailed picture of the distribution of plants, vertebrates, and major invertebrate groups throughout the tropics.

—The cost of investigating each of these sites, including only the field work and processing the resulting data, has been estimated as between $300,000 and $750,000. The total cost for the project is estimated at between $60 million and $200 million over a ten year period.

—Studies of additional groups of organisms would add to the expense, partly because extensive primary monographic studies would be required to characterize the organisms sufficiently.

These figures are consistent with the recommended level of expenditure. On the one hand, by no means would all the work be funded by NSF, and on the other, various kinds of additional studies would be funded in the program proposed above.

The comparable costs for the inventory of freshwater and marine biota need to be added. That might, owing to the high cost of ship time, double these figures.

We recommend significant expansion of support of microbial systematics and ecology, with an initial funding of $8 million and growth to approximately $20 million annually.

It is tempting to focus solely on larger organisms. It is critical to understand that little information is available about microbial communities in most tropical, subtropical, or marine habitats. Microbial systematics and ecology have been so seriously underfunded that scientific understanding of the organisms is simply inadequate. As terrestrial habitats, especially in the tropics, are destroyed and marine and freshwater habitats polluted, the bacteria, fungi, and protoctists in these habitats are also destroyed.

Microorganisms are one of the bases of food webs and are crucial links in the transfer of energy and nutrients in all communities on land, in fresh waters, and in the seas. More complete scientific knowledge of microbial ecology will be necessary for effective restoration ecology. For example, microbially-mediated rhizosphere processes are crucial in maintaining the plant-soil system, both for individual plants and on an ecosystem level. In addition, mesofauna (e.g., collembola, mites, and nematodes) are an integral part of the soil biota. Ecological studies of the interactions between microorganisms and other soil biota must not be neglected. Successful reforestation and revegetation apparently requires re-establishing the belowground mutualists, not just restoring the aboveground plant community (Perry et al., 1989).

The classification of bacteria and fungi has not yet been established clearly. Current methods for studying these organisms require expensive molecular technologies to complement traditional means of identification. No less than a sustained effort in the systematics and ecology of bacteria and fungi will result in anything approaching an adequate knowledge base in this field.

The problems of understanding many of the groups of the kingdom Protoctista (Protista) parallel those for bacteria and fungi. Specimens are difficult to preserve, and previous methods were inadequate. Consequently, efforts to develop modern systematics for these organisms must go far beyond re-interpretations of old illustrations. Only a dedication to developing a modern systematics of these organisms will yield a comprehensive outline of their taxonomy and basic morphology.

Understanding the ecological interactions of microorganisms is crucial, because the activities of microorganisms have substantial economic impact on humans. For example, bacteria, fungi, and protoctists all cause plant and animal diseases, including those of humans. Systematics studies provide the basis for future biological research. Better knowledge of microbial systematics will allow more productive investigation of microbial ecology.

We additionally propose that the Biological Research Resources Program be enhanced. Support for those institutions most active in the inventory should be funded at the rate of $5 million annually. This will supply funding necessary to handle the increased numbers of specimens generated by the inventory. A comparable sum will be needed for information management, e.g. data banks, Geographic Information Systems (GIS), to handle and disseminate the data generated by the inventory.

Surveying the world's biota will send a flood of specimens to the museums of the world. The NSF Biological Research Resources (BRR) Program, established about 17 years ago to address the needs of systematics collections, has not been able to keep pace with current growth in the numbers of specimens.

For the proposed inventory to be effective, new specimens must be incorporated into existing collections rapidly and efficiently. This, plus incorporating the information into data banks, will allow further exploratory and monographic studies to proceed more rapidly. Having the information easily accessible will be an aid in conservation. Additional funding should be provided for facilities and collections in the major museums of the U.S., in addition to strengthening museums in developing countries.

The construction of adequate data banks is imperative. Since data banking *per se* is costly and not often funded adequately, we recommend the special provision of funds to enlarge and improve the existing operations and develop new ones. Supplementary funding should be provided for some existing grants to allow the incorporation of these surveys or monographic studies into data banks that are generally accessible. For example, the *Flora of North America* program, which is operated by a network of more than 20 institutions in the U.S. and Canada, is generating a data bank on the plants of the region. The Missouri Botanical Garden, in conjunction with the California Academy of Sciences and Harvard University, is starting to add data on the plants of China by means of a comparable joint Sino-American project. A data bank containing the characteristics of some 30% of the plants of the world may not be not far off. Can this be used as a model for other groups and extended to the tropics?

Data-processing strategies that make the data available in machine-readable form should be emphasized. This would make information about previously studied organisms easily available. Such easy access will help determine which groups or areas are the least known or are the most promising for further investigations. Faster inventories of biota may be possible by using automated taxonomic methodologies.

On the other hand, we do not envision the program we have outlined here as a substitute for the Smithsonian Institution's BIOLAT program, which deals with small areas in great depth and stresses ecology as well as systematics. Ecology, ecosystem, and related programs within the NSF Directorate of Biological, Behavioral, and Social Sciences should continue to emphasize tropical ecology to the extent possible.

2. The inventories for which we are calling, and the enhanced training activities in developing countries, will help provide the underpinning for the newly emerging fields of restoration ecology, conservation biology, and environmental planning and management.

There are many important reasons for learning about organisms, but one of the most obvious is saving them. Effective conservation, ecosystem restoration, and environmental management require specific knowledge of species and ecosystems.

Restoring damaged ecosystems and enhancing existing ones can reverse the losses of natural ecosystems and associated biota. Many wetlands restoration projects are currently underway. Some projects have successfully restored natural forest habitats. Experiments have been conducted on building artificial reefs to enhance marine ecosystems.

We recommend increased support across the Federal government to develop the scientific base underlying the emerging fields of restoration ecology, conservation biology, and environmental management. Effective preservation and restoration must include social and economic considerations. This will involve multidisciplinary research in ecosystem restoration, creation and enhancement, in development of environmental planning and management methods, and in development of environmentally compatible technology. More research is needed in population biology and genetics, agro-ecology, wildlife biology and fisheries ecology as well as on preservation of genetic material and captive propagation.

Federal agencies involved in resource management decisions, such as the Forest Service, the Park Service, the Bureau of Land Management, and the Environmental Protection Agency, could make a strong contribution. AID might participate in the international efforts. These programs should be funded at a level of $3.5 million the first year, building to a level of $10 million per year.

3. We recommend special emphasis on biological diversity education, including K-12 and informal science education. Specifically needed are opportunities for predoctoral and postdoctoral training in the fields such as systematics, ecology, conservation biology, and environmental management. Support of international students studying these disciplines in U.S. institutions should be included. NSF has virtually the full responsibility for the health of these fields of biology in the U.S.

Historically, the biological fields considered important to human health were the best funded. For example, most predoctoral and postdoctoral fellowships in the biological sciences are provided by NIH. This pattern made possible an impressive acceleration of knowledge about molecular biology, genetics, metabolism and structural details of cells, tissues, and organs and the ways their actions are integrated.

On the other hand, knowledge about organismal biology has not increased proportionately. Within biology departments, the lack of fellowship or training grant support for evolutionary and systematic biology has exacerbated the sometimes low regard for these traditional and now critically important fields. To increase training opportunities, systematics and organismal biology must also be given more importance in university curricula.

For these reasons, we recommend that the NSF, which has virtually the full responsibility for the health of these areas of biology, emphasize educational and training support. The enhanced levels of research support we have recommended will lead directly to additional educational opportunities. Students are often, and should be, supported on research projects. Recruitment of additional students will depend, in part, on the availability of funding.

Primary research support in the U.S. goes to universities, and, for obvious reasons, educational funding is almost exclusively centered there. However, many leading systematics institutions—the Field Museum, Bishop Museum, California Academy of Sciences, and New York Botanical Garden are examples—are not operated by universities. These free-standing museums actually carry out much of the research in these fields and contain the majority of the national collections of organisms. Creation of adequate educational support programs for systematic and evolutionary biology may require viewing these museums and collections as educational institutions. At the very least, it will be desirable to support linkages between them and universities and to consider modest new funding in this area.

Although predoctoral and postdoctoral opportunities are vital at this time, primary and secondary education should not be ignored. The present mode of primary support for the K-12 level should include the development of materials pertinent to systematics and ecology. These subjects are of interest to most students, and it is increasingly important that all citizens be educated about the global biodiversity crisis. Early education in these subjects is now as important to the national interest as early education in mathematics and other sciences.

Educational collaboration with developing countries is crucial to the success of the program outlined here. Building an adequate research base in developing countries is of fundamental importance. Special efforts should be made to encourage the enrollment of foreign students, especially those from developing countries, in U.S. institutions. It is also important to encourage researchers from developing countries to use the extensive facilities and research groups that are available in the U.S. Collaboration of all kinds should be sought aggressively; for example, participation of foreign scientists in NSF-supported research projects should be strongly encouraged.

4. We recommend additional funding, initially at the level of $1 million annually, for theoretical and empirical studies of the economic and social causes, consequences, and remedies of the biodiversity crisis. These funds would be added to the budgets of the appropriate programs in the Division of Social and Economic Sciences.

One of the key questions is, "Who pays for the conservation of biological diversity?" Most of the threatened species are located in low-income countries of the humid tropics; most arguments for preserving genetic diversity are framed in terms of global benefits for humanity. Current economic policies, methods of analysis, and practices contribute to the biodiversity crisis; they are not neutral. Until connections between methods of economic analysis and the depletion of natural resources are better recognized and understood, rates of biological extinction will probably not be reduced significantly.

National income accounting is the framework normally used for analyzing a country's economic performance and providing policy signals to national decision-makers. These accounts completely ignore the depletion of natural resource assets; they recognize only the income which such resources generate. Counting natural resource extraction only as income results in the overstatement of consumption benefits and erroneous incentives for over-exploitation.

Many national economic policies contribute directly to environmental degradation and the loss of biodiversity. These policies create perverse incentives to deforest lands, drain wetlands, reduce fishery species (in national and international waters) to alarmingly low levels, erode soils, pollute water and air, and dangerously overharvest wild animals. Subsidies, investment credits, taxes, trade regulations and governmental foreign exchange rates comprise a set of instruments which often cause destruction and/or depletion of natural resources. Two examples are the tax and investment incentives for converting tropical forests to cattle ranches in parts of Latin America, and pesticide subsidies for rice production in Asia.

The debts of developing countries are also associated with the loss of biodiversity. Debtor countries must generate foreign exchange earnings to service their debts; debt-servicing pressures stimulate (and may even require) higher levels of natural resource exploitation.

In addition, social and cultural customs heavily influence natural resource stewardship practices. Local conventions governing the management of common property resources often lead to immediate over-exploitation. For example, ownership of timberland is obtained by demonstrating a willingness to "develop," which often is most effectively achieved by burning off the primary forest.

The challenge is designing monetary incentive schemes that enhance the probability of preserving habitats through time, particularly in nations with unstable political regions. "Debt-for-nature" swaps (purchasing a portion of country's debt in exchange for habitat preservation) is only one of many imaginative financial instruments. Long-term purchase of habitat preservation rights is another. There are alternative payment policies. Examples include lump-sum payments in the beginning; balloon payments at the end of a specific period; or annual payments. These different strategies have not been evaluated to determine which best insures habitat preservation through time.

NSF should create a research program that would:

—Identify and assess governmental decisions that create perverse policy incentives to extinguish species. These decisions are imbedded in institutional and policy flaws and omissions.

—Develop alternative socio-economic policies and institutional mechanisms to substitute for the flawed ones.

—Study mechanisms that effectively transmit information about preferred policies, institutions, and market forms to nations with habitat needing preservation.

—Identify institutional mechanisms for maintaining the quantity and quality of the preserved habitats.

—Identify institutional arrangements that enable habitat preservation to contribute to the local economy.

—Encourage synthetic analysis of case studies to identify specific policies, as well as common ingredients, which have played a major role in successful individual preservation schemes.

5. We recommend that NSF, in concert with bilateral and multilateral development assistance agencies, devise new mechanisms to fund biodiversity scientists and institutions in developing countries. NSF leadership is critical, in part because of a vacuum. These activities will involve U.S. scientific collaboration, but their primary focus must be directed to improving institutional infrastructure, educational opportunities, and employment of systematists, ecologists, and environmental management specialists in the developing countries. Initial funding should be at the level of approximately $2 million.

We recommend expansion of support for cooperative research and related development of capabilities in other countries (under the existing Science in Developing Countries guidelines). Further, we recommend that the NSF take the initiative in fostering a consortium of U.S. and foreign sources of support for related scientific infrastructure. Unless NSF, with an authorized expanded international biodiversity mandate, is able to provide *funding* leadership for such a consortium, its *scientific* leadership role will likely be weakened.

The museums located in tropical countries are key institutions for promoting biological inventories on a worldwide basis. Although operating within the limited national budgets of their individual countries, the museums have often done an outstanding job of preserving representative samples of their biological diversity. They are frequently the primary agencies for granting permits of all kinds to foreign scientists, and often receive, by law or custom, large and sometimes unique samples of collections made within their borders. For these reasons, international mechanisms for funding these institutions are urgently required.

Educational institutions in developing countries that have programs in biodiversity studies need support. They are essential components for producing personnel. Regional groupings of institutions, such as the Latin American Botanical Network, which attempt to build on several centers and thereby provide opportunities for students on a regional basis, have an important role to play.

Training local people as technicians both educates more local people and provides personnel for inventory work. Many individuals can effectively participate in biodiversity projects with only a limited amount of training. Such technicians should often be trained and supported with grant funds. The possibility of major programs, involving extensive biodiversity surveys and many people, should be investigated thoroughly.

Not every country has the resources to have a major university program in biodiversity studies; only about 6% of the world's scientists live in developing countries. Sharing the available opportunities and strengths can be an ingredient in building regional consciousness. As in the case of museums, even if NSF is unable to provide a major portion of the support, it can certainly emphasize what is possible and play a lead role in encouraging other kinds of institutions to fund university-based programs.

X. CONCLUSION

The loss of biological diversity threatens both scientific understanding and human prosperity. The diversity of species is the heart of biological research. Human existence requires natural resources: humans use the earth's biological resources for food, clothing, medicine, and shelter. Counteracting the current wave of extinctions will require increased knowledge and concerted action by all the nations of the world.

The National Science Foundation has three guiding themes: scientific opportunity, education and human resources, and science infrastructure. Of all the Federal agencies, the Foundation is in a key position to mobilize the resources of the scientific community to focus on the task before us. The National Science Foundation must take a leadership role to establish cooperative international efforts in conservation and in biodiversity studies and to bring new energy, determination and funding to strengthen U.S. domestic scientific capability and explorations.

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