THE BIOLOGICAL DIVERSITY CRISIS: A Challenge to Science

Edward O. Wilson

PROLOGUE: *The worldwide deterioration of natural environments, especially severe in the tropics, is causing the extinction of species at a rate considered by many ecologists to be without precedent in the history of the Earth. Yet the extent of biological diversity, and hence the magnitude of its current decline, has never been precisely measured. Although 1.7 million species of plants, animals, and microorganisms have been formally identified and classified, the total number of species may exceed 30 million, with the great majority living in tropical forests. Each of these species is a unique product of thousands or millions of years of evolutionary history; most contain on the order of a billion bits of genetic information.*

The pool of species diversity is more than a continuing challenge to basic science. It comprises a vast reservoir of potential new crops, pharmaceuticals, and other natural products, as well as plant species capable of restoring depleted soils. Thus, for practical reasons as well as esthetic ones, an increasing number of countries have begun to treat native faunas and floras as part of their national heritage. Conservation and development are now widely understood to be closely linked.

In this article biologist Edward O. Wilson makes a case for a strengthened program to analyze organic diversity. He suggests that a complete catalog of species can be compiled at a relatively low cost, especially if already available computer-aided techniques are used. An attempt to measure global diversity is "a mission worthy of the best effort of science" that would more than pay for itself in economic and environmental benefits.

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Certain measurements are crucial to our ordinary understanding of the universe. What, for example, is the mean diameter of the Earth? It is 12,742 kilometers. How many stars are there in the Milky Way? Approximately 10^{11}. How many genes are there in a small virus particle? There are 10 (in ϕX174 phage). What is the mass of an electron? It is 9.1×10^{-28} grams. And how many species of organisms are there on Earth? We do not know, not even to the nearest order of magnitude.

Of course, the number of described species is so impressive that it may appear to be complete. The corollary would be that systematics, defined broadly as the description and analysis of biological diversity, is an old-fashioned science concerned mostly with routine tasks. In fact, about 1.7 million species have been formally named since Linnaeus inaugurated the binomial system of species identification in 1753 (two familiar examples are the white pine, *Pinus strobus*, and the tiger, *Panthera tigris*). Some 440,000 species are plants, including algae and fungi; 47,000 are vertebrates; and according to one meticulous estimate published in 1985,[1] 751,012 are insects. The remainder consists of assorted invertebrates and microorganisms.

But these figures grossly underestimate the diversity of life on Earth, and its true magnitude is still a mystery. In 1964 British ecologist Carrington B. Williams, employing a combination of intensive local sampling and mathematical extrapolation, projected the number of insect species at 3 million.[2] During the next 20 years, systematists described several new complex faunas in relatively unexplored habitats, such as the floor of the deep sea. They also began to employ protein analysis and ecological studies routinely, enabling them to detect many more "sibling species"—populations that are reproductively isolated from other populations but difficult to distinguish on the basis of museum specimens alone. A few writers began to put the world's total as high as 10 million species.

In 1982 the ante was raised threefold again by Terry L. Erwin of the National Museum of Natural History. He and other entomologists developed a technique that for the first time allowed intensive sampling of the canopy of tropical rain forests. This layer of leaves and branches conducts the vast bulk of the photosynthesis for the forest as a whole and is clearly rich in species. It had been largely inaccessible, however, because of its height (a hundred feet or more), the slick surfaces of tree trunks, and the dangers from swarms of stinging ants and wasps at all levels. To overcome these difficulties, the entomologists first fired a projectile with an attached line over one of the upper branches. They then raised a canister containing an insecticide and swift-acting knockdown agent up into the canopy and released the contents as a fog by radio command. As insects and other arthropods fell out of the trees (the chemicals did not harm vertebrates), the researchers collected them in sheets laid on the ground. The number of species proved to be far greater than previously suspected, because of unusually restricted geographical ranges and high levels of specialization on different parts of the trees. Erwin extrapolated a possible total of 30 million insect species, mostly confined to the rain forest canopy.[3] Research is in an even earlier stage on epiphytic plants (such as orchids), roundworms, mites, fungi, protozoans, bacteria, and other mostly small organisms that abound in great diversity in the tree tops.

If astronomers were to discover a new planet beyond Pluto, the news would make front pages around the world. Not so for the discovery that the living world is richer than earlier suspected, a fact of much greater import to humanity. Organic diversity has remained obscure among scientific problems for reasons having to do with both geography and the natural human interest in big organisms. The great majority of organisms in the world are tropical and inconspicuous invertebrates, such as insects, crustaceans, mites, and nematode worms. The mammals, birds, trees, shrubs, and smaller flowering plants of the North Temperate Zone, the subjects of most natural history research and popular writing, comprise relatively few species. In one area of 25 acres of rain forest in Borneo, for example, about 700 species of trees were identified; there are no more than 700 tree species in all of North America.[4] Familiarity with organisms close to home gives the false impression that the Linnaean period of formal taxonomic description has indeed ended. But a brief look almost anywhere else (for example, at the Australian fauna illustrated in Figure 1) shows that the opposite is true.[5]

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Why does this lack of balance in knowledge matter? It may still be argued that to know one kind of beetle is to know them all, or at least enough to get by. But a species is not like a molecule in a cloud of molecules. It is a unique population of organisms, the terminus of a lineage that split off from the most closely related species thousands or even millions of years ago. It has been hammered and shaped into its present form by mutations and natural selection, during which certain genetic combinations survived and reproduced differentially out of an almost inconceivably large possible total.

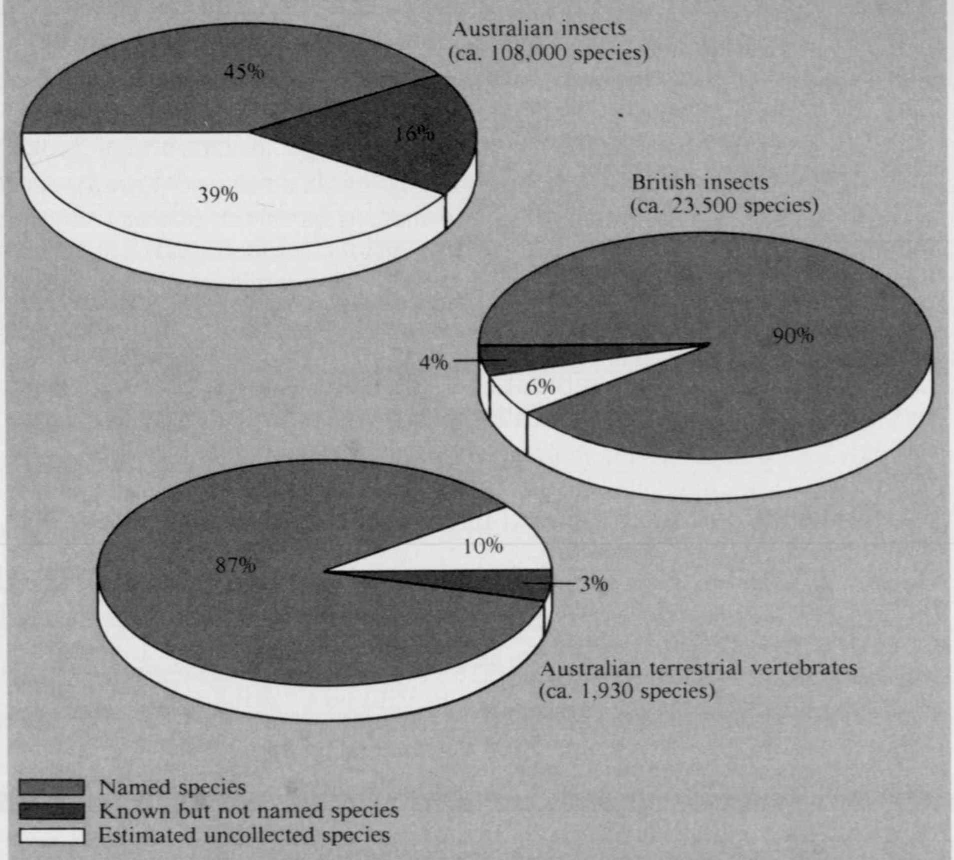
In a purely technical sense, each species of higher organism—beetle, moss, and so forth—is richer in information than a Caravaggio painting, a Mozart symphony, or any other great work of art. Consider the house mouse, *Mus musculus*. Each of its cells contains four strings of DNA, each of which comprises about a billion nucleotide pairs organized into 100,000 structural genes. If stretched out fully, the DNA would be roughly 1 meter long. But this molecule is invisible to the naked eye because it is only 20 angstrom units in diameter. If we magnified it until its width equaled that of wrapping string, the fully extended molecule would be 600 miles long. As we traveled along its length, we would encounter some 20 nucleotide pairs or "letters" of genetic code per inch. The full information contained therein, if translated into ordinary-sized letters of printed text, would just about fill all fifteen editions of the *Encyclopaedia Britannica* published since 1768.

II

Perhaps because organic diversity is so much larger than previously imagined, it has proved difficult to express as a coherent subject of scientific inquiry. To use the common phrase of experimental science, what is the central problem of systematics? Its practitioners, who by necessity limit themselves to small slices of the diversity, understand but seldom articulate a mission of the kind that enspirits particle physics or molecular genetics. For reasons that transcend the mere health of the discipline, the time has come to focus on such a mission. It can be said that if other disciplines are considered that depend directly upon systematics, including ecology, biogeography, and behavioral biology, an entire hierarchy of important problems is presented. But one stands out, in the sense that progress toward its solution is needed to put the other disciplines on a solid basis. In the case of descriptive systematics (in other words, "taxonomy"), the key question is the number of living species. How many exist in each major group, from bacteria to mammals? I believe that we should aim at nothing less than a full count, a complete catalog of life on Earth. To attempt an absolute measure of diversity is a mission worthy of the best effort of science.

The magnitude and cause of biological diversity is not just the central problem of systematics; it is one of the key problems of science as a whole. It can be said that for a problem to be so ranked, its solution must promise to

Figure 1. Estimated sizes of Australian insect, British insect, and Australian terrestrial vertebrate faunas and levels of taxonomic knowledge of them.



Source: Modified from Robert W. Taylor, "Descriptive Taxonomy: Past, Present, and Future," in *Australian Entomology: A Bicentenary Perspective*, ed. E. Highley and R. W. Taylor (Melbourne: Commonwealth Scientific and Industrial Research Organization, 1983).

The status of research on diversity

yield unexpected results, some of which are revolutionary in the sense that they resolve conflicts in current theory while opening productive new areas of research. In addition, the answers should influence a variety of related disciplines. They should affect our view of man's place in the order of things and open opportunities for the development of new technology of social importance. These several criteria are very difficult to satisfy, of course, but I believe that the diversity problem meets them all.[6]

To this end the problem can be restated as follows: If there are indeed 30 million species, why did there not evolve 40 million, or 2,000, or 1 billion? Many ramifications spring from this ultimate Linnaean question. We would like to know whether something peculiar about the conformation of the planet or the mechanics of evolution itself has led to the precise number that does exist. At the next level down, why is there an overwhelming preponderance of insect species on land but virtually none in the sea? "Hot spots" of disproportionately high diversity of plants and animals occur within larger rain forests, and we need to know their contents and limits, as well as the peculiarities of their evolution at the species level. Would it be possible to increase the diversity of natural systems artificially without destabilizing them? The greater such diversity, the more likely we are to discover new species and genetic varieties for use in agriculture, forestry, and medicine. Only taxonomic analysis can guide research on these and related topics.

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The relation of systematics research to other disciplines of biology becomes clearer by considering the way diversity is created. A local community of plants and animals, of the kind occupying a pond or offshore island, is dynamic. New colonists arrive as old residents die off. If enough time passes, the more persistent populations evolve into local endemic species. On islands as large as Cuba or Oahu, the endemics often split into two or more species living side by side. The total play of these evolutionary forces (immigration, extinction, and species multiplication) determines diversity. To understand each of the forces is automatically to address the principal concerns of ecology, biogeography, and population genetics. Our current understanding of the causes of diversity is still crude. The science addressing it can be generously put at about the level of physics in the late nineteenth century.

III

There is, in addition, a compelling practical argument for attempting a complete survey of diversity. It is well known that only a tiny fraction of the species with potential economic importance has been utilized.[7] Tens of thousands of plants, and millions of animals, have never been studied well enough to assess their potential. Throughout history, for example, a total of 7,000 kinds of plants have been grown or collected as food. Of these, 20 species supply 90 percent of the world's food, and just 3—wheat, maize, and rice—supply more than half. In most parts of the world this thin reservoir of diversity is sown in monocultures particularly sensitive to insect attacks and disease. Yet waiting in the wings are tens of thousands of species that are edible, and many are demonstrably superior to those already in use. In addition, the vast insect faunas contain large numbers of species that are potentially superior as crop pollinators, control agents for weeds, and parasites and predators of insect pests. Bacteria, yeasts, and other microorganisms, which are also poorly known, are likely to yield new medicinals, food, and procedures of soil restoration. Biologists have begun to fill volumes with concrete proposals to explore and make better use of diversity.

The case of natural sweeteners serves as a parable of the potential of untapped resources among wild species. A plant has been found in West Africa, the katemfe (*Thaumatococcus daniellii*), that produces proteins 1,600 times sweeter than sucrose. A second West African plant, the serendipity berry (*Dioscoreophyllum cumminsii*), produces a substance 3,000 times sweeter. The parable is the following: Where in the wild universe does the progression end? To cite a more clearly humanitarian example, one in ten plant species contains anticancer substances of variable potency, but relatively few have been bioassayed. Economists use the expression "opportunity costs" for losses incurred because certain choices were made rather than others. In the case of systematics—or more precisely the neglect of systematics and the biological research dependent upon it—the opportunity costs are very high.

No comfort should be drawn from the spurious belief that because extinction is a natural process, man is merely another Darwinian agent.

Biological diversity is declining. Destruction of natural environments, a worldwide phenomenon, is reducing the numbers of species and the amount of genetic variation within individual species. The loss is most intense in the tropical rain forests. In prehistoric times these most species-rich of all terrestrial habitats covered an estimated 5 million square miles. Today they occupy 3.5 million square miles and are being cut down at an annual rate of 0.7 percent—that is, 24,500 square miles, about the size of West Virginia. The effect of this deforestation on diversity can be approximated by the following rule of thumb in biogeography. When the area of a habitat is reduced to 10 percent of its original size, the number of species that can persist in it indefinitely will eventually decline to 50 percent. That much habitat reduction has already occurred in many parts of the tropics. The forests of Madagascar now occupy less than 10 percent of their original area, while the once-teeming Brazilian Atlantic forests are down to less than 1 percent of their original size. Even great wilderness areas such as the Amazon and Oronoco basins, equatorial Africa, and Borneo are giving way. If present levels of deforestation continue, the stage will be set within a century for the inevitable loss of about 12 percent of the 700 bird species in the Amazon basin and 15 percent of the plant species in South and Central America.[8]

No comfort should be drawn from the spurious belief that because extinction is a natural process, man is merely another Darwinian agent. The rate of extinction is now about 400 times that recorded through recent geological time and is accelerating rapidly. If we continue on this path, the reduction of diversity seems destined to approach that of the great natural catastrophes at the end of the Paleozoic and Mesozoic eras—in other words, the most extreme in 65 million years. And in at least one respect this man-made hecatomb is worse than anything that happened in the geological past. In the earlier mass extinctions, which some scientists believe were possibly caused by large meteorite strikes, most of the plants survived even though animal diversity was severely reduced. Now, for the first time ever, plant diversity too is declining sharply.[9]

IV

A complete survey of life on Earth may appear to be a daunting task. But compared with what has been dared and achieved in high-energy physics, molecular genetics, and other branches of "big science," it is in the second or third rank. To handle 10 million species even with the least efficient old-fashioned methods is an attainable goal. If one specialist proceeded at the cautious pace of an average of ten species per year, including collecting, curatorial work, taxonomic analysis, and publication, about 1 million person-years of work would be required. Given 40 years of productive life per scientist, the effort would consume 25,000 professional lifetimes. That is not an excessive investment on a global scale. The number of systematists worldwide would still represent less than 10 percent of the current population of scientists working in the United States alone and fall short of the standing armed forces of Mongolia and the population of retirees in Jacksonville, Florida. Nor does information storage present an overwhelming problem, even when left wholly to conventional libraries. If each species were given a single, double-columned page for the diagnostic taxonomic description, a figure, and brief biological characterization, and if the pages were bound into ordinary 1,000-page, 6-centimeter-wide hardcover volumes, the 10,000 or so final volumes of this ultimate catalog would fill 600 meters of library shelving. That is far below the capacity of some existing libraries of evolutionary biology. The library of Harvard's Museum of Comparative Zoology, for example, contains 4,850 meters of shelving.

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But I have given the worst scenario imaginable in order to establish the plausibility of the project. Systematic work could be speeded up many times over by new procedures now coming into general use. The Statistical Analysis System (SAS), a set of computer programs currently running in more than 4,000 institutions worldwide,[10] permits the recording of taxonomic identifications and localities of individual specimens and the automatic integration of data into catalogs and biogeographic maps. Other computer-aided techniques rapidly compare species across large numbers of traits, applying unbiased measures of overall similarity, in a procedure known as phenetics. Still others assist in sorting out the most likely patterns of the phylogeny by which species split apart to create diversity, the method called cladistics. Scanning electron microscopy has speeded up the illustration of insects and other small specimens and has rendered descriptions more accurate. The DELTA system, developed and used at Australia's Commonwealth Scientific and Industrial Research Organization in Canberra, codes data for the automatic identification of specimens.[5, 11] Elsewhere, research is being conducted that may lead to computerized image scanning for purposes of automatic description and data recording.

In North America about 4,000 systematists work on 3,900 systematics collections. But a large fraction of these specialists, perhaps a majority, are engaged only part-time in taxonomic research. More to the point, few can identify organisms from the tropics, where the great majority of species exist and where extinction is proceeding most rapidly. Probably no more than 1,500 professional systematists in the world are competent to deal with tropical organisms, and their number may be declining, owing to decreased professional opportunities, reduced funding for research, and assignment of higher priority to other disciplines.[12] To take one especially striking example, ants and termites make up about one-third of the animal biomass in tropical forests. They cycle a large part of the energy in all terrestrial habitats and include the foremost pests of agriculture, causing billions of dollars in damage yearly. Yet there are exactly eight entomologists worldwide with the general competence to identify tropical ants and termites, and only five of these are able to work at their specialty full-time.

V

It is not surprising to find that neglect of species diversity retards other forms of biological research. Every ecologist can tell of studies delayed or blocked by lack of taxonomic expertise. In one recent and typical case, William G. Eberhard, an entomologist at the University of Costa Rica, consulted most of the small number of available (and overworked) authorities to identify South and Central American spiders used in a study of behavior. He was able to place only 87 of the 213 species included, and then only after considerable delay. He notes that "there are some families (e.g., Pholcidae, Linyphiidae, Anyphaenidae) in which identifications even to genus of Neotropical species are often not possible, and apparently will not be until major taxonomic revisions are done. On a personal level, this has meant that I have refrained from working on some spiders (e.g., Pholcidae—one of the dominant groups of web spiders in a variety of forest habitats, at least in terms of numbers of individuals) because I can't get them satisfactorily identified."[13]

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If systematics is an indispensable handmaiden of other branches of research, it is also a fountainhead of discoveries and new ideas, providing a remedy for what biologist and philosopher William Morton Wheeler once called the "dry rot" of academic biology. Systematics has never been given enough credit for this second, vital role. If a biologist can identify only a limited number of species, he is likely to gravitate toward them and end up on well-trodden ground; the remainder of the species remain a confusing jumble. But if he is well-trained in the classification of the organisms encountered, his opportunities multiply. The known facts of natural history become an open book, patterns of adaptation fall into place, and previously unknown phenomena offer themselves conspicuously. By proceeding in this opportunistic fashion, the biologist may discover a new form of animal communication, a previously unsuspected mode of root symbiosis, or a relation between certain species that permits a definitive test of competition theory. The irony of the situation is that such successful research then gets labeled as ecology, physiology, or almost anything else but its *fons et origo*, the study of diversity.

Systematics is linked not only to the remainder of biology but to the fortunes of the international conservation movement, which is now focusing its attention on the threatened environments of the tropics. Plans for systems of ecological reserves have been laid by the International Union for the Conservation of Nature and Natural Resources (IUCN), by UNESCO, and by a growing number of national governments ranging from Australia and Sri

Lanka to Brazil and Costa Rica. The aim is to hold on to the greatest amount of species within the limits imposed by population pressures and the costs of land purchases. The long-term effects of this enterprise can only be crudely predicted until systematics surveys are completed on a country-by-country basis. In the United States a proposal for a National Biological Survey (NABIS) has been presented to Congress. The program would (1) establish a survey to describe all of the plants and animals, (2) fund basic taxonomic studies to this end, and (3) produce identification manuals, catalogs, and other practical aids.[14] If multiplied across many countries, such efforts could bring the full assessment of biological diversity within reach.

Systematics surveys have been a relatively small part of the national research effort in biology. In fiscal year 1985 the National Museum of Natural History, the largest organization of its kind in the United States, spent $12.8 million to support the activities of 85 scientists engaged partly or wholly in taxonomic studies. In the same year the Program in Systematic Biology of the National Science Foundation (NSF) granted $12 million for basic taxonomic research, while other programs of the NSF and Department of Interior provided $13.8 million for support of museum services, studies of endangered species, and other activities related to systematics. Worldwide support for basic tropical biology, including systematics and ecology, is approximately $50 million per year.

Biological diversity is unique in its importance to both developed and developing countries.

Congress addressed the problem of biological conservation in the tropics through a 1980 amendment to the Foreign Assistance Act, which mandates that programs funded through the Agency for International Development (AID) include an assessment of environmental impact. In implementing this policy, AID recognizes that "the destruction of humid tropical forests is one of the most important environmental issues for the remainder of this century and, perhaps, well into the next," in part because they are "essential to the survival of vast numbers of species of plants and animals."[15]

Moving further, AID set up an interagency task force in 1985 to consider biological diversity as a comprehensive issue. In its report to Congress the task force evaluated the current activities of the dozen federal agencies that have been concerned with diversity, including the Smithsonian Institution, the Environmental Protection Agency, and AID itself.[16] The most important recommendations made by the group, in my opinion, are those that call for the primary inventory and assessment of native faunas and floras. In fact, not much else can be accomplished without this detailed information.

AID also supports research programs in which nationals of the recipient countries are the principal investigators and United States citizens serve as collaborators. This arrangement is a proven way to build science and technology in the third world, and it is particularly well suited to tropical biology. Studies of diversity are best conducted at the sites with the maximum amount of diversity. Such studies are labor intensive and require less expensive instrumentation than most kinds of research. Perhaps most importantly, their relevance to national identity and welfare are immediately obvious.

To put the matter as concisely as possible, biological diversity is unique in its importance to both developed and developing countries and in the cost-effectiveness of its study. The United States would do well to seek a formal international agreement among countries, possibly in the form of an "International Decade for the Study of Life on Earth," to improve financial support and access to study sites. To spread technical capability where it is most needed, arrangements could be made to retain specimens within the countries of their origin while nationals are trained to assume leadership in systematics and the related scientific disciplines.

In *Physics and Philosophy*, Werner Heisenberg suggested that science is the best way to establish links with other cultures because it is concerned not with ideology but with nature and man's relation to nature. If that promise can ever be met, it will surely be in an international effort to understand and save biological diversity. This being the only living world we are ever likely to know, let us join to make the most of it. ■

NOTES:

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4. Peter S. Ashton, personal communication (May 1985).
5. Robert W. Taylor, "Descriptive Taxonomy: Past, Present, and Future," in *Australian Entomology: A Bicentenary Perspective*, ed. E. Highley and R. W. Taylor (Melbourne: Commonwealth Scientific and Industrial Research Organization, 1983).
6. I am indebted to John Daly of the Agency for International Development for an invaluable discussion of the criteria of key scientific problems.
7. See, for example, *Underexploited Tropical Plants with Promising Economic Value*, 2d ed. (Washington, D.C.: National Academy of Sciences, 1975), known informally as the "Green Book"; also Norman Myers, *A Wealth of Wild Species: Storehouse for Human Welfare* (Boulder, Colo.: Westview Press, 1983), and Margery L. Oldfield, *The Value of Conserving Genetic Resources* (Washington, D.C.: U.S. Department of the Interior, 1984).
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10. John C. La Duke, David Lank, and Tim Sirek, "Utilization of Statistical Analysis System (SAS) as a Revisionary Tool and Cataloguing Program," *ASC Newsletter* (Association of Systematics Collections) 12, no. 2 (April 1984).
11. Michael J. Dallwitz, "A General System for Coding Taxonomic Descriptions," *Taxon* 29, no. 1 (1980).
12. Data concerning the number of taxonomists, as well as detailed arguments for the need to improve research in tropical countries, are given by Peter H. Raven et al. in *Research Priorities in Tropical Biology* (Washington, D.C.: National Academy of Sciences, 1980). A partial updating has been provided by Stephen R. Edwards, "The Systematics Community: Priorities for the Next Decade," *ASC Newsletter* (Association of Systematics Collections) 12, no. 5 (October 1984), and personal communication (May 1985). Tropical ecology research as a whole is also declining, as documented by N. H. Ayodele Cole in *Nature* 309 (May 17, 1984).
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