SYSTEMATICS AGENDA 2000

CHARTING THE BIOSPHERE

TECHNICAL REPORT

A GLOBAL INITIATIVE TO DISCOVER, DESCRIBE AND CLASSIFY THE WORLD'S SPECIES

Prologue

Imagine yourself transported to a strange, but magnificent, planet. The scenery around you is awe-inspiring. As you walk along a coast, waves pound a shoreline that gives way to grassy meadows, meandering rivers, luxuriant forests, and far-off, snow-clad mountain peaks. Even a glance shows that this world is teeming with life — bewildering in variety, and sometimes vaguely menacing in appearance.

Imagine how much there would be to learn about this new planet, and how important that knowledge might become. Some of the plants might provide new foods to help feed starving human populations, or new drugs to fight illness. Some of the animals might successfully control the pest species that devastate crops. The microorganisms might be able to break down pollutants, or help maintain the atmosphere of a crowded world. Imagine, too, that you can stay on this fascinating new world for less than a generation, so that you only have a narrow window of time in which to make all of these discoveries.

In fact, little imagination is required, for this little-known planet is our own Earth. Life on our planet is astoundingly diverse and holds as much promise for potential benefit as that on any planet we might imagine, much less explore in the near future. And the window in time is just as real, for large parts of our planet's surface, both land and water, are facing rapid degradation by growing human populations with needs for shelter, food, and fuel. Another generation or two of rapid population growth and resource consumption will destroy much of life's diversity, long before we have had a chance to discover, much less investigate in detail, what it is we are losing.

Many people are surprised to learn that millions of species on Earth have not yet been discovered or described. In fact, because the Earth is so rich with life, and some groups of organisms are so poorly studied, we still have no clear idea of how many species actually live on our planet. If there turn out to be ten, or even fifty, million species on Earth, few biologists would find that surprising.

We do, however, have a clear idea of how important life's diversity has been to us in the past, and how important it may prove to be in the future. We also have a clear idea of what the study of that diversity can tell us about the history of life on this planet, and how that study can help us solve some of the most pressing problems confronting the world as we move into the 21st century. We face an unprecedented opportunity, one that our grandchildren will not have should we fail.

The science of systematics is the branch of biology that seeks an understanding of life's diversity. Systematists order this knowledge into classification systems that represent what we know about species existing today, or in ages past, and that best predicts what we do not yet know. Systematic biologists worldwide are being asked to accelerate their exploration of life on Earth to provide society with essential background knowledge to discover and utilize new biological resources and make informed decisions that will ensure preservation of the Earth's biological diversity.

Systematics Agenda 2000: Charting the Biosphere

Technical Report

Produced by Systematics Agenda 2000

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Executive Summary

Earth's species, including humans, comprise an intricate fabric, a fabric that has shaped the atmosphere, climate, soil, water, and other ecological features of the planet that are essential for the very existence of life. More than a million of the individual threads (species) that make up this fabric have been discovered and described by systematic biologists, the scientists responsible for exploration of the world's biological diversity. Descriptions of species set the stage for studies of their relationships, as well as for classifications that tell us about the organization and history of life's diversity. These classifications are powerful tools that help us to understand, maintain, and rationally utilize the great biological wealth we have inherited.

Yet, despite over two centuries of accomplishment in systematic biology, we have much to learn about the fabric of life. Tens of millions of species remain unknown to us, species that stabilize the delicate balance of ecosystems, species that have potential for expanding and diversifying our agricultural production, and species that hold new and effective cures for the diseases that plague human populations. Fortunately, recent advances in systematics offer the prospect of undertaking in a timely fashion the daunting task of charting the biosphere in a way that will capture the enormous scope of species diversity.

Meeting this challenge, now more than ever, is pivotal to our survival and well-being. We are faced on a world-wide scale with rapidly declining diversity, disappearing habitats, and increasing demand for precious biological resources. Basic systematic research on species diversity is urgently needed for international efforts by natural resource managers, pharmaceutical explorers, conservation biologists, ecologists, and many others.

The more we know about Earth's biological diversity, the better will be our capacity to conserve natural habitats on land and in the oceans. This knowledge is critical if future generations are to share this planet with the myriad life forms on which we depend.

The international community of systematic biologists proposes Systematics Agenda 2000 to achieve a scientific objective sought by the nations of the world: To discover, describe, and classify the world's species. Meeting this goal will require an intensive international effort involving three interrelated scientific missions.

Mission 1:
To discover, describe, and inventory global species diversity.

Mission 2:
To analyze and synthesize the information derived from this global discovery effort into a predictive classification system that reflects the history of life.

Mission 3:
To organize the information derived from this global program in an efficiently retrievable form that best meets the needs of science and society.

The benefits to science and society will be significant:

- The newly discovered species will multiply society's inventory of usable resources.

- New systematic data will arm conservationists, policy makers, and biological resource managers with the knowledge necessary to sustain and use their nation's species diversity.

- Knowledge of species diversity will assist in the discovery of new products and will guide the selection of new and improved food crops and medicines.

- Baseline data will be generated to monitor global climate and ecosystem change, including rates of species extinction, ecosystem degradation, and the spread of exotic, disease-causing, and pest organisms.

Introduction

> *"To waste, to destroy, our natural resources ... will result in undermining in the days of our children the very prosperity which we ought by right to hand down to them amplified and developed"*
>
> — Theodore Roosevelt,
> message to Congress, December 3, 1907

We share the Earth with millions of other species, whose diversity of forms and complex relationships have been fashioned over more than three billion years of evolutionary change. Earth's species, including our own, are interconnected in an intricate ecological fabric that has shaped the atmosphere, climate, and physical features of the planet and forms the basis for life itself.

Human populations depend upon a vast number of other species, which means that the quality of our life is related directly to the health of the global ecological web. We use tens of thousands of species for food, shelter, clothing, medicines, commerce, and other essential services. This use of other life forms fuels the world economy and makes life richer and healthier for each of us.

Our ability to utilize other species effectively comes from knowledge about them, beginning with understanding what kinds there are, where they occur, what their characteristics might be, and how they are related to other species. Earth's life-forms are enormously diverse. Slightly less than one-and-a-half million species have been described to date, but experts estimate that we may share the planet with tens of millions of others. Documenting and understanding this diversity will be crucial for the future welfare of all human populations. Providing this basic knowledge is the task of the science of systematics.

Systematic biologists are dedicated to the discovery, description, and understanding of the Earth's species. From this information, systematists produce classifications that serve as the foundation for organizing all biological knowledge about these species and providing a framework to predict characteristics of known, and yet to be discovered, life forms. Although we have incomplete knowledge of Earth's species, new methods of systematic analysis, direct access to the genetic material (DNA) of organisms, and powerful technologies for manipulating information, along with growing natural history collections and their associated databases, provide the foundation needed to understand biological diversity on a global scale.

We are presently experiencing a major extinction episode brought on by unchecked human activities. Now, more than ever before, our goal to understand biological diversity has a special urgency. According to a report of the National Research Council (U.S.), more than half of all species are likely to become extinct by the year 2100 (NRC 1980). This estimate, moreover, may be conservative given current rates of ecosystem degradation; the noted Harvard biologist, E. O. Wilson, cautiously projects that 27,000 species are being driven to extinction each year (Wilson 1992). Expanding human populations, increasing poverty, global conflicts, and overexploitation of natural resources all contribute to the accelerating degradation of environmental quality, with its irreversible loss of species diversity.

A reduction in diversity, with its consequent loss of biological knowledge, erodes our ability to enhance the economic well-being and quality of life of all peoples. The tragic extinction of species challenges the world community to discover, preserve, and understand its diversity before our biological heritage is lost forever. The future welfare of the biosphere depends upon the collective actions of the world's governments over the next few decades. This was underscored at the recent United Nations Conference on Environment and

Development (UNCED) in Rio de Janeiro. There, the world community recognized the necessity of continued economic growth while at the same time maintaining the integrity of the biosphere. Through their global action plan, *AGENDA 21*, these nations called for increased knowledge about the Earth's biodiversity.

Simultaneously attaining economic growth and sustainability will entail complex political and economic decisions, which to be successful must be informed by diverse and accurate scientific information about the earth's reservoir of species. To meet the challenge of comprehending life's diversity, the international systematic community proposes a program of discovery and research — **Systematics Agenda 2000: Charting the Biosphere**. Given the resolve and support of a concerned society, the world's systematists propose an accelerated program of research to answer these questions over the next 25 years:

- **What are the Earth's species?**
- **Where do they occur?**
- **What properties do they have?**
- **How are they related?**

The knowledge derived from this research will be organized into predictive classifications and databases that can be used as powerful tools to understand, maintain, and sustainably use the great biological wealth we have inherited.

Systematics is the science built on the following tasks:

Taxonomy:
The science of discovering, describing, and classifying species or groups of species (together termed taxa)

Phylogenetic analysis:
The discovery of the evolutionary relationships among a group of species

Classification:
The grouping of species, ultimately on the basis of evolutionary relationships

Systematics Agenda 2000: Charting the Biosphere

The global community of systematists, through Systematics Agenda 2000, proposes a bold initiative having a clear scientific objective defined by the needs of society:

To discover, describe, and classify the world's species.

Meeting the challenges of the biodiversity crisis and successfully completing this agenda will require an intensive international effort, involving three related research missions:

- To discover, describe, and inventory global species diversity
- To analyze and synthesize the information derived from this global discovery effort into a predictive classification system that reflects the history of life.
- To organize the information from this global program in an efficiently retrievable form that best meets the needs of science and society.

Systematic Knowledge and the Value of Biodiversity

"Every country has three forms of wealth; material, cultural, and biological. The first two we understand well because they are the substance of our everyday lives. The essence of the biodiversity problem is that biological wealth is taken much less seriously. This is a major strategic error, one that will be increasingly regretted as time passes"

— E.O. Wilson, 1992, p.311

Although humans depend on tens of thousands of species for food, shelter, medicines, and other essential services, science suggests that a much greater potential exists for the unknown part of the biosphere. In the face of adverse changes to our global environment, more knowledge about species diversity is essential. Much of this knowledge will come from the basic activities of systematics, namely the discovery and description of new species, the determination of their characteristics and relationships to other species, and the use of these data to form classifications and predictive information retrieval systems. Systematic knowledge thus provides a foundation for basic and applied scientists who are seeking to understand life in all its variety and to preserve and manage it for future generations.

Human Health

Hundreds of millions of persons suffer from diseases caused by living organisms. Billions of dollars are spent annually world-wide in an attempt to cope with the diverse burdens caused by these diseases. Collectively, three parasite groups are currently the world's worst scourges among all diseases: protozoans that cause malaria, blood worms causing schistosomiasis, and the HIV virus causing AIDS. Moreover, 25% of the world's population harbors intestinal roundworms that retard the physical and cognitive development of children. Since 1979, 270 new genera and almost 1100 new species of bacteria have been described. The number of pathogenic or opportunistically pathogenic genera and species now recognized has increased concomitantly.

No progress would be made toward coping with these diseases without the science of systematics. Systematists recognize, differentiate, and characterize both non-pathogenic and pathogenic organisms that affect human health, including hundreds of thousands of species and millions of strains of organisms such as bacteria, viruses, fungi, yeasts, protozoa, roundworms, flatworms, tapeworms, insects, ticks, mites, spiders, scorpions, and snails, among many others. It is not sufficient to know the suspected organism causing a disease; it is necessary to differentiate among all known species of a group to know when a new one has been found, or to establish that a known strain or species has changed from non-pathogen to pathogen (see Box 1).

An understanding of the evolutionary relationships of disease-causing organisms also plays a critical role in promoting human health. By studying the affinities among disease vectors and their related non-vectors, it has been possible to predict the direction of change of disease-causing organisms and to uncover new pathogenic forms. Because of growing populations of immunocompromised patients caused by AIDS, and our ability to transplant organs, heal serious burns, and keep elderly and cancer patients alive, even the most innocuous bacterium and virus can be life-threatening. Thus, despite antibiotics, vaccines, and better sanitation and diet, many traditional diseases are undergoing a resurgence and other, previously unknown diseases are emerging. Scores of species, once thought to be non-pathogenic, are now being isolated from cases of human disease. Knowledge about the evolutionary relationships and geographic distributions of entire groups of organisms has proven essential for understanding the transfer of pathogens from other animals to humans, as well as for discovering why some species of pathogen are more virulent than others.

"We make a potentially dangerous mistake when we assume that we must choose between serving humanity or serving the environment. It must be a priority to bring these goals into harmony. They need not and they must not be mutually exclusive."

– Orville Freeman,
former U. S. Secretary of Agriculture, 1989

Box 1.
Malaria and Systematics:
Saving Lives and Money

Without accurate systematic information about parasites and their vectors, control efforts will often be a waste of time and money. Malaria is a case in point.

Malaria is caused by parasitic protozoa of the genus *Plasmodium.* There are four species of *Plasmodium* that infect humans, but the one most responsible for mortality and morbidity is *Plasmodium falciparum*, which is transmitted to vertebrates through the bite of a mosquito. A number of different species of mosquitoes, whose distributions and vectorial capacity differ, can carry the parasite. The World Health Organization estimates that between 200 and 300 million cases of malaria per year result in nearly a million deaths, mostly in young children.

In the 1960s, there were many studies of insecticide resistance in *Anopheles gambiae*, the principal vector in Africa. Dozens of strains were shipped to London, tested with insecticides and crossed to determine their mode of inheritance to resistance. In a significant number of crosses, infertility resulted. Systematists discovered that what was thought to be one species, "*A. gambiae*," turned out to be six distinct species that differ markedly in their biology and ability to transmit malaria. The same situation has been found repeated in mosquitoes. *Anopheles quadrimaculatus* in the United States, *A. culicifacies* in India, and *A. dirus* in Thailand have each been shown to be complexes of species, with differences in their ability to transmit malaria.

Species Economics

The use of species contributes many trillions of dollars to the global economy. International agreements and treaties pertaining to the use and management of species are gaining in importance as more countries seek to inventory, study, and lay claim to the diversity within their borders. The more species that are discovered and described, and the more we understand their distribution and relationships to other species, the more likely it will be that they can make a positive contribution to a country's economy, and the more likely it will be that those species can be conserved for future generations. The research missions outlined by Systematics Agenda 2000 provide a program for obtaining this crucial knowledge.

History has shown that the discovery of a new species, followed by study of its properties, has frequently led to major economic benefits. Systematic analysis, involving comparisons with other species whose properties have been studied, allows predictions to be made about the properties of new species, and those predictions in turn make assessments of those species' potential economic value more efficient and reliable.

Medicines and Pharmaceuticals

Over 20,000 different plants names are listed by the World Health Organization as having been used for medicinal purposes by human populations. In fact, 80% of the peoples living in developing countries still rely on traditional medicines for their primary health care. Given that most of these medicines are derived from the direct harvest of wild plants, there is intense pressure on many populations of these species.

> *"In the United States a quarter of all prescriptions dispensed by pharmacies are substances extracted from plants. Another 13 percent come from microorganisms and 3 percent more from animals, for a total of over 40 percent that are organism-derived. Yet these materials are only a tiny fraction of the multitude available."*
>
> – E. O. Wilson, 1992, pp. 283-285

It has been shown that screening for pharmaceutically active compounds has a much greater chance of success if done with species used in traditional medicine than with random samples of plants collected from the same regions. Our ability to utilize plants and animals is a function of prior testing, on a long-term trial-and-error basis, by human groups that live in close association with the natural world. Systematists specializing in the ethnobiota — the native plants and animals used by human populations — play a major role in describing and studying these economically important species. Comprehensive ethnobiological surveys of the plants, animals, and microorganisms used by humans are immediate and urgent tasks. Documentation of the interaction between traditional human societies and their useful plants and animals, including the preservation of germplasm, is an important area of research within systematic ethnobiology.

The most important contribution of systematic ethnobiology lies in the creation of classification systems. Much of the scientific work involving the genetic diversity of the ethnobiota —- preservation, conservation, breeding, the search for useful genes, and biotechnology—- hinges on the determination of close relatives by systematic ethnobiologists. The results of their studies are communicated to the scientific community in the form of classifications, taxonomic monographs, or phylogenetic analyses. These studies also contain fundamental biological information, including that about species distributions and structural variation, which is essential for research involving domesticates and wild relatives. Many examples can be given of the importance of systematic ethnobiology in the discovery of new drugs (see Box 2).

Pharmaceuticals derived from flowering plants generate many billions of dollars in sales worldwide. Yet much of this wealth comes from only a relatively few species. Compared to the 250,000 species of flowering plants, microbes are vastly more diverse and potentially a major source of pharmaceuticals and other biotechnological products (Bull et al. 1992). The most famous example is penicillin, produced by the microorganism *Penicillium notatum*, which revolutionized medicine in the treatment of infectious diseases.

The search for new drugs from microbial sources has hardly begun. Systematic knowledge contributes immeasurably to efforts to find these products in that an understanding of the relationships of organisms, developed through phylogeny and classification, provides a predictive roadmap for screening the large numbers of species that exist in nature. Unfortunately, the systematics of microorganisms —-especially of viruses, bacteria, and fungi—- is very poorly understood; millions of species remain to be discovered and described, and the relationships of most groups are still unresolved. Moreover, the number of systematists trained to investigate many groups of microorganisms is declining. Unless this situation is corrected, many opportunities for technological and economic development will be lost (Hawksworth and Ritchie 1993).

BOX 2.
Systematic Ethnobiology and the Discovery of New Drugs: Some Examples from Madagascar

The island-continent of Madagascar houses about 13,000 species of plants, and, remarkably, more than 80% of those are found nowhere else. Numerous medicines have been developed by scientific study of these endemic species and their role in native health care systems.

The most famous example is the rosy periwinkle, *Catharanthus roseus*. Until recently, this species was used only as an ornamental plant in gardens. But the rosy periwinkle had a following in folk medicine as a treatment for diabetes, and it was selected for further study by researchers seeking an oral insulin substitute. Although its value in treating diabetes was not substantiated, extracts of the plant were found to reduce white blood cell counts drastically and to depress bone marrow activity in laboratory animals. These observations eventually led to the isolation of two chemicals, vinblastine and vincristine, which have been successful in fighting leukemia. Since those drugs were first marketed, childhood leukemia survival rates have increased from 10% to 95%.

The roots of two species of the genus *Rauwolfia*, *R. serpentina* and *R. vomitoria*, provide the raw materials for the extraction of several alkaloids or for powdered root material. Pharmaceutical preparations derived from these products are used to treat hypertension and as tranquilizers in the treatment of mental disorders.

"...the problem is that rates of extinction are escalating so quickly that if one were to find a plant that displayed interesting bioactivity, it is quite possible to go back and find its habitat destroyed. It is a race against time."
Michael Balick, Director, Institute of Economic Botany, New York Botanical Garden

Agriculture

Agricultural preeminence on the world market depends on technological advances derived from agricultural research. Throughout the world, advanced agricultural systems are in the process of reducing the amount of pesticide, fertilizer, and herbicide usage by emphasizing practices such as biological control, integrated pest management, and sustainable agriculture. These technologies rely heavily on systematic knowledge of pest groups, their plant hosts, and the natural enemies that keep them in check. Systematic information is the language and predictive basis for agricultural management, and there are numerous examples of programs that were delayed or failed because of insufficient systematic information (see Box 3).

With increased interest in non-pesticide control strategies, the need to understand the wide variety of organisms that play roles in our agroecosystems is increasingly critical. It can be expected, for example, that thousands of potentially useful biological control agents are currently unknown to science. Thus, before they can be economically useful, these organisms must be discovered, described, and integrated into classification and information systems. If organisms that can enhance a productive and environmentally sound agroecosytem are unknown or confused with other organisms, or their relationships to other species are unknown, progress in agriculture will be significantly hindered.

One of the most destructive phenomena to agriculture worldwide is the introduction of exotic pests. Unfortunately, with the growth of international trade and rapid transportation systems, the possibility of introducing new pests is greatly increased. Many countries inspect incoming commodities, locate any exotic contaminants, and make regulatory decisions about entry. This activity is strongly dependent on information provided by systematists. Because no country has a complete inventory of all its species, it is not always possible to know whether an intercepted organism is naturally occurring. Furthermore, definitive identification aids often are unavailable for most agriculturally important groups. In some instances the lack of systematic information for a group of pests can be a special problem. Tobacco budworms, for example, frequently are found on commodities intercepted from Central and South America. Budworms were long believed to include only three species, but a recent monographic study demonstrated that the complex is comprised of 12 different forms.

Countries also must make decisions about allowing the importation of specific agricultural prod-

BOX 3.
Systematic Studies Save Billions of Dollars: Examples From Biological Control

In the late 1800's the cottony-cushion scale was decimating the citrus industry in California. Based on information provided by a systematist, foreign exploration was undertaken in Australia, and the discovery and introduction of a lady beetle that feeds on the scale brought this pest under control and saved the California citrus industry.

For many years biological control specialists were unsuccessful in locating effective natural enemies of the California red scale. A systematist who specializes on scale insects was asked to study the species, and he discovered that there actually were three similar species, the California red scale, the yellow scale, and the taxus scale. Systematists specializing on parasitic wasps later discovered that incorrect identifications had caused effective natural enemies to be ignored; successful biological control agents were subsequently introduced.

Discovery of the area of origin of a pest species often is critical to locating effective biological control agents. One such agent, the sugar-beet leafhopper (*Circulifer tenellus*) originally was thought to be a member of the genus *Eutettix*, which is of South American origin. Unfortunately, exploration for control agents in South America was unsuccessful and considerable time and effort were wasted. When systematists discovered that the species really belonged in the Old World genus, *Circulifer*, several effective natural enemies were located in the Mediterranean area and were introduced into California.

In 1974 an introduced mealybug species was discovered in Zaire. This pest was costing cassava growers in West Africa nearly 1.4 billion dollars in damage each year. The species was described as *Phenacoccus manihoti*, and a search was made for biological control agents in northern South America. When no effective parasites were discovered, a mealybug systematist was asked to reexamine the species and found that a closely related species, *P. herreni*, was found primarily in northern South America and that *P. manihoti* actually occurred further south. With this information, effective parasites were located and introduced into the infested areas of Africa.

ucts from exporting nations. These decisions are strongly dependent on systematic information and are based on the identity of all plant-feeding organisms that occur on the commodity in the country of origin, their pest potential, and their world distribution (see Box 4).

BOX 4.
Systematic Information and Agricultural Trade

In some instances, knowledge of the systematics of potentially damaging organisms has paved the way for increased export of commodities or has averted a serious international trade incident. For example, a smut associated with wheat imported into Canada from the United States initially was identified as *Neovossia indica*, a high risk exotic pathogen. A ban on the import of wheat from the U.S. to Canada was suggested. A systematist was asked to study the material, and it was eventually identified as *Tilletia barclayana*, a species that occurs on rice, which had been stored in the same warehouse before the wheat. Because of this bit of systematic detective work, a potentially costly international incident was averted.

Because of limited systematic information, even on pest species, the scientific basis for these important decisions often is weak.

Agriculture and Genetic Resources

In the past, agricultural programs promoted the use of pesticides and fertilizers that often had adverse environmental impacts. With low impact strategies such as pest management and biological control now being adopted, crop germplasm may need significant restructuring. This will require a detailed understanding of the world's valuable agricultural biota, including potential crop systems, along with their pests and the natural enemies that reduce their population levels. Because genetic engineering permits moving genes from one organism to another, maintenance of species diversity becomes especially crucial inasmuch as the genetic material of any organism may prove to be useful in an agricultural system. Systematic information allows scientists to better understand disease resistance in crops and thus to choose the best genetic stocks for a given situation (see Box 5).

Forestry

Forest land in the United States occupies 2.3 million acres. Although timber products have a value of US$ 136 billion, other forest commodities and non-commodity uses such as recreation and watershed resources have an even greater value. Changes in the public's perception of the value of forest lands have led to a major shift in their management. This new management philosophy has resulted in the maintenance of older tree stands and in greater value being placed on non-timber species. Long-term forest management has a different set of problems than those associated with traditional approaches. Whereas most forest managers are capable of measuring the physical and chemical conditions of forests, as well as monitoring changes in the flora and fauna, they generally do not have the expertise to measure the biological diversity of these forest systems. Lack of systematic knowledge of invertebrate and microbial species places forests at risk, particularly with respect to controlling introduced arthropod pests and pathogens. In 1992, for example, an unusual insect was observed in the forests of British Columbia. Due to a lack of trained specialists, it took one year to identify the insect as *Buprestis haemorrhoidalis*, an exotic boring beetle. By the time it was identified, the insect had had two growing seasons to become established. As a consequence, instead of designing an eradication program for a small area, control measures had to be aimed at a larger region. Delays such as this lower the chances of successful eradication, while at the same time raise costs of the program.

BOX 5.
Taxonomic Discoveries and Crop Improvement: Two Examples

CORN

In 1977, Rafael Guzman, a Mexican plant systematist, successfully rediscovered (in a ditch between two giant cornfields) the long-lost *Zea perennis*, a rare perennial species of teosinte, or wild corn. *Zea perennis* is a close relative of *Zea mays*, the cultivated corn, which is one of mankind's three most valuable crop plants (the others being rice and wheat). Shortly thereafter, Guzman discovered another perennial teosinte population in the cloud forests of a nearby mountain range, and he sent seeds to corn systematists Hugh Iltis and John Doebley. The plants grown from those seeds belonged to a previously unknown species, named *Z. diploperennis*. Unlike *Z. perennis*, this species has the same chromosome number as cultivated corn, and hence readily hybridizes with it. Furthermore, *Z. diploperennis* is resistant to the seven main types of viral diseases that infect *Z. mays*, and it is now possible to transfer some of the viral resistance to domestic corn. Already, four commercial lines have been produced that are virus resistant. Considering that the annual world-wide value of corn is nearly $60 billion, the potential economic benefits of this discovery are staggering.

Another aspect of the story deserves emphasis. The new species was found in a biologically diverse area of southwestern Mexico that was experiencing rapid deforestation through logging, cattle-grazing, and agriculture. The few populations of this rare plant might now be extinct, if the whole of the Sierra de Manantlán mountain range had not been declared a Biosphere Reserve. And if its discoverer had not been an alert specialist in grass systematics, or had failed to send it to experts on the difficult taxonomy of the genus *Zea*, this rare species probably would have been overlooked. Near-misses such as this reinforce the need to increase both the number of trained systematists and the resources available to explore, document, and preserve the world's remaining biotic diversity.

TOMATOES

During an Andean expedition in 1962, Hugh Iltis and Don Ugent collected more than 1,000 numbered herbarium collections. Among these collections were seeds from a new species of wild tomato that, when crossed with cultivated tomatoes, increased the soluble solid content of hybrid fruits. The potential value of this increase to the tomato industry has been estimated at $8 million per year.

Fisheries

Products derived from the fisheries industries provide the world's primary source of protein (Norse 1993). Differentiating among species of fish and other commercial seafood is of obvious importance for managing natural resources and selecting species for aquaculture (see Box 6). Systematic information is also critical for policy issues involving the enforcement of national and international laws, treaties, and conventions.

Introductions of non-indigenous species potentially can cause serious damage to aquatic habitats. Some of the most devastating introductions have been deliberate attempts to spread the supposed benefits of an exotic species. Many aquatic species are also suited to accidental dispersal through

BOX 6.
Systematic Research Increases Fisheries Productivity: Two Examples

Proper identification of target species has been the primary connection between systematics and fisheries. In the northeast Pacific, the fisheries for walleye pollack (*Theragra chalcogramma*) constitute one of the largest and most economically important in the world, and during the 1980's, walleye pollack was the single most important species, by weight, in the world's fish catch. Walleye pollack is just one of several closely related fish species occurring in the northeast Pacific, and until recently, very little was known of its early life history, in part because its larva could not be separated from those of other species in field samples. Systematic studies over the last decade have solved this problem, allowing accurate identification of different larvae. This has permitted implementation of programs that will help increase the proportions of harvestable fishes recruited from larval populations. The systematists involved continue to provide ongoing services to the industry, both on board commercial vessels and by offering identification seminars to managers.

Accurate systematic information is necessary to maintain, or increase, harvestable population sizes of fish. Most of the data available on Spanish mackerel, for example, are based on Brazilian populations, and fishery workers originally planned to use that information in managing the Spanish mackerel in the Gulf of Mexico and along the east coast of the United States. A systematic study showed, however, that the Brazilian population represents a species (*Scomberomorus brasiliensis*) different from that in North America (*Scomberomorus maculatus*). The biological differences between the two species are sufficiently great that management based on the southern species alone probably would have failed.

colonization of ship's hulls or survival in ballast water. Many of these introduced species can cause severe economic damage to native species. Introduced species, moreover, bring with them a suite of parasites and pathogens. Systematic research plays a key role in providing correct identifications of introduced species, as well as their parasites and pathogens, and thus lays the foundation for effective management policies.

Understanding and Conserving Earth's Life Support System

The Earth's physical environment changes over time through complex interactions with living organisms. The millions of Earth's species interact with one another and with their physical surroundings to form a complex ecological web that ultimately sustains all of life. These interactions result in ecological services that provide — free of charge — clean air and water, fertile soils, and regulation of the Earth's geochemical cycles (primarily through the actions of microorganisms). Green plants capture solar energy, thereby making it available to other organisms. The plant cover of the world, especially the rainforests, recycles water to the atmosphere, thus effecting a major control over climate.

With the explosive growth of human populations, the life support system of Earth is becoming increasingly threatened as the rate of global change accelerates. Human use of the world's natural resources to provide food, shelter, clothing, and fuel has led to major environmental impacts, including massive deforestation, air and water pollution, and global warming.

Systematic knowledge plays a fundamental role in monitoring this global change. Collections of specimens provide a record of alterations in biological communities and ecosystems, and thus document responses to environmental stresses over time. These same collections, because they contain the primary scientific evidence for the existence and identification of different species, also provide the most reliable documentation of species extinction. Current projections of species loss over the next century are derived primarily from general information on the rate of deforestation and habitat destruction. Without documented scientific knowledge of which species exist and where they live, accurate evaluations of ecological change and species extinction are not possible. Only systematics provides a reliable benchmark to the dimensions of the biodiversity crisis.

Accurate species identifications are essential for monitoring global change in yet another way. All communities contain some species that are especially sensitive to particular environmental changes. For example, some species of frogs appear to be especially sensitive to changes in air quality, and within some aquatic communities certain species of fish are highly sensitive to changes in water purity. The use of these indicator species is increasingly important as scientists seek to monitor global change by examining its effect on natural communities. Such monitoring activities are made possible by accurate identifications and descriptions of species, detailed information about their distribution, and knowledge of their close relatives.

Many habitats and ecosystems in the world contain tens of thousands of species having extraordinarily complex interactions. Ecologists and resource managers study the dynamics of these interactions, but because of gaps in our knowledge about the identity of even the most common species, and where they can be found, basic descriptions of how these habitats and ecosystems work are necessarily incomplete. Intensive systematic research will be required to describe and identify the species that occur in the Earth's myriad ecological communities, yet such information is critical for providing a baseline against which environmental stresses can be measured.

Systematics plays a fundamental role in the management and conservation of natural resources. Managers charged with conserving biodiversity in protected areas need to know the identities and geographic distributions of species so that they can design and implement effective management strategies. Systematists provide information on species identifications, measures of diversity, and knowledge about which species require special conservation effort. Systematic information, moreover, is of immediate relevance for choosing and designing sites for preservation, development, and for assessing compliance with local and national regulations. Accurate systematic data are also urgently needed for the effective management of the huge international trade in plants and animals. These data contribute directly to the implementation and enforcement of international treaties and conventions, such as the Convention on International Trade in Endangered Species (CITES).

Enhancement of the Quality of Everyday Life

The diversity of organisms invites us to seek answers to questions that help define the human consciousness and intellect. The search for solitude or comfort in natural surroundings is deeply embedded in the human spirit, which is why the ethical and religious beliefs of so many cultures encompass a stewardship role to protect and revere their natural surroundings. Because of our capability to drive other species to extinction, it is widely recognized that we possess an ethical responsibility to prevent such tragedies. As Ehrlich and Ehrlich (1992, p. 220) note, however, "We suspect that the basic problem of conserving biodiversity is not likely to be solved until and unless a much larger proportion of the human population comes to share this view."

Throughout their history humans have shown a strong curiosity about, and esthetic attachment to, other species. That this connection to nature is important to all peoples is shown by the numerous activities involving other species, particularly gardening, petkeeping, and wildlife and bird watching. At the same time, this esthetic and emotional bond to other species has enormous economic consequences for many people. Two activities, in particular, generate substantial economic exchange: nature tourism and the local and international trade of species.

Tourism generates approximately US$ 250 billion a year in commerce. Perhaps as much as 20% of that is ecological or nature tourism, when this is taken to include all travel activities that involve the enjoyment of other species. Many countries derive most, or a substantial proportion, of their gross national product from ecotourism, and some species, by themselves, create substantial income. In East Africa, for example, a single lion in Amboseli Park can generate over US $500,000 in foreign exchange for Kenya over a 15 year period, whereas elephants produce over US $600,000 each year. Coupled with the many industries supporting, or based on these natural areas, many tens of billions of dollars are involved worldwide (See Box 7).

BOX 7.
Systematics and Ecotourism

Systematic research contributes substantially to the ecotourism industry. Systematic publications, including revisions, keys, monographs, and inventories, along with the use of specimens in collections, form the essential scientific background upon which field guides, travel guides, movies, videos, sound recordings, and other media depend.

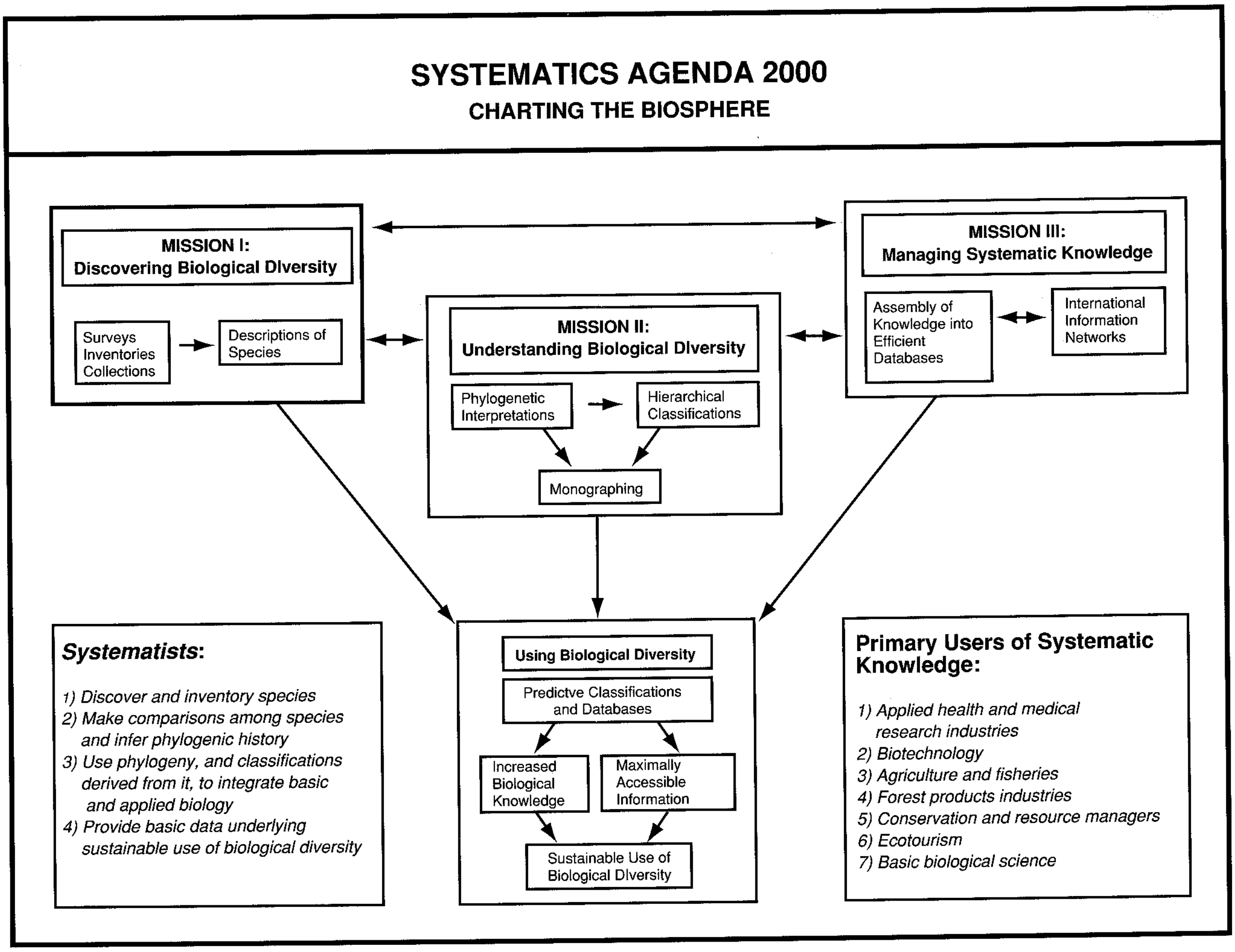
For thousands of years humans everywhere have interacted with other species through domestication and cultivation. Tens of thousands of species of plants and animals are kept in cultivation or captivity, and their breeding and trade generates many billions of dollars in commerce (Groombridge 1992). To cite several examples, about 3,000 species of decorative plants are cultivated in the United Kingdom alone, and over 5,000 species of orchids have been traded worldwide. At the level of international commerce, hundreds of millions of dollars each year are generated through exportation of animals such as birds, reptiles, frogs, tropical fishes, butterflies, and spiders. Systematic research plays a vital role in monitoring and managing the world's natural resources by providing accurate diagnoses, keys, and information about species' distributions. The vast worldwide trade in plant and animal species has placed severe pressures on natural populations, especially since many species are harvested directly from the wild. Effective monitoring of species and enforcement of laws preventing illegal trade depend on accurate identifications of species, many of which often look very similar.

Enhancement of Scientific Research

Systematics provides a general framework within which data resulting from biological research can be organized and communicated. Biological studies that compare two or more species, or focus on single organisms that eventually will be consulted by biologists interested in other organisms, incorporate some element of systematics. The results of systematic research play an important role in the selection of study systems and in assessing the generality of biological phenomena of interest.

A phylogenetic tree produced by an analysis of the relationships of species constitutes a hypothesis of descent (common ancestry), of character modification over time, and of changes in geographic distribution (historical biogeography). In theory all biological changes that occur during evolutionary descent can be incorporated into these trees. Rigorous comparative approaches that depend on the phylogenetic hypotheses provided by systematists have been widely developed in recent years, and these methods are being used to study a variety of phenomena including the biogeography and coevolution of parasites and their hosts, as well as historical changes in ecology and behavior (Brooks and McLennan 1991). At the same time, these phylogenetic hypotheses are serving as a foundation for scientific studies about basic evolutionary processes such as adaptation, speciation, and extinction.

The Missions of Systematics Agenda 2000



Mission I:

To discover, describe, and inventory global species diversity

An essential contribution to managing the biosphere intelligently is to discover, describe, and inventory its species. Because most species are very small organisms that are difficult to study, the biological diversity of all parts of the world remains poorly known. It is not possible, for example, to list all the species living in a typical backyard found anywhere on the globe, let alone in our more complex ecosystems.

To date systematists have described about 1.4 million species of organisms, most of which are insects. Estimates of the numbers of undiscovered and undescribed species range from 10 million to over 100 million [see Box 8].

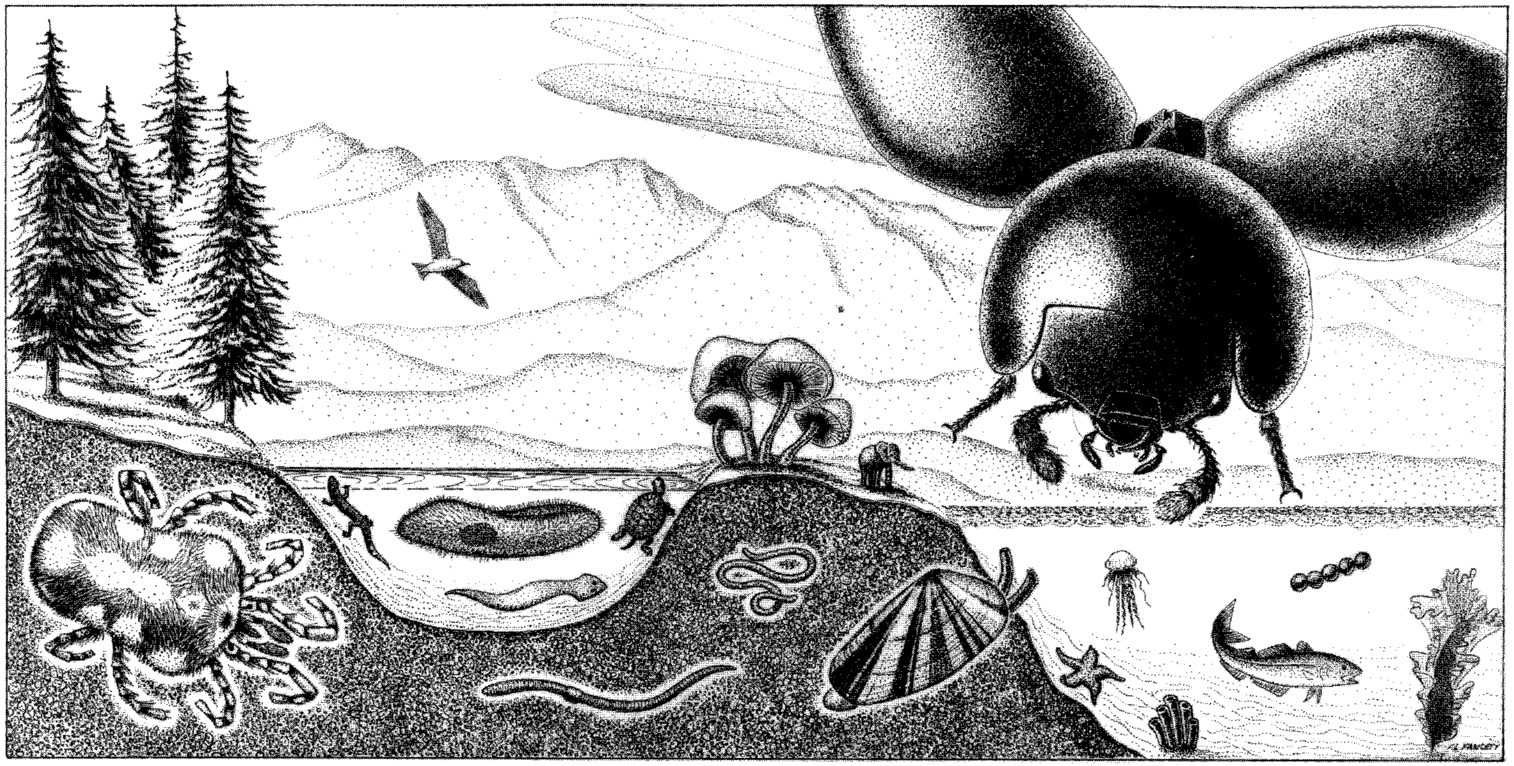
Such staggering numbers of unknown species may seem at odds with the small numbers of trees, mammals, birds, butterflies, and other common species we know from our everyday experience. Yet think of the vast tracts of rain forests, where hundreds of species of insects can be found on a single tree, hundreds of different kinds of trees can grow in a small patch of forest, and literally thousands of species of tiny mites, roundworms, fungi, and microorganisms can occur in just a few cubic feet of soil and leaf litter on the forest floor.

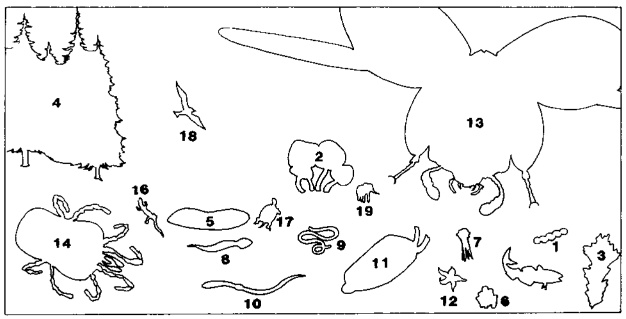
BOX 8.
How Many Species Are There? Some Examples

	Species Described	Estimated Numbers of Species Existing on Earth
Viruses	5,000	perhaps 500,000
Bacteria	4,000	400,000 - 3 million
Fungi	70,000	1.0 - 1.5 million
Protozoans	40,000	100,000 - 200,000
Algae	40,000	200,000 - 10 million
Plants	250,000	300,000 - 500,000
Vertebrates	45,000	50,000
Roundworms	15,000	500,000 - 1.0 million
Mollusks	70,000	200,000
Crustaceans	40,000	150,000
Spiders, mites	75,000	750,000 - 1.0 million
Insects	950,000	8 - 100 million

From Groombridge (1992)

The Species Scape





Size of individual organisms represents number of described species in major taxon.
Unit Area: ☐ = approximately 1,000 described species.

Taxon

1 Monera (Bacteria, Blue-green Algae)
2 Fungi
3 Algae
4 Plantae (Multicellular Plants)
5 Protozoa
6 Porifera (Sponges)
7 Coelenterata (Jellyfish, Corals, Comb Jellies)
8 Platyhelminthes (Flatworms)
9 Nematoda (Roundworms)
10 Annelida (Earthworms etc.)
11 Mollusca (Mollusks)
12 Echinodermata (Starfish etc.)
13 Insecta
14 Non-insect Arthropoda (Mites, Spiders, Crustaceans etc.)
15 Pisces (Fish)
16 Amphibia (Amphibians)
17 Reptilia (Reptiles)
18 Aves (Birds)
19 Mammalia (Mammals)

Illustration by Frances L. Fawcett. From Q.D. Wheeler. 1990. Ann. Entomol. Soc. Am. 83:1031-1047.

Species - scape*, an imaginary landscape on which the size of organisms is proportionate to the number of species in the group it represents. The accuracy of those numbers, however, is uncertain. Many species remain undiscovered or undescribed, and phylogenetic relationships among most species remain poorly understood. For example, the insect (beetle) is based on the 950,000 species described to date. Entomologists estimate that the insects may have ten million or more species. Other groups named- such as reptiles and many invertebrate taxa - may not constitute natural groups, that is, may not share a unique common ancestry. As species are described, relationships analyzed, and classifications made to reflect phylogeny, this species-scape will come into sharp focus, providing a broad and predictive overview of biodiversity.*

Human-caused stresses on the global environment make it imperative that we acquire knowledge about the world's biological diversity as expeditiously as possible. This effort will necessitate a new and expanded exploration of our planet to assemble samples of these species, followed by detailed analysis of the specimens discovered in order that they might be discriminated accurately from those species already known. To this end, comprehensive surveys and inventories of the Earth's habitats, followed by collections-based research, must be supported. With as many as one-fifth of our planet's species threatened with extinction over the next few decades, existing efforts to inventory global biological resources are inadequate and cannot provide the information about species diversity that will be vital for leading the world to a sustainable future.

A series of goals for this mission are recognized as having high priority:

- To survey marine, terrestrial, and fresh-water ecosystems to achieve a comprehensive knowledge of global species diversity.
- To determine the geographic and temporal distributions of these species.
- To discover, describe, and inventory species living in threatened and endangered ecosystems.
- To target the least known groups of organisms.
- To undertake inventories that target groups critical for maintaining the integrity and function of the world's ecosystems, for improving human health, and for improving the world's food supply.

Benefits of a Global Species Inventory

- Species will be discovered and classified so that information about them can be summarized and incorporated into databases for efficient retrieval.
- Information on the diversity, distribution, and properties of species throughout the world's ecosystems will be generated.
- Baseline assessments will enable long-term monitoring and analysis of global change.
- New biological resources will be discovered.

For scientific, economic, and ethical reasons we must resolve to describe and understand the significance of species diversity before the opportunity to do so is lost. The benefits of this mission far exceed the investment required to meet the challenge of the biodiversity crisis. No greater scientific endeavor, nor promising opportunity, exists.

Mission 2:

To analyze and synthesize the information derived from this global discovery effort into a predictive classification system that reflects the history of life.

The first research mission of Systematics Agenda 2000 embraces the most fundamental question that can be asked about biological diversity: what species share planet Earth with us? Systematists have an additional research goal, namely to document the properties of species, integrate data from other fields of biology, and provide a conceptual framework for interpreting biological information. Simply having a list of species will not provide a predictive framework for organizing our knowledge about them, yet predictive efficiency is imperative if we are to achieve sustainable use of the Earth's biological diversity. Systematists, in fact, have developed a scientific basis for organizing knowledge about biological diversity, and it consists of a classification system that emerges from an understanding of the genealogical, or phylogenetic, relationships among species (see Box 9).

The species living today are the end products of a long history of evolutionary diversification. The unique pattern of common ancestry and relatedness embodied in that history provides the basis for constructing species phylogenies. A classification based upon this phylogenetic heritage is termed a natural classification.

Access to knowledge of species, organized around a phylogenetic classification of life, will allow scientists to make predictions about species and their properties that are of particular scientific or societal interest and will facilitate the creation of efficient information systems to store this knowledge (see Box 10). Such knowledge will foster new interdisciplinary research. Storing and retrieving information within the conceptual framework of a natural classification permits more efficient and economical use of our knowledge about species and their habitats (see Box 11).

BOX 9.
Knowledge of Phylogeny Serves to Integrate Basic and Applied Biology

The analysis of phylogenetic relationships is an integrative endeavor and can be likened to a grand synthesis in which data come from many avenues of investigation: comparative gross and microanatomy, developmental biology, genetics, molecular biology, comparative physiology, geology and paleontology, ecology, behavior, and biogeography. The data eventually used in a study depend on the kinds of organisms being investigated, available knowledge about them, and the degree to which different types of data serve to resolve relationships among the species.

Similarities in the characteristics of organisms are organized into hierarchical patterns that reflect their phylogenetic history. Thus, species of cats share similarities not shared with species of bears, and all carnivores, which include cats and bears, share similarities not found in other mammals. At a more general level, all mammals have characteristics — fur and mammary glands are two examples — not shared with other vertebrates, and so on until we arrive at the group that includes all of life. Having knowledge of this historical hierarchy thus permits systematists to make powerful predictions about the characteristics of species that have not yet been studied in detail. These predictions have major economic implications, such as when searching for new pharmacologically active compounds that might be present in less well-known species (see Box 11).

BOX 10.
How Natural Classifications are Predictive

Just as the comparative study of species characteristics can be used to discover their evolutionary relationships to one another, those relationships can be expressed explicitly in what are termed natural classifications. Because the relationships of species are hierarchical, so too are the resulting classifications. Such classifications are called Linnean hierarchies after the eighteenth century Swedish taxonomist Carl Linnaeus, and the levels of the hierarchy have names such as **species, genus, family, order, class, phylum, and kingdom**. Thus, all mammals are in the **class** Mammalia, which among other groups includes the **order** Carnivora. The latter includes bears and cats, which are classified, respectively, into the **families** Ursidae and Felidae. Within the Felidae are cats in the genus *Panthera*, and within that genus are species such as the tiger, whose scientific (Latin) name is *Panthera tigris*. These unique names provide a scientific language that makes it straightforward to communicate and store information about any of these groups of organisms.

It can be readily appreciated that a list of species' names arranged according to this hierarchy is far more predictive of their characteristics than would be a list of those names arranged alphabetically. Thus, a little known species of cat would be predicted to share many characteristics with other cats, some with other carnivores, and finally some found in all mammals. Such predictive power would be impossible to retrieve from an alphabetical list, or from a hierarchical classification that did not reflect the relationships of those species accurately.

This simple example has profound implications for mankind's efforts to apply knowledge about species. If that knowledge is to be organized into databases so as to maximize our ability to predict the biological properties of species, and thus utilize those properties more efficiently and economically, then we will want to store and retrieve that knowledge within the conceptual framework of a natural classification. This underscores the fundamental importance of discovering, to the maximum extent possible, the phylogenetic relationships of all species.

BOX 11.
The Predictive Value of Classifications: The Case of Taxol and Cancer

The natural product taxol — shown to be a powerful drug agent against ovarian and breast cancer — is derived from the bark of the Pacific Yew (*Taxus brevifolia*). Unfortunately, it takes the bark of three trees to provide sufficient taxol for a single cancer patient, and the trees are killed in the process. A random search for plants containing similar products might have taken many years, but an understanding of the evolutionary relationships of the Pacific Yew quickly led researchers to examine its close relatives. From this work, it was discovered that a small quantity of leaves from the European Yew (*Taxus baccata*) can also be used to produce taxol, eventually at less cost and with no harm to the European Yew itself.

Perhaps even more remarkable is the discovery of a new species of fungus (*Taxomyces andreanae*) living in the bark of the Pacific Yew. This has led to the finding that the fungus is also capable of producing taxol, thus opening the possibility that this potent anti-cancer drug eventually will be produced inexpensively.

The past two decades have brought rapid advances in systematic theory and practice that make uncovering the diversity and phylogeny of life on Earth an achievable goal. New methods of gathering data, ranging from electron microscopy to the sequencing of genes, have opened broad vistas for obtaining information that help us place species into hierarchical classifications that serve, in all areas of comparative biology, as essential frameworks for organizing our knowledge about species diversity. New computer technologies provide means of handling massive databases that would have overwhelmed systematists a mere generation ago.

A series of goals for this mission are recognized as having high priority:

- To determine the phylogenetic relationships among the major groups of organisms, thus providing a general conceptual framework for basic and applied biology.
- To discover the phylogenetic relationships of groups of species that are critical for applied biology, targeting species that are important for human health and food production, as well as for conservation of the world's ecosystems.
- To discover the phylogenetic relationships of groups of species that are of critical importance for the basic biological sciences, such as those having broad relevance for experimental science or those critical for maintaining the integrity and function of ecosystems.
- To continue to develop more powerful techniques and methods for systematic data analysis.

Benefits of a Phylogenetic Classification of Life Include:

- Establishing a framework for measuring rates of extinction and patterns of global change.
- Directing the search for genes, biological products, biocontrol agents, and potential crop species.
- Providing a predictive framework for the management of biological knowledge and a basis for communication across science and society.
- Assisting in setting priorities for conservationists, resource managers, and policy makers.
- Creating a foundation for comparative studies linking all fields of biology and for interdisciplinary studies encompassing all groups of organisms.
- Furnishing the scientific context for understanding processes of speciation, extinction, and adaptation that have produced the present diversity of life.

Mission 3:

To organize the information from this global program into an efficiently retrievable form that best meets the needs of science and society.

The accumulation of vast amounts of knowledge about millions of species from around the world will demand innovative organization so that it can be utilized and retrieved efficiently. This information system will encompass systematic, geological, and ecological data derived from the current holdings of natural history collections, libraries, and archives, as well as from ongoing surveys and inventories. Knowledge about species will need to be updated continuously as new ones are discovered, phylogenetic relationships are clarified, and other information is accumulated. Electronic knowledge bases on a global scale will ensure access for the benefit of all nations. Databases, such as those for molecular genetics, must be linked with other biotechnological databases through the use of standard species names and phylogenetic classifications.

Progress in systematics depends on the accumulation and communication of information about species. Traditionally, this has been accomplished through printed media such as floras, faunas, monographs, and ethnobiological studies; in addition, hundreds of millions of specimens and data associated with them are stored in systematics collections around the world. This information must be organized by scientific names that are arranged in a hierarchical classification based on the relationships of species.

Given the availability of modern, high-speed information processing technologies, hardware, and the potential for creating relational databases, information about species can be extracted in any combination for any desired purpose. Integrated with information stored in other databases, it will provide a foundation for creating new insights into the organization of life on Earth. Moreover, the availability of these databases will save millions of dollars by eliminating redundancies in research and management activities. Due to the lack of resources, however, the potential for revolutionizing the practice of systematics and for greatly expanding its value to science and society has not been realized. This task should be undertaken in order to take full advantage of the information about the world's species that already resides in numerous scattered sources. Indeed, conservation biologists, resource managers, and other users of natural products have repeatedly called for access to this information.

A series of goals for this mission are recognized as having high priority:

- To develop systematic, biogeographic, and ecological databases of species information based on specimens housed in the world's natural history collections.

- To integrate data from specimens housed in systematic collections with information contained in GIS (geographic information systems) databases, thus providing a means to monitor past and present effects of global change on species distributions and extinction.

- To develop linkages among databases for the efficient retrieval of all available information about taxa and the places they occur.

- To develop and implement an information system that can be accessed efficiently by a broad international user community.

- To develop data dictionaries of taxonomic names, geographic localities, and other information basic to all systematics databases.

- To develop data products, including guides, keys, electronic floras and faunas, and monographic works.

- To develop mechanisms for maintaining and updating databases and information networks, including continuing hardware and software support.

Benefits of an Efficient Systematic Information System Include

- Allowing policy makers to implement better informed decisions regarding sustainable resource management.
- Providing better documentation of extinction and distributional change of species.
- Managing biological resources more cost-effectively as online databases provide increasingly efficient communication of systematic and associated information.
- Providing ready access to systematic knowledge for problem solving.
- Facilitating new kinds of comparisons and associations among data from biology and other sources, especially biotechnology.
- Enhancing global communication and collaboration and reducing duplication of scientific effort.

Meeting the Challenge: Infrastructure and Human Resources

The global action plan (*AGENDA 21*) adopted by the United Nations Conference on the Environment and Development at Rio de Janeiro, as well as by the Convention on Biological Diversity, calls for each participating country to establish national strategies to inventory and understand their own biodiversity and develop programs to conserve it for the future. The international community faces two major challenges in attempting to document and understand the world's species diversity: first, the need for significant expansion and improvement of systematic research infrastructure, especially that housing biological collections, and, second, the necessity to increase the training and employment of professional systematists, thereby eliminating what some have called "the taxonomic impediment."

Systematics Forms the Foundation for the Study of Biological Diversity

"Many of the recommendations [to promote basic and applied conservation research] presume the existence of the taxonomic expertise to carry them out. Yet, the cadre of trained taxonomists necessary to perform this work simply does not exist. To describe, inventory, classify, monitor, and manage biodiversity, such expertise must be cultivated. It is the foundation on which the study and conservation of biological diversity are built."

National Research Council, Conserving Biodiversity, 1992, p. 71

The systematics community, through Systematics Agenda 2000, proposes a systematics action plan, the implementation of which is essential for the success of the three research missions described earlier. Major elements of the plan include the following:

- Establishing and enhancing systematic research centers housing collections in all countries committed to understanding, preserving, and using their biodiversity.
- Supporting institutions that educate systematists and train support staff.
- Expanding the number of research positions in basic and applied systematics.
- Developing cooperative international research and educational links among systematic institutions worldwide.
- Creating electronic communication linkages among those same institutions, with outreach to society.
- Supporting comparative systematic research that is taxon-based and worldwide in scope.

Establishment and Enhancement of Systematics Research Centers and Collections

One limitation to obtaining a comprehensive knowledge of biodiversity is the inadequacy of systematic infrastructure in those countries housing most of the world's species diversity. At the same time, systematic research centers in the wealthy nations are insufficiently supported to assume their share of the responsibility for undertaking the research missions described here. The future prosperity of the species-rich countries will depend on developing the capacity to manage their own biotic resources. This includes having appropriate scientific infrastructure to provide the knowledge necessary for effective decision-making. The lack of sufficient scientific capacity must be overcome by a plan that builds new, or enhances existing, collection-based infrastructure such as museums, herbaria, and repositories for microorganisms and genetic resources in all countries.

Natural history collections throughout the world house over two billion specimens (Duckworth et al. 1993). Despite these vast holdings of our biological heritage, only a small fraction of the Earth's species diversity is documented by preserved material. Systematic collections of plants, animals, and other organisms are the only permanent record of our biota, and the specialized libraries and databases attached to these collections are our written record of the Earth's natural history (see Box 12). Systematic collections of preserved specimens are found in natural history museums, herbaria, university facilities, and in governmental agencies such as departments of agriculture, natural resources, or biological surveys. Collections may also take the form of living organisms maintained in zoos, aquaria, insectaries, aviaries and botanical gardens, or specialized repositories of germplasm, frozen tissue, and type cultures of microorganisms.

Systematic research centers housing collections of specimens are national and international repositories of knowledge about biodiversity. Although national collection-based infrastructure will vary from country to country, nearly all will be organized to serve two main functions. Some will be national research centers and will function as repositories for specimens, libraries, and databases that document national biodiversity. Secondly, there is also a need for centers that function to support systematic research and collections having an international, taxon-based focus. Some centers may serve only one function; others will contain sufficient infrastructure and scientific expertise to do both. Many centers will build on preexisting institutions and their collections; others must be newly created. In all cases, however, it is critical that the scientific core facilities include professional systematists with taxon-based expertise.

BOX 12.
Why Systematics Collections Are Important

"Scientific collections are a continuing investment by society in the effort to understand the natural world...In the face of disappearing habitats, species extinctions and the destruction of sites of geological and paleontological significance, the specimens in these collections have become nonrenewable resources."

- Preserving Natural Science Collections: Chronicle of our Environmental Heritage, p. 6

- Collections are the permanent record of our natural heritage, and thus contain the materials that support the research of many scientific disciplines, including those working to preserve biodiversity and monitor global change.
- Collections meet the needs of applied biology, including the health sciences (parasitology, epidemiology, diagnostics), agriculture, resource management, and biotechnology.
- Collections provide broad support for public and formal education programs.
- Through exhibits, collections serve a primary role in promoting public awareness of nature and biodiversity.

National systematic research centers. National centers should house systematic reference collections of the local and regional flora and fauna so that in-country biodiversity study and management can be based on accurate, up-to-date systematic data. Thus, professionally-staffed collections are required throughout the world to provide access to accurately identified specimens from local biotas, many of which will contain species found nowhere else. In addition, verification of data collected by national biological surveys depends upon voucher specimens in these systematic collections. Only by study of these specimens can investigators be sure the same species is being identified in different localities.

The increasing development of national biological resource centers and initiatives in countries around the world, such as the Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO) in Mexico, the Instituto Nacional de Biodiversidad (INBio) in Costa Rica, and the National Biological Survey in the United States, supplies mechanisms for building appropriate national contexts for many of these activities. The role of these initiatives is of critical importance, since they provide the basis for studying, managing, and conserving the biodiversity of each country and also serve as a focal-point for enlisting national support for these actions.

International systematic research centers. A major component of the SA2000 action plan is to help establish new, or enhance existing, systematic research centers that can contribute to the international goal of documenting the world's biodiversity. It is impractical and unnecessary to duplicate collections or taxonomic expertise for each group of organisms at every national research center. Instead, systematists with global knowledge of particular taxa must be funded, through centers having collections of international breadth, to conduct research at many sites around the world — especially since species are often distributed across national boundaries. Systematic research is ultimately taxon-oriented, and thus comprehensive worldwide collections will be required for each group of organisms. Because regional collections are rarely sufficiently comprehensive to facilitate broadly comparative systematic studies, the full participation of institutions in all countries will be necessary. Thus, cooperative research and database linkages among institutions worldwide are essential. In addition, partnerships among institutions in the species-rich countries should be formed to foster the growth and stability of these systematic collections as well as to establish networks for the exchange of specimens, biodiversity information, training capabilities, and scientific expertise. No collection can have specialists in all groups of organisms, hence the need for the exchange of experts having world-wide expertise on each group. Such linkages are crucial if the systematic community is to inventory and classify the world's species diversity efficiently and economically.

Major international cooperative programs will be required to establish systematic research centers in all interested countries. With some notable exceptions, collections in the species-rich countries of the world either do not exist or are poorly supported. Most of these collections are inadequately staffed with professional systematists and trained support personnel. Research budgets for surveys and inventories, moreover, are generally meager, and few resources are available for systematists to visit major collections elsewhere in the world to undertake necessary comparative research. These problems must be remedied if species-rich countries are to develop a systematic knowledgebase that will support the conservation and sustainable use of their biodiversity (see Box 13).

Within the developed nations, systematic collections vary in size and importance. There are, for example, currently more than 50 major systematic research centers in the United States that house collections of worldwide coverage of all types of life forms, from bacteria to whales. The large

BOX 13.
Using Collections to Solve Problems

- When public health officials were concerned about levels of mercury in fishes, they took samples from specimens in museums in order to understand historical patterns of mercury contamination.

- When populations of many bird species began to decline in the 1960's, study of egg collections in museums revealed that egg shells had been thinning. This was eventually linked to the presence of DDT in the environment.

- Because the viruses that cause AIDS and other diseases often mutate rapidly, comparisons to previously described strains housed in type culture/frozen collections help public health officials understand the spread of disease.

collection centers exist in major natural history museums and botanical gardens, state and federal agencies, and many universities. In addition, there are numerous smaller institutions that emphasize regional collections that are often historically and scientifically important.

Data centers, libraries, and archives associated with systematics collections also provide an essential resource for research in systematic biology. These specialized libraries are not limited to bound books and periodicals but may also include card indices, catalogs, manuscripts, illustrations and photographs, microfiche records, cartographic information, bibliographic files, and different forms of electronic media. The enormous proliferation of scientific information over the past few years has exceeded the acquisition capabilities of most institutions. If international efforts to survey and inventory the world's biodiversity are successful, storage and information management capabilities of even the largest research centers will be increasingly impacted. Significant expansion of infrastructure, along with major advances in the storage, retrieval, and utilization of systematic databases, will be required in order to make information readily available to scientists worldwide, to avoid unnecessary duplication of effort, and to provide effective outreach to society.

Improving Systematic Infrastructure : Recommendations

- Establish and enhance national systematic research centers in all countries of the world. Such centers should house local and regional reference collections to document the national biological wealth, contain facilities for research and information storage, and have capacity for training and education.

- Establish new, or enhance existing, international systematic research centers that support systematic expertise and world-wide collections having a taxon-based focus.

- Improve the care and preservation of collections worldwide, by establishing an international network to share expertise, information, and resources.

- Strengthen and expand the storage and research capabilities of existing systematic research centers, including undertaking initiatives to database all presently accessioned biodiversity.

- Strengthen and expand programs of international cooperation among systematic research centers.

Education, Training, and Human Resource Development

A critical limitation to obtaining the scientific knowledge necessary for understanding and using biological diversity effectively is the fact that only about 6% of the world's scientists live in those countries possessing 80% of terrestrial diversity. A second severe limitation is that there are few, if any, taxonomic specialists in the world for many groups of organisms, including some of the most diverse and economically important. Therefore, perhaps the greatest challenge to accomplishing the three research missions proposed by Systematics Agenda 2000 is to recruit, educate, specially train, and employ a sufficient number of systematists and technical support staff throughout the world. Numerous organizations and task forces, such as the Task Force on Global Biodiversity of the U.S. National Science Board (1989) and the U.K. House of Lords Select Committee on Science and Technology (1991) have concluded that effective management of the problem of declining global biological diversity is severely hampered by the shortage of systematic biologists to identify, document, and classify organisms.

> **Removing "The Taxonomic Impediment"**
>
> *"...it is the fields of taxonomy and systematics that have suffered the most serious declines in the last years, resulting in an acute shortage of trained taxonomists, with almost none in the tropical countries. Also, there is a lack of specialists for many important groups of organisms, even in the developed countries. This is compounded by the fact that reference collections are few and unevenly located, very often far from the place of origin of organisms being studied. And current practices of taxonomy are often inefficient, with much duplication of effort. Hence, in launching any study on biological diversity, the question of removing the 'taxonomic impediment' must be addressed."*
>
> – DIVERSITAS: IUBS-IUMS-SCOPE-UNESCO
> Programme on Biodiversity

Many reasons exist for the decline in trained systematists. A recent survey of U.S. universities, conducted under the direction of the National Science Foundation, found just 940 systematic biologists employed in the doctorate-granting institutions surveyed, and 25% of these only have adjunct appointments (Higher Education Survey 1990). Ominously, only 18% of the responding institutions indicated they would hire systematists in the future if new faculty positions became available. In the United States and United Kingdom, research and/or teaching positions for systematists have been retrenched over the past several decades due to competition from other areas of biology. Thus, when surveyed, most academic institutions indicated they would choose to expand their molecular biology programs rather than systematics, because of "greater opportunities for funding in this area."

Because of these trends, the numbers of newly trained systematists are being reduced from what they were just two decades ago. Increasingly, there are fewer taxonomic specialists for many groups of organisms, including algae, bacteria, fungi, lower invertebrates, and many groups of insects and their relatives. Some of the most economically and ecologically important groups of organisms are in desperate need of professionally trained specialists to study them. Roundworms (nematodes) are a case in point. In the United States, for example, there are only 15 institutional collections and 12 full-time systematic nematologists, and just two of the latter have students. Inevitably, the absence of trained specialists will have economic consequences because of the agricultural importance of nematodes.

Although there is universal agreement that systematic expertise for many groups is lacking, or is substantially underrepresented, most of the evidence for trends within the discipline is anecdotal. There is a pressing need to document the worldwide availability of systematic expertise for all groups of organisms so that training and employment programs can be prioritized more accurately and made more effective.

The lack of human resources in systematic biology is even more apparent in the developing countries. The paucity of trained scientists, as well as the absence of curatorial positions, adequate research funds, and institutional support, mean that few systematic biologists are entering the work force. To help remedy this situation, it is imperative that local natural history institutions within the developing countries be strengthened and that linkages with institutions in the developed nations be established (National Research Council 1992). Because of the accelerated trends in environmental degradation and biodiversity loss in many developing nations, programs to train "parataxonomists" to work with available professional systematists offer a partial solution to the human resources problem but do not substitute for efforts to build effective scientific infrastructure and adequate numbers of scientists.

Many research institutions in the developed nations, such as museums and botanical gardens, have initiated joint graduate and postgraduate training programs in systematic biology in conjunction with nearby universities. These programs, moreover, generally have a significant international component. Despite these encouraging developments, the magnitude of the species diversity crisis and the scientific and economic imperative to describe the world's biological resources require increased access to funds for educating and training new scientists at the graduate and postgraduate levels. Anecdotal evidence suggests that college students are interested in species diversity, and are excited by the intellectual vigor and importance of modern systematic research, but the lack of appropriate funding for graduate education and the dismal prospects for postdoctoral employment combine to discourage students from pursuing a career in systematics.

Improving Human Resources: Recommendations

- International agencies engaged in programs promoting sustainable development and environmental conservation within developing countries should make funds available for basic systematic research and for training and hiring professional and paraprofessional systematists.

- Each nation should establish systematic research centers and collections, national biological surveys, and national biodiversity monitoring agencies that are staffed with professional systematists.

- All universities and institutes with training and educational programs in biodiversity should include professional systematists on their faculties.

- Governmental agencies and natural history institutions located in the developed nations should make available increased support for the training of international students and other scientific investigators from the species-rich countries.

- Resource management agencies (e.g., forestry, fisheries, wildlife) should include professional systematists on their staffs.

Systematics Agenda 2000 Complements Other Biodiversity Initiatives

The imperative to describe and understand the Earth's species diversity has been recognized by the international community through numerous agencies and institutions, including:

- UN Conference on Environment and Development (UNCED) and its AGENDA 21
- UN Environment Program (UNEP)
- UN Development Program (UNDP)
- *Diversitas*, a consortium including:
  The International Union of Biological Sciences (IUBS)
  Scientific Committee on Problems of the Environment (SCOPE)
  UN Education, Scientific and Cultural Organization (UNESCO)
  International Union of Microbiological Societies (IUMS)
- Microbial Diversity 21, an action plan of IUBS and IUMS

Similar calls have been made by nongovernmental organizations, in particular:

- World Resources Institute (WRI)
- World Wildlife Fund (WWF)
- World Conservation Union/International Union for the Conservation of Nature and Natural Resources (IUCN)
- The Nature Conservancy (TNC)

Systematics Agenda 2000 provides a global taxon-based perspective on biological diversity and thus contributes to the scientific framework for conserving and managing this indispensable resource. Systematics Agenda 2000 is thus complementary to all initiatives designed to learn about, conserve, and utilize biodiversity, including, for example, the Sustainable Biosphere Initiative (SBI) of the ecological community.

Investment in Systematics Agenda 2000

Systematics Agenda 2000 is an ambitious program that will require a significant level of support. No single government or international agency can be expected to fund this entire initiative. Rather, funding must be obtained from the collective support of many institutions and governments worldwide. The missions of SA2000 will encompass a 25 year program of intense effort, at an investment of approximately US $3 billion per year.

Funding estimates are based on calculating the cost of developing human resources and computer networks, providing support for collections (including type culture and germplasm repositories), and undertaking and disseminating research findings to the world community. At current rates of funding, the missions outlined in the SA 2000 initiative will require minimally 150 years. Because of the urgency imposed by the accelerating loss of biodiversity, however, the current annual global level of research and infrastructural support (about US $ 0.5 billion) must be increased approximately six-fold to accomplish these missions during a 25-year period.

Considering the demonstrated scientific, economic, and aesthetic value of biological diversity, returns on this investment are assured. Humanity has already benefited immeasurably from incremental progress in discovering, describing, understanding, and utilizing other species. Expanding this effort today will result in even greater benefits tomorrow — and will help preserve life's magnificent diversity for generations to come.

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Glossary

Biodiversity: the variety and variability among living things, including the number of species, number of distinct clades, within-species genetic variation, and "functional" diversity (the countless ways in which organisms function and interact with each other and their environment).

Biogeography: the study of the geographic distribution of plants, animals, and microbes.

Biological Resource (Bioresources): a living organism or product derived from a living organism with real or perceived value to humankind.

Biosphere: that portion of the Earth where life exists.

Biotechnology: any technique that uses living organisms or substances derived from them to make or modify a product, to improve plants or animals, or to develop microorganisms for specific purposes.

Clade: a branch or lineage in the phylogeny of a taxon.

Classification: the formal scientific ordering of species into a hierarchical system and the application of scientific names to species and groups of species.

Comparative biology: studies that compare more than one species.

Endemic: a species that is unique to a habitat or geographic area.

Extinction: the death of the last individual of a species.

Inventory: the listing by name or description of all the species of plants, animals, and microbes in a defined area.

Monograph: a comprehensive treatment integrating all that is known about a taxon worldwide, including new and previously known species and organized around what is known about phylogeny.

Phylogenetic diversity: number of distinct lineages or clades represented among a group of species.

Phylogeny: the pattern of evolutionary history and common ancestry among species.

Species: kinds of living organisms; the basic units of classification and phylogenetic analysis.

Species diversity: literally, the number and kinds of species on Earth; used here also in a broad sense to encompass both the number of species and their interrelationships (i.e., phylogenetic diversity).

Survey: a methodical exploration of a selected area to discover all species of the macro- and micro-flora and fauna occurring therein.

Systematics: the comparative study of the kinds of living and fossil organisms (species), including their description, distributions, and the phylogenetic relationships that they share.

Taxon: a species or a group of related species.

Taxonomy: the scientific classification of species into a hierarchical system that reflects what is known about their phylogeny.

SA2000 was initiated by three international systematics societies: the American Society of Plant Taxonomists, the Society of Systematic Biologists, and the Willi Hennig Society, in cooperation with the Association of Systematics Collections, and with financial support from the U.S. National Science Foundation. Initial documents were prepared by 27 Standing Committees composed of over 300 scientists representing a broad array of institutions and specializations. Drafts of this document have been reviewed by interested individuals, scientific societies, and national and international agencies and organizations.

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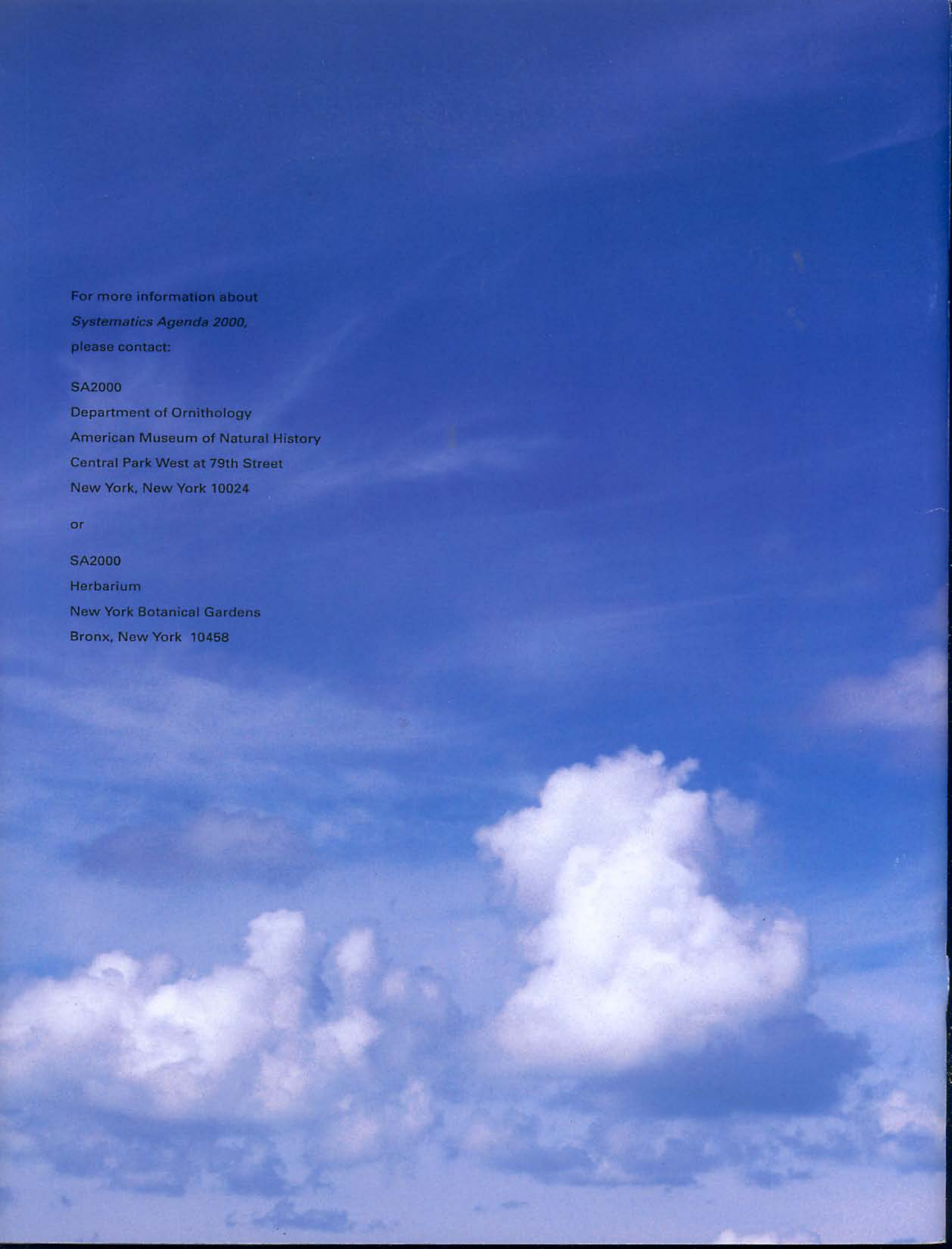

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