EARTH '88

Changing Geographic Perspectives

PROCEEDINGS OF THE CENTENNIAL SYMPOSIUM

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EARTH '88

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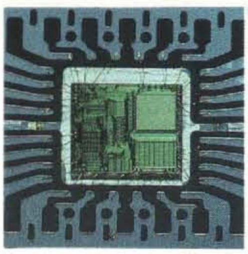
Visions, Explorations, and Discoveries



The Dynamics of Science and Technology

Beyond Earth

Toward an Environmental Ethic

Humankind and its Future

Editor's Preface

H. J. de Blij
Editor
National Geographic Research

This volume represents the record of a week-long symposium held in Washington, D. C., in January 1988, to commemorate the centennial of the National Geographic Society. The Centennial Symposium was convened under the auspices of the Society's Committee for Research and Exploration, chaired by Dr. Melvin M. Payne. It was organized by Dr. Barry C. Bishop, the Committee's Vice Chairman.

Earth '88: Changing Geographic Perspectives was convened to address relevant topics related to the advance of science, technology, and exploration over the century following the year of the Society's birth, and to discuss concerns for the future in the general context of the quality of life on this planet.

The *Symposium Proceedings* were produced by members of the staff of the Society's scholarly journal, *NATIONAL GEOGRAPHIC RESEARCH.* The symposium was divided into five major parts. Papers are presented here in the order in which they were delivered. Symposium speakers in a few instances slightly revised their manuscripts following delivery, but the *Proceedings* constitute a faithful record of the presentations. A comparatively small number of illustrations were deleted for the published format. The question sessions that followed each presentation were recorded and transcribed, and edited slightly for publication.

The editor wishes to acknowledge the assistance provided by a number of persons in other divisions of the Society. Ken Florence of National Geo-

The Diversity of Life

Edward O. Wilson
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The zoology of dreams is poorer than the zoology of the Maker. –Jorge Luis Borges

The history of life is traced through its four great revolutions: first procaryotic organisms, first eukaryotic cells, first multicellular organisms, and first cultural species. The magnitude of diversity has fluctuated widely through the agency of mass extinctions and bursts of adaptive radiation, concluding in the millions of species alive today—of which only 1.4 million have been given scientific names. A few headquarters of evolution—notably the tropical forests, coral reefs, and deep sea—have special significance in our story. As humankind takes control of the Earth's management, and of evolution itself, life approaches its fifth great revolution.

The past 100 years have seen a remarkable expansion in our knowledge of global biodiversity: how much there is, where it is concentrated, where it comes from, and how long it takes to create. Yet these key questions have been only partially answered. Despite the fact that the formal study of biodiversity began in 1753, with Linnaeus' inauguration of the binomial system of classification, the field remains intellectually young. Fewer than half the species of organisms have received scientific names, and only a minute fraction have been studied with any care. The principal generalizations about diversity are relatively new and in many cases subject to controversy. They all begin with the events in evolution that made diversification possible.

Evolution in Four Steps

Four great steps, occurring about a billion years apart, have profoundly altered the direction of evolution and added whole new layers of species in the energy pyramids of the ecosystems. The first was the origin of life itself about 3.5 billion years ago. The earliest known organisms were bacteria-like filaments and blue-green algae composed of prokaryotic cells, which lacked cell membranes, mitochondria, chloroplasts, and other organelles. The assembly of organelles into the eukaryotic cell was the second seminal advance. It required another 1.9 billion years, occurring no later than 1.4 billion years before the present. About 700 million years ago came the third step, the origin of the first multicellular animals. The earliest of these creatures known in the fossil record composed the Ediacaran fauna, named for the Ediacara Hills of South Australia where many of the first specimens were found. The animals were predominantly flat and soft-bodied. About 100 million years later, the first shelled creatures began to appear in substantial number and variety. Their appearance was accompanied by a rapid proliferation of body plans among species.

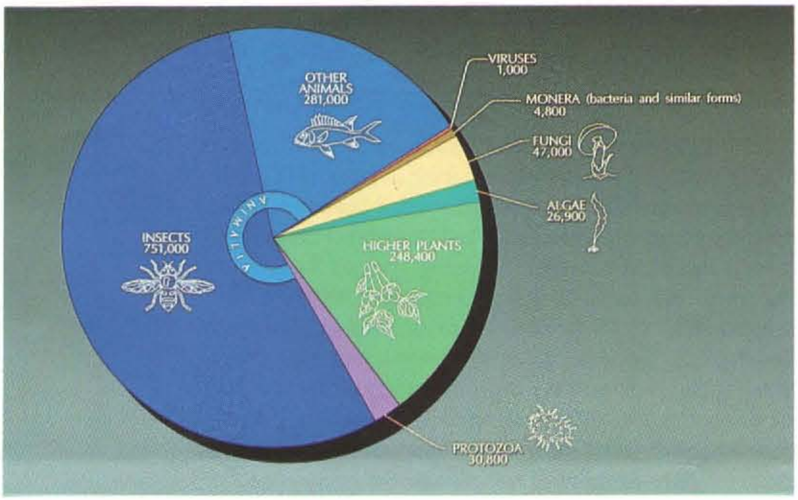
This period, spanning the transition from Precambrian to Cambrian times, was the great age of experimentation. Most kinds of animals persisted for only a short time, their *bauplan* never to be repeated in later eras. With the appearance of multicellular animals, complex food chains were created. Shelly animals, predators, and deep burrowers then rose to abundance. Their analogs and successors were destined to dominate the marine environment from that time on (McMenamin 1987, Morris 1987). During the Ordovician Period, about 450 million years ago, the first animals and bryophytic plants colonized the land (Retallek & Feakes 1987). By Devonian times, 375 million years before the present, terrestrial arthropods made their appearance, including mites and the most primitive wingless insects (Shear *et al.* 1984). In the Pennsylvanian Period, 100 million years later, a wide diversity of winged insects occupied the now dense forests of vascular plants. At this point all the major physical zones of the Earth had been conquered: water, land, and air.

The stage was now set for the fourth great step in evolution, the origin of Man. To put it this way is not to be unduly homocentric. The creation of a cultural species, in which most information is transmitted by open, creative language and learning, was a unique and profoundly important event for all of life. Culture energized a rapid and unique evolutionary change in our own species. Within less than 2 million years, from the appearance of the earliest "true" Man *Homo habilis* to the earliest *Homo sapiens* half a million years ago, the cerebral cortex enlarged 3.2 times, and an important architectural reorganization occurred in the speech-control centers of the parietal regions and memory banks of the forebrain. The rate of morphological change alone was possibly the most rapid in the history of life. It was driven by gene–culture coevolution, in which the genetically prescribed properties of cognition influence the evolution of culture, and cultural changes simultaneously guide genetic evolution by influencing which cognitive genotypes survive and reproduce. This coupled system of biological evolution and cultural evolution somehow accelerated the later stages of human evolution (Lumsden & Wilson 1983).

How Much Diversity Is There?

From literature sources such as the authoritative *Synopsis and Classification of Living Organisms* (Parker 1982) and new information provided by experts on various groups (see Acknowledgments), I have estimated the total number of living species known at the present time to be approximately 1,390,900. The breakdown of this diversity is presented in Figures 1 through 3. Several generalizations emerge from these data. First is the preponderance of multicellular organisms, which if genuine is an enduring heritage of the diversification that occurred during the Precambrian–Cambrian transition. Second is the far greater number of species—at least species known to science—on the land. The flowering plants (angiosperms) and especially the dicots prevail among the plants at the present time. The Animal Kingdom is dominated by medium-sized creatures between 1 and 10 millimeters in length, and these are overwhelmingly insects. When diversity is plotted against size of organism in the plants, the result is an inverted triangle, with relatively few known species at the bottom and the largest number near the top. The animals yield a diamond-shaped figure, with diversity swelling to the maximum near the middle of the size range. Going from the species to the phylum level (for example, all sponges taken together, all corals taken together, and so on), the greatest diversity is in the sea, where multicellular animal life originated and experimented during the Precambrian–Cambrian transition. But plant phyla are most diverse on land, where multicellularity evolved most vigorously during mid-Paleozoic times, following the golden age of animal experimentation. The prevailing plant forms in the sea remain algae, including forms resembling some of the early eukaryotic cells and filaments that dominated plant life a billion years ago.

Turning to the biomass of organisms in tropical forests (where most of the species of organisms live), an equally lopsided picture emerges. The vegetation consists overwhelmingly of flowering plants and especially dicots, with the monocotyledonous palms nevertheless holding their own among the trees and shrubs. Among the animals, insects again predominate—as detailed in Figure 4. And among the insects, the highly social forms—specifically termites, ants, social wasps, and stingless bees—make up an incredible 80 per cent of the biomass (Figure 5). These various proportions are probably not far from those occurring in grasslands and other major terrestrial habitats in most parts of the world. The proportions reflect the coevolution between the flowering plants and the insects that has occurred since early Mesozoic times, approximately 250 million years ago. Most of the plants depend on insects for pollination and seed dispersal, while a great majority of the insects depend on the plants for food and shelter. When mankind joined the social insects 2 million years ago, another important trend was completed: social life had come to largely dominate and manipulate the environment of the land.



ALL ORGANISMS: TOTAL SPECIES, 1,390,900

Figure 1. **The number of living species of all kinds of organisms known at the present time, according to major taxonomic group, are shown in this diagram. The actual number, including undescribed species, is much greater.**

Although the estimates on biomass are relatively firm, those on diversity are still very incomplete. In 1964 C. B. Williams, employing a combination of intensive local sampling and mathematical extrapolation, put the number of insect species at 3 million (and the number of living insects at any given moment at 10^{18}). During the last 20 years, systematists have 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," in other words populations that are reproductively isolated from other populations but difficult to distinguish on the basis of museum specimens alone. As a result of these discoveries, a few writers began to put the world's total as high as 10 million species.

The estimates were raised yet again when Terry L. Erwin (1983) and other entomologists employed a technique that for the first time allowed intensive sampling of the canopy of the tropical rain forests. The number of species proved to be far greater than expected, because of unusually restricted ranges and high levels of specialization of different parts of trees. According to Erwin, a total of 30 million insect species may exist (mostly beetles). However, his estimate must be tested with many more samples from additional rain-forest localities before the true figure can be approximated with confidence.

The least that can be said is that biological diversity is still very incompletely mapped. We do not know the number of species even to the nearest order of magnitude. It could be as low as 3 million or as high as 30 million, or still more. Research is at an early stage in the exploration of not only tropical insects but also mites, nematodes, and other small organisms in the soil, and the complex invertebrate faunas of coral reefs and the deep sea. The present count of 3,000 bacteria must be drastically low. The niches into which these microorganisms can evolve are extremely numerous. Each of the millions of insect species, for example, is a potential host for specialized mutualistic and pathogenic forms. Other bacterial species live virtually incommunicado in very sparse populations, increasing to conspicuous numbers only under special conditions of nutrition, pH, and temperature. Thorough studies of local bacterial floras have been so few and far between as to leave bacterial diversity a mostly unexplored field.

Two Major Centers of Biological Diversity

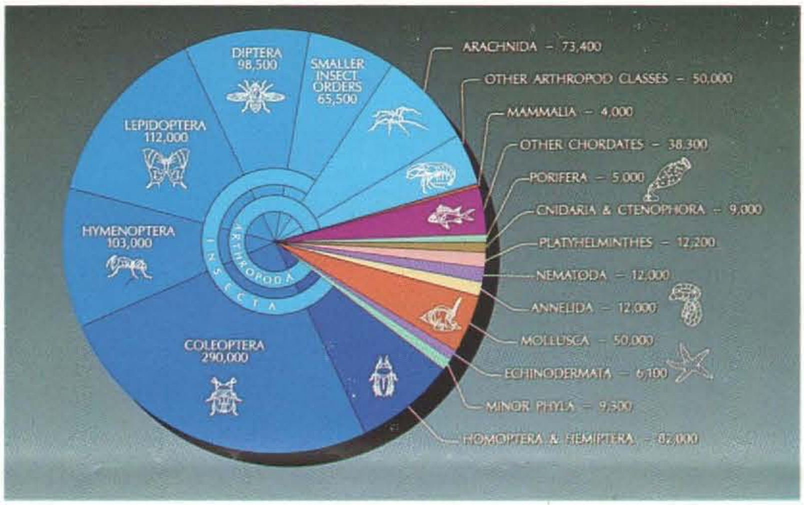
The tropical moist evergreen forests, or rain forests, occupy only 7 per cent of the land surface but contain at least half the species of organisms. In a few square kilometers in Ecuador or Malaysia can be found hundreds of species of birds, thousands of species of plants, and tens of thousands of species of beetles. Peter S. Ashton (personal communication) identified 700 species of trees in 10 selected hectares in Kalimantan; no more than 700 native tree species occur in all of North America. From a single tree in Peru, I identified 43 ant species belonging to 26 genera, approximately the same number as are in all of the British Isles (Wilson 1987a). The biologist studying the rain forest still addresses a mostly unknown terrain, much as did biologists a century ago.

The floor of the deep sea is another understudied reservoir of global biodiversity, containing as many as a million mostly undescribed species (H. L. Sanders personal communication). Many are annelid worms, molluscs, and echinoderms that scavenge detritus, which in turn falls from the upper lighted layers onto the vast abyssal plains. Others are limited to thermal vents that occur along the volcanically active subduction zones of the Pacific rim and mid-Atlantic ridge. The primary energy source of these abyssal sites is not detritus from above but bacteria that metabolize sulfur from subterranean sources. Each vent is an islandlike oasis with its own distinctive fauna. The commonest organisms include giant tube worms, colonial siphonophore "jelly fish," mussels, and galatheid squat crabs—most new to science and many constituting novel genera and even families of organisms (Childress *et al.* 1987). Elsewhere, cold seeps on the ocean floor possess a wholly different set of distinctive faunas, supported in this case mostly by methane-metabolizing bacteria (Turner 1985) (Figures 6 & 7). The organisms of the thermal vents and cold seeps, which were unknown before 1977, perhaps come as close as we will ever know to what life could be like on another planet. They demonstrate how resourceful organisms are when adapting to radically different environments.

How Species Are Created

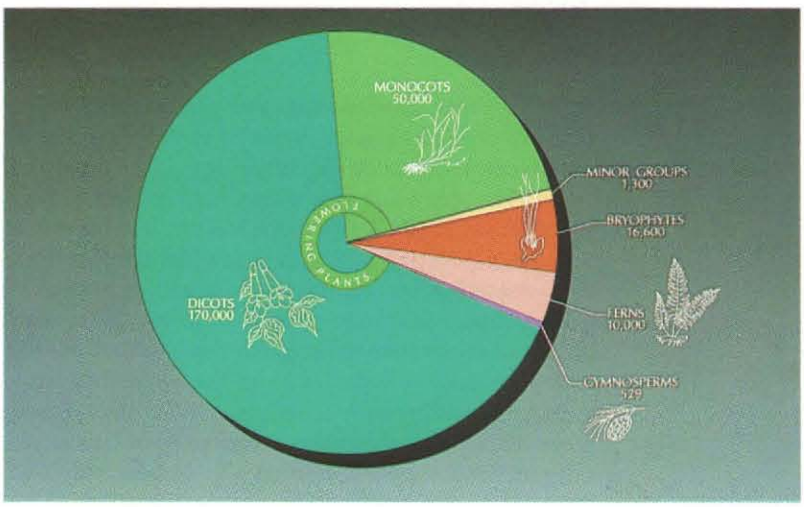
Organisms diversify through the formation of species, and all of classification is based on the species as the atomic unit. What, then, is a species? The modern "biological species concept" defines this unit as a population or series of populations within which gene flow occurs freely under natural conditions. This means that all of the normal, physiologically competent individuals at a given time are capable of breeding with all of the other individuals of the opposite sex belonging to the same species, or else they are linked to them genetically through chains of other breeding individuals. In brief, members of one species do not breed freely under natural conditions with those of other species. Tigers and lions hybridize when confined in captivity, but during historical times at least, they have never interbred where they lived together in the wilds of southern Asia. Hence, even though lions and tigers are capable of hybridization, they comprise two different species.

The biological species concept is the best ever devised, but it remains less than ideal. It works very well for most animals and some kinds of plants, but must be replaced with arbitrary divisions in many other plants (and in a few animals) where intermedi-



ANIMALS: TOTAL SPECIES, 1,032,000

Figure 2. **The number of living animal species known at the present time, according to major taxonomic group.**

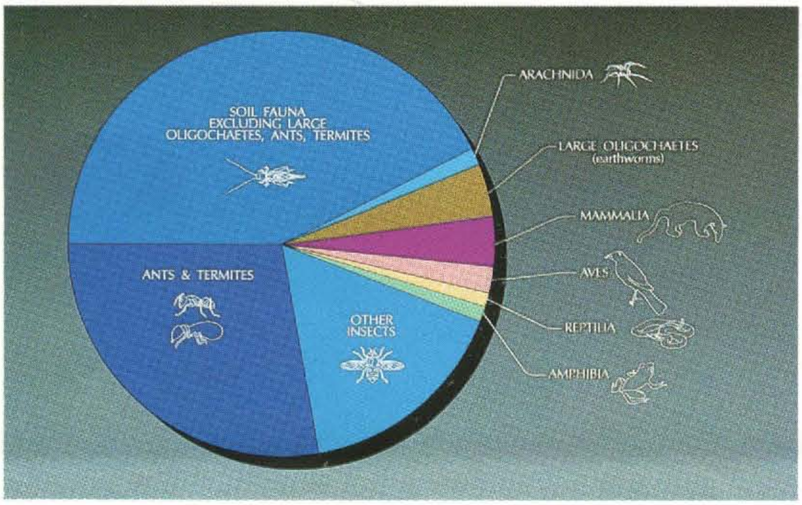


HIGHER PLANTS: TOTAL SPECIES, 248,000

Figure 3. **The number of living species of higher plants known at the present time, according to major taxonomic group.**

ate amounts of hybridization occur among natural populations, or where ordinary sexual reproduction has been replaced entirely or in part by self-fertilization or parthenogenesis.

New species are usually created in one of two ways. A large minority of plant species came into existence in one step, through polyploidy. This is a simple multiplication in the number of gene-bearing chromosomes, sometimes within a preexisting species and sometimes in the hybrids that infrequently



TOTAL ANIMAL BIOMASS

Figure 4. **The apportionment of biomass, measured in dry weight, among groups of animals in a rain forest near Manaus, Brazil. [source: Fittkau, E. J. & Klinge, H. 1973. On biomass and trophic structure of the central Amazonian rain forest ecosystem. *Biotropica* 5:2–14]**

occur between two species. Polyploids formed this way are typically unable to breed back to the parent species to produce fertile offspring.

The second major generative process, geographic speciation, takes much longer. It starts when a single population (or series of populations) is divided by some barrier extrinsic to the organisms, such as a river, mountain range, or arm of the sea. The isolated populations then diverge from each other in evolution because of adaptation to the inevitable environmental differences on either side of the barrier. Since all populations evolve if given enough time, divergence between all extrinsically isolated populations must eventually occur. By this process alone the populations can acquire enough differences to reduce interbreeding between them should the extrinsic barrier be removed and the population again come into contact. If sufficient differences have accumulated by this time, the populations can coexist as newly formed species. If they have not occurred, the populations will resume exchanging genes; in other words, they will still belong to the same species.

Adaptive Radiation and Convergence

On different continents and islands and in different geological times, the relentless multiplication of species has created ecological communities that resemble each other in broad features. The origin of the species that make up these separated communities are often drastically different, yet the final products tend to be similar. Today the reefs of shallow tropical seas are made up largely of corals, which are colonial coelenterates that secrete calcareous skeletons. However, in the Tethyean Basin of Late Cretaceous times, prior to the formation of the Mediterranean Sea, they were composed of bivalve molluscs (Stanley 1987). In other places and geological periods they were built variously by calcareous algae, bryozoans, and other kinds of coral coelenterates. The proliferation of species into different niches of a community is called adaptive radiation. Thus coelenterates are said to have radiated into many niches, of which one is the formation of shallow-water reefs. On the other hand, a similarity acquired by species that occupy approximately the same ecological position but in difference places or times, such as reef building, is called evolutionary convergence.

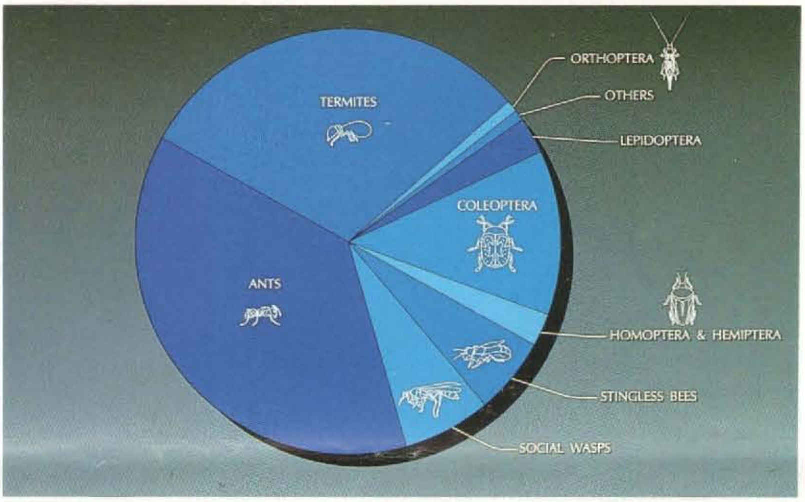
The dual processes of adaptive radiation and evolutionary convergence have been endlessly repetitive through time. Like a human dynasty, one group supplants another, radiates for a while, and then makes way for still another group. Paleontologists generally agree that more than 99 per cent of all evolutionary lines in geological history have become extinct (Raup 1979, 1981). In some cases, as in the complex lines that led from amphibians to reptiles and then to mammals, the ancestors of the new radiations were products of the previous ones. But in many other instances, such as the reef-building invertebrates, entire groups were supplanted by lines remote from their own, and often by invaders from other continents.

The most famous and instructive case is the triple adaptive radiation that produced the modern mammals. When the southern supercontinent of Gondwana broke up during the Mesozoic Era, two of the fragments were landmasses destined to become present-day Australia and South America. In the following 70 million years, separate radiations of mammals occurred on these two island continents, as well as on the northern "world continent" comprising Africa, Europe, Asia, and North America. Mammals were able to spread to some extent from one end of the world continent to the other.

The contemporary products of their evolution are our familiar dogs, antelopes, rhinoceroses, mice, and other warm-blooded animals. They are almost all descended from placental mammals, the females of which carry the young to an advanced stage of development in the uterus. In Australia, some two thirds of the mammal species are marsupials, in which the young are born while still very young and undeveloped; they then crawl into a pouch (the marsupium) located on the mother's belly and attach themselves to the mother's teats to complete their development. The degree of convergence that occurred during the simultaneous radiations on the two continents is astonishing. In some instances—for example, the flying squirrel (placental) versus the sugar glider (marsupial), the woodchuck (placental) versus the wombat (marsupial), and the placental versus the marsupial versions of the wolf and the mole—the external resemblance is so close that special instruction is needed to place a given species to the correct continent.

A third comparable mammalian radiation unfolded on South America, but in this case the plant-eating mammals were primarily placental and the carnivores marsupial (Figure 8). When South America and North America were connected by the rise of the Panamanian land bridge about 5 million years ago, the world-continent mammals largely replaced their South American analogs. At the present time world-continent elements, such as jaguars and deer, coexist with armadillos, prehensile-tailed monkeys, and other products of the early, autochthonous South American radiation.

My own favorite among adaptive radiations is that of the sharks. These fishes, after flourishing in the Paleozoic and shrinking to low levels of diversity in the Mesozoic, expanded once again to their present high level of about 350 species. Today they include some of the most diverse forms found in any animal group of comparable size. The smallest species, the cigar shark *(Squaliolus laticaudus)*, is only a foot long at maturity, and the largest, the plankton-feeding whale shark *(Rhincodon typus)*, reaches 60 feet. In between are gulper sharks, bramble sharks, wobbegongs, spurdogs, crocodile sharks, and others. Most look like conventional sharks but a few resemble variously salmon, eels, sawfish, and rays. The great white shark *(Carcharodon carcharias)* specializes to some extent on sea lions and other mammals. As a result it mistakes human swimmers for its normal prey. The cookie-cutter shark *(Isistius brasiliensis)* is a parasite of porpoises, whales, and large fishes such as bluefin tuna. Only about 18 inches long, it has a curving row of very long teeth on its lower jaw, which it thrusts into the bodies of its victims and twists to slice out 1- to 2-inch conical plugs of skin and flesh. My half-serious criterion for a fully developed adaptive radiation is that at least one species should specialize in feeding on other members of the same group. The sharks qualify very nicely: bull sharks, which can grow to 500 pounds, prey preferentially on smaller sharks of other species.



INSECT BIOMASS

Figure 5. **The apportionment of biomass among groups of insects in a rain forest near Manaus, Brazil. [source: Fittkau, E. J. & Klinge, H. 1973. On biomass and trophic structure of the central Amazonian rain forest ecosystem.** ***Biotropica*** **5:2–14]**

Extinction and Renewal

Both plants and animals have gradually become more diverse since the origin of multicellular life. The variety of terrestrial plants, measured by the mean number of species per flora, rose steadily after the conquest of the land until early Carboniferous times, then remained on a plateau for 220 million years. In Late Cretaceous times, buoyed by the rise of the flowering plants, floral diversity began a prolonged and steep rise until a few tens of thousands of years ago, when it reached the highest level ever at-

THERMAL-VENT COMMUNITY

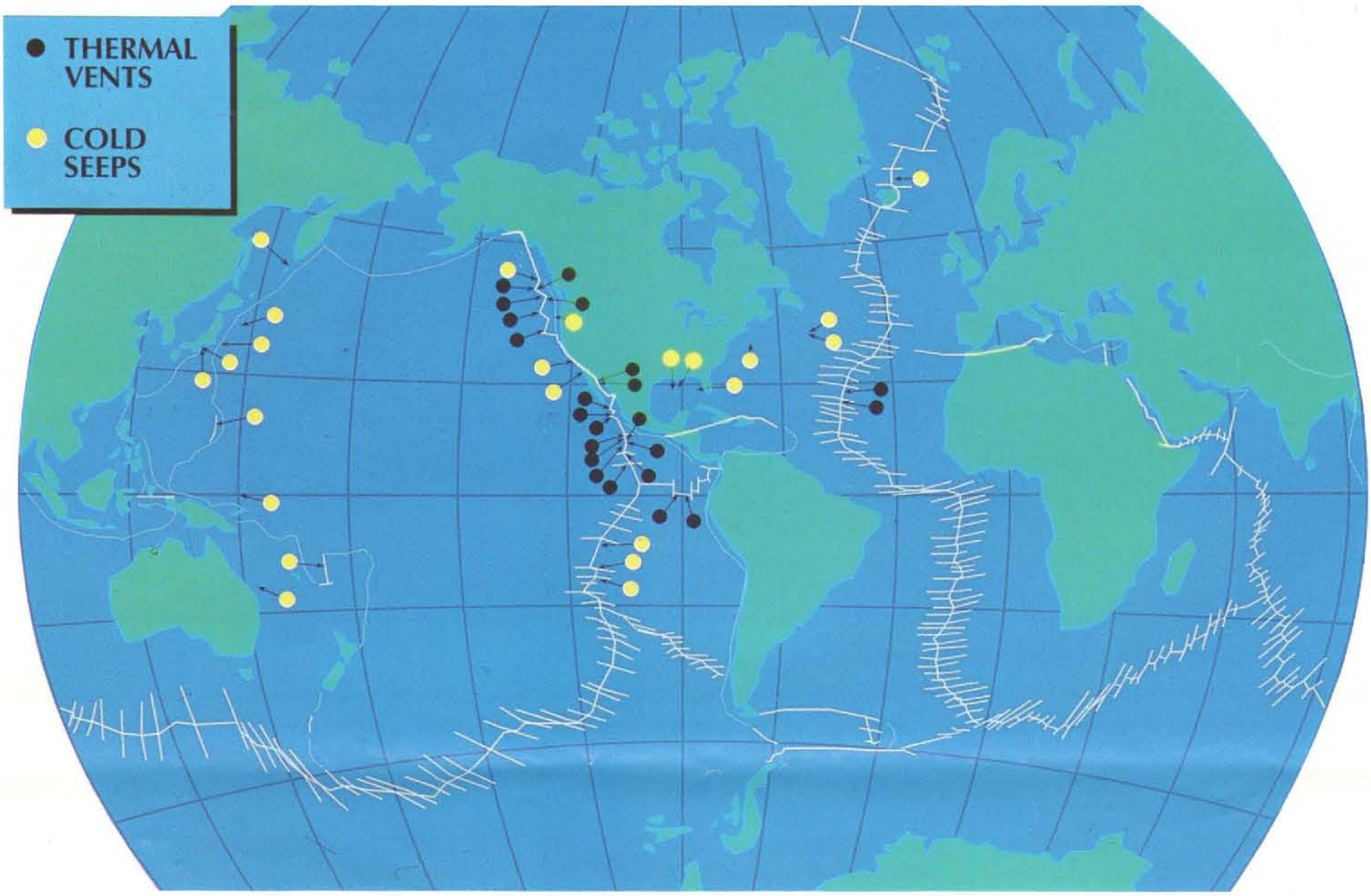
Figure 6. **This community, found in the Galápagos rift, includes *Riftia* tube worms, some as long as 8 feet. The rich and unique assemblages of the thermal vents and cold seeps were unknown before 1977. [photo: ©Al Giddings, Ocean Images]**

tained in geological history (Knoll 1986). It has begun to drop again through the massive alteration of natural habitats, especially the destruction of tropical forests. In parallel manner, marine animal diversity, which paleontologists have measured by various methods, rose to a plateau in the Devonian and Carboniferous, plummeted in the Permian and Triassic, and then rose again to a record peak in the late Tertiary (Raup & Sepkoski 1981, 1984) (Figure 9).

In short, global biological diversity is now at or close to its all-time high. Another way of putting it is that mankind came into existence in the most interesting time in which any sentient species could live. The living world arrived at this summit through an incessant turnover in principal organisms from one geological period to the next. Tree-like seed ferns and lycopsids dominated the Paleozoic forests. During the first part of the Mesozoic, they yielded to ferns, conifers, and cycads, which retreated in turn before the spread of the flowering plants. Among marine invertebrates, dominant elements of the Paleozoic Era included trilobites, brachiopods, and coelenterates. They were largely replaced by molluscs, protozoans, and non-trilobite arthropods during the Mesozoic Era.

Groups classified as high as orders and classes in the taxonomic scheme, such as cycads and brachiopods, turn over only across intervals of hundreds of millions of years. On the other hand, species, which collectively make up these higher taxa, persist for a much shorter period of time. Because of the proportionate richness of fossils in shallow marine deposits, the longevity of fish and invertebrate species living there can often be determined with a modest degree of confidence. During the Paleozoic and Mesozoic Eras, the average persistence of most fell between 1 million and 10 million years, that is, 6 million for echinoderms, 1.9 million for Silurian graptolites, 1.2 million to 2 million for ammonites, and so on (Raup 1984). These order-of-magnitude figures might not have broad generality. Terrestrial organisms are far less well known. Few estimates have been attempted, and hence different survivorship patterns might have been followed (although Cenozoic flowering plants, at least, appear to fall within the 1-million- to 10-million-year range). More importantly, a great many organisms on islands and other restricted habitats, such as lakes, streams, and mountaintops, are so rare or local in occurrence that they could appear and vanish through short periods of time without leaving any fossils.

In computing the longevity of species, paleontologists make a fundamental distinction between background extinction—the more or less continuous and seemingly random deaths of individual species here and there—and episodic mass extinction, which is the geologically relatively sudden and nearly simultaneous demise of large numbers of species. The "big five" of mass extinctions occurred, respectively, in the last Ordovician, Devonian, Permian, Triassic, and Cretaceous Periods (Figure 9). The Cretaceous episode is of course the most celebrated, because it included the end of the dinosaurs.



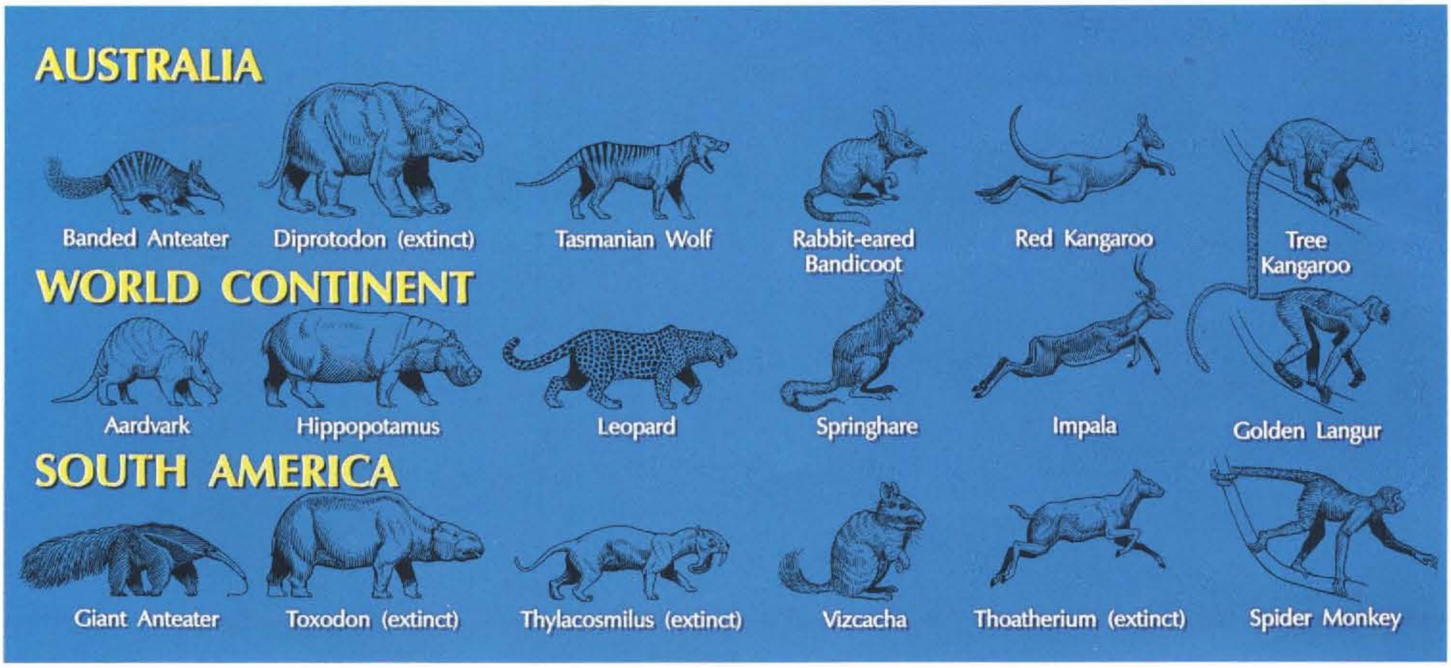
THERMAL VENTS AND COLD SEEPS

Figure 7. **The distribution of thermal vents and cold seeps on the floor of the deep sea. These recently discovered sites contain dense concentrations of unusual organisms whose energy sources are sulfur- and methane-metabolizing bacteria. [source: Ruth D. Turner; data collected by the Deep Sea Biology Group of Woods Hole Oceanographic Institution]**

But the most devastating occurred much earlier, at the close of the Permian. Between 77 and 96 per cent of all marine animal species were extinguished, as well as 52 per cent of the animal families. As David Raup (1987) said, "If these estimates are even reasonably accurate, global biology (for higher organisms, at least) had an extremely close call." For some 5 million years afterward, well into the early Mesozoic, diversity remained low, then began a climb that was never again to be so seriously threatened—never, at least, until the arrival of Man.

As shown in Figure 10, the Permian, Triassic, and Cretaceous peaks of extinction were interspersed by a series of smaller peaks. Taken all together, the episodes occurred at remarkably even intervals, which average 26 million years. Does a periodic cataclysm threaten humanity? We can relax a bit: the last episode was 11 million years ago, leaving us another 15 million years to prepare for the next.

Walter Alvarez and his coworkers, noting the presence of relatively large quantities of iridium and other rare elements at the Cretaceous–Tertiary boundary, proposed that the extinction spasm was caused by the strike of one or more large meteorites. This hypothesis, modified somewhat to include either meteorites or comets, has spurred an extraordinary growth of studies on the extinction process. In essence, a clear distinction has been drawn in theory between spasms due to Earth-bound changes (such as volcanic activity or reduction in the area of shallow seas) and spasms due to catastrophes of extraterrestrial origin (Officer *et al.* 1987).



THE THREE GREAT ADAPTIVE RADIATIONS OF MAMMALS

Figure 8. **These radiations have produced a remarkable series of convergences among species that fill the same major niche in Australia, South America, and the "world continent" of the northern hemisphere, respectively. [drawings: Theophilus Britt Griswold]**

Proponents of both hypotheses are locked in debate. The issue is neither clear-cut nor easily resolved. No high concentrations of iridium have been found at the geological boundary zones that mark other mass-extinction events, making it difficult to invoke the extraterrestrial model as a general explanation. Nor was the Cretaceous catastrophe as sharply demarcated as might be expected from a single bolide strike. The mollusc reef-builders declined drastically 3 million to 4 million years before the end of the Cretaceous. Dinosaur diversity also deteriorated during the concluding 2 million years; the *Triceratops* dominated the fauna, constituting about three quarters of all the large dinosaurs (Stanley 1987).

Of course, the boundaries of diversity loss could have been "smeared" by a sequence of bolide strikes over many thousands of years. Perhaps, on the other hand, the entrainment of more gradual climatic change by one strike caused the extinction of some groups before that of others (Weisburd 1986).

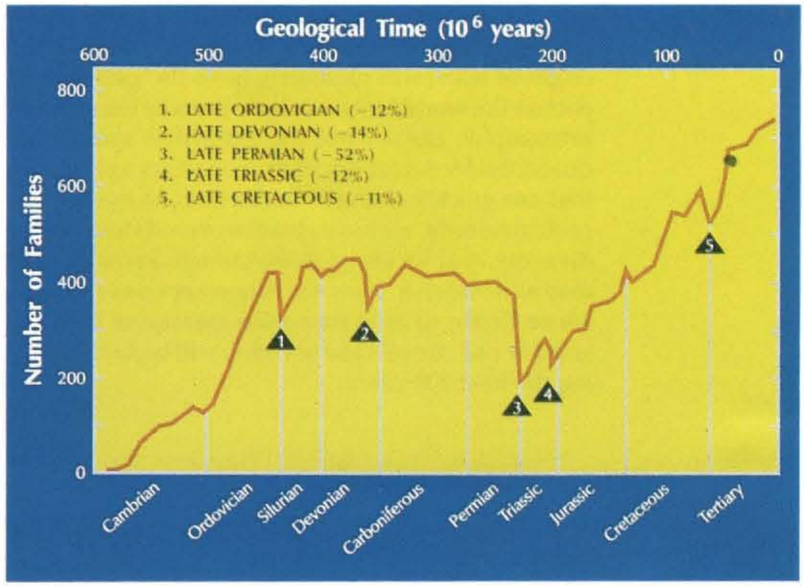
Whatever that prime cause of the mass extinction, without doubt some groups were affected more drastically than others. In the Cretaceous paroxysm, dinosaurs were hard hit, as were cephalopods, sponges, and a few other marine groups. In contrast, foraminifera, some insect groups, and flowering plants endured little loss (McKinney 1987, Whalley 1987, Wilson 1987b). McKinney has provided evidence that the groups most vulnerable to extinction during the five major episodes also suffered the highest background extinction rates during the periods in between. In other words, the environmental changes merely intensified the ordinary pattern of differential selection. However, even if this proves to have been generally the case, many major groups of organisms became *entirely* extinct while others survived with at least a few resistant species. The survivors were destined in many cases to spawn new adaptive radiations. In this way the great extinction spasms have had a major impact on evolution throughout the history of life.

The Future

Virtually all students of the extinction process agree that biological diversity is in the midst of its sixth great crisis, this time precipitated entirely by Man. The chief damage is due to the clearing of tropical forests, now proceeding at the rate of about 1 per cent of the total cover per year. The basis of this statement is not the direct observation of extinction in the threatened forests. To witness the death of the last member of a parrot or orchid species is a near impossibility. With the exception of the showiest birds, mammals, or flowering plants, biologists are reluctant to say with finality when a species has finally come to an end. Instead, extinction rates are usually estimated from principles of island biogeography: the areas of surviving habitats are related to the numbers of surviving species and the rate at which diversity is most likely to decline (Nitecki 1984, Soule 1986). Using calculations of this kind, Simberloff (1984) has projected ultimate losses due to the destruction of rain forests in the New World tropical mainland. If present levels of forest removal continue, he believes, the stage will be set within a century for the inevitable loss of 12 per cent of the 704 bird species in the Amazon Basin and 15 per cent of the 92,000 plant species in South and Central America.

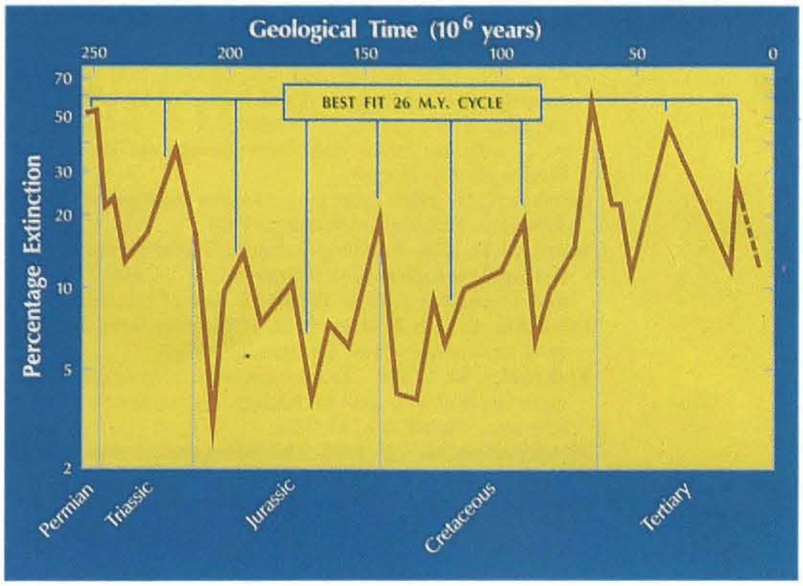
As severe as these regional losses are, they are far from the worst, because the Amazon and Orinoco Basins contain the largest continuous rain-forest tracts in the world. Less continuous tracts, which often harbor species found nowhere else, are far more threatened. An extreme example is the Pacific Coast forest of Ecuador. This habitat was largely undisturbed until after 1960, when a newly constructed road network led to the swift incursion of settlers and clear-cutting of most of the area. Now only patches remain, such as the 0.8-square-kilometer tract at the Río Palenque Biological Station. This tiny reserve contains 1,033 plant species, perhaps a fourth of which are known only from coastal Ecuador. Many are currently known only from a single living individual (Gentry 1982).

In general, the tropical world is clearly headed toward an extreme reduction and fragmentation of tropical forests, which will be accompanied by a massive extinction of species (Myers 1984, Raven 1980). Now less than 5 per cent of the forests are protected within parks and reserves, and even these are vulnerable to political and economic pressures: 4 per cent in Africa, 2 per cent in Latin America, and 6 per cent in Asia. In a simple system envisioned by the basic models of island biogeography, the number of species of all kinds of organisms can be expected to be reduced by at least half unless the destruction is slowed and halted. In other words, we will probably lose hundreds of thousands or even millions of species. Already, both the per-species rate and the absolute loss in number of species due to the current destruction of tropical forests (setting aside for the moment extinction due to the disturbance of other habitats) is likely about one to 10,000 times that prior to human intervention (Wilson 1987c).



MASS EXTINCTIONS

Figure 9. **The standing diversity through geological time of marine vertebrates and invertebrates. Clearly illustrated in these estimates are the rise of diversity to the Paleozoic plateau, the rise to the maximum just before historical times, and the five great extinction episodes, of which the late Permian (number 3) was the most severe. [source: Raup, D. M. & Sepkoski, J. J. Jr. 1982. Mass extinctions in the marine fossil record.** ***Science*** **215:1501–1503]**



EXTINCTION RECORD

Figure 10. **Extinction rates in species of marine organisms during the past 250 million years have apparently been periodic, with the average time between peaks being 26 million years. [source: Raup, D. M. & Sepkoski, J. J. Jr. 1984. Periodicity of extinctions in the geologic past.** ***Proceedings of the National Academy of Sciences, U.S.A.*** **81:801–805]**

I began this exposition with an account of the four great steps in evolution. The fourth of these, the origin of Man, will ultimately have the greatest impact on the world biota. We have become the greatest catastrophic agent since the extinction spasm that closed the Mesozoic Era 65 million years ago. But all that can quickly change. In less than an eyeblink of geological time, we have also discovered the origin of diversity, and we also possess enough knowledge to save and enrich it. How the human species will treat life on Earth, so as to shape this greatest of legacies, good or bad, for all time to come, will be settled during the next 100 years.

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Questions & Answers

***Question:** Please comment on how aware you think the political leaders of the world are, concerning the problem you have described.*

Wilson: About 10 years ago, hardly any except in a few countries like Costa Rica. I used to say that the president of Costa Rica should get the Nobel Peace Prize because of the dedication of that country to conservation and its enlightenment. And it is kind of ironic that Arias was given the Nobel Peace Prize for an entirely different reason. Anyway, almost zero 10 years ago, but I think it is rapidly increasing. I cannot name names and cite figures except for Prime Minister Gandhi of India—I know he is an activist. But I know that awareness among many influential political leaders and journalists and intellectuals in Third World countries is rising. In Brazil there is now a reasonably viable, politically active, conservation movement in reference to the remaining forest. And in the Western European countries there are movements that are going to exert quite an influence in the tropics. And in the Soviet Union very recently there has been a much greater awareness of the problems.

And finally we are getting focused on what I consider to be the problem, which is species extinction. I mean that is the one that is irreversible. It is one thing to talk about environmental pollution around São Paulo or the degradation of soils in Rondônia and so on—and those are serious problems that deserve a lot of attention by us and by these countries with whom we collaborate in research and assistance. But a very strong focus needs to be put on species extinction. The conservation effort should be devoted with maximum efficiency to hold onto that biological diversity pool. And as I pointed out, a species lasts on the average of 1 million to 10 million years. These are ancient entities. To hold onto that we pass through this bottleneck of the next century. One of our speakers pointed out—I guess more than one today—that the 21st century is going to be a time of global coherence and unity and a coming to terms with the global environment and the population and the like. And it would be a dreadful thing if 100 years from now our descendants, having made it through that bottleneck, woke up to find that it had lost half or more of its species diversity. That would be something for which I think they would never forgive us.

***Question:** Over a 25-year period in West Africa I have seen equatorial high forest, 70 feet high with self-sustaining agriculture in it, with good diversity so far as one can judge. I have seen that destroyed by overpopulation, producing a savanna succession so that you go there today and there are no trees left. And you have a permanent savanna with laterization of the soils and high temperatures and really, in a sense, permanent destruction. So I am very sensitive to these changes although unaware of the details of effects on biota. But what then do you say to agriculturalists who describe the deforestation of Western Europe and the rise of highly productive agriculture there and who cynically—and I disagree with this point of view, by the way—argue that we are holding the custodians of the tropical forest to higher standards for forest preservation than West European countries did in the past, say since Roman times.*

Wilson: Yes, who are we to tell them to save their biological diversity at the cost of not converting more forestland to more agricultural fields for the production of more food? Well, we did our damage before we knew any better, to start with. And moreover we lucked out because our soils are deep humus-bearing soils in which a very large percentage of the organic matter is at all times invested in leaf litter or in humans. Moreover, a large percentage of our flowering plants and the insects and the other animals with them are accustomed to deforestation to some extent or at least preadapted to it. Their seeds are long-lived. They do not need to be germinated quickly. Thus we have clear-cut a large part of North America and Europe, of course: but it can be grown back and has been grown back, moreover. We have so few species, relatively speaking—for example, only 700 species of trees in all of North America—that it is very difficult, even with 90 per cent of clear-cutting, to eliminate more than a small number. And thus you can reseed most of that diversity back in, at least at the species level.

In the tropics the situation is radically different. Two thirds of the soils are underlain by the so-called lateritic or tropical red earths, tropical red and yellow earths. They are very peculiar because they bind the phosphorus; they allow the irons to be leached out at a rapid rate. And moreover the tropical forests are distinctive in that most of their organic material is locked up in living trees at all times. The characteristic of the tropical forest is that as soon as a tree falls, or a branch falls, or leaves fall to the earth they are, in relative terms, gobbled up by termites and fungi; and much of the surface of the tropical forest ground is bare, or in very thin litter. These trees, in fact, are living on desertic soils, barren, nutrient-poor soils, by virtue of delicate symbiotic associations with fungi. Many of these fungi species are specific to particular tree species among these thousands upon thousands of plants. They exist in a very delicate situation among the roots.

Incidentally, most of the fungal fauna and flora of the world is unexplored. So that when the trees are cut and burned as typically occurs in tropical forest clearing—and especially if it is done over a wide area, not just the local slash-and-burn method of more primitive agriculture—the organic material enriches the soil for about two or three years and then it is washed away and is gone, for we do not know how many centuries. And that is what is happening in these tropical countries. They go through, they clear-cut, they get a yield for two or three years, and then it is over. The solution to the problems in the Third World—never mind the example we may or may not have set for them—is not immediate agricultural yield. The optimum solution is not to cut the remaining forest to get that little bit more yield, but to go to other areas of those countries. These are already under cultivation and they offer promise for long-term sustained yield. For example, in Brazil over much of the south where the cutting has already occurred and where there is richer, more sustainable-yield soil, agriculture should be greatly improved. The forest should be left alone for the watershed, for the immense biological diversity which we have scarcely begun to explore and utilize. And thus to maintain a kind of biological balance within the country.

Question: *You mention and we often hear about these poor soils that underlie the tropical forests in developing countries. Taking a view in geological time, those forests got started somehow. I know it is a very long-term thing in cold comfort, but Dan Jansen in Costa Rica is experimenting with the reconstitution of the tropical dry forest and he argues that with persistence this can actually be done in a historic period. It can even be done in perhaps a generation or two. That may be very optimistic, but recognizing that we are not being very persuasive in getting developing countries to stop cutting them down, what is the outlook for restoration ecology?*

Wilson: I realize that I may, in my enthusiasm, have left too dark a picture. I did not bring up the possibility of restoration ecology. And Dan Jansen's project in the dry forest in Costa Rica is an example to follow. I do not know the geology of that region, the ecology of the region. My impression is that that forest is on land that makes regeneration much more practicable than in tropical moist forests. And that will be true in many parts of the tropics but it may not be true in considerably more than half of the land area. I do not know very much about the history of these soils but my understanding is that the red and yellow soils are the ones least promising for regeneration and tend to be the ancient soil, the ancient weathered soil. But we certainly ought to be considering restoration of tropical forests where it can be done. And in many areas sometimes there will be local, perhaps riverine areas or valleys, with particular contours and accumulations of peculiar forms of soil or denser than usual layers of humus and the like, where restoration might be inaugurated. I think then that in addition to bringing as much of the deforestation as possible to a halt, we should undertake restoration and begin rebuilding some of it.

Question: *As we talk I think of an organization that has approached an admittedly much more limited problem, the International Whaling Commission. And the International Whaling Commission has been criticized and sneered at and editorialized about because of its weaknesses, its wishy-washiness, but this was based upon the fact that they never came to an absolute confrontation. There was always a way out and a time for more negotiation. And I think over the last 40 years this is beginning to pay off. Perhaps this is a philosophy to be thought about regarding the rain forests: an International Rain Forest Commission in which people would talk and negotiate and perhaps reduce the amount of clear-cutting by 20 per cent in a year, or something like that. Looking back at the Whaling Commission, it has done well.*

Wilson: Yes, that is an encouraging example. There are a lot of technologies already available to us that would allow us to cut down drastically on lumbering and clear-cutting right now. Just to mention a few, there is the remarkable tree-grass technology which is to use trees that are extremely fast-growing, sometimes a couple of feet in a year; some of them are nitrogen-fixing and they can be put onto soils that are depleted where the original flora could not possibly grow. They also can be cut by gigantic mowers down to the base, like grass. And then harvested for pulp and fiber. Then there is no replanting; they just grow up again. That technology is at a very early stage of development that would allow many tropical countries to get huge quantities of woody vegetable material for gasohol, or whatever, and take the pressure off the forests there.

Another technique is contour-strip lumbering, which is to cut the tropical forests but to cut them in strips along the contour of appropriate width which has been determined by earlier studies. It is not as cost-effective as clear-cutting but it is already cost-effective in some circumstances anyway. And that allows regeneration because if you cut the forest in strips and follow the contours, then humus tends to wash down from the upper contours into the stripped area and the seeds can regenerate in time to get a new forest developed.

There are many other very simple, straightforward techniques. I know experiments are going on in the western Amazon, in areas intermediate in soil stability and richness, that suggest that with some fertilization you can maintain forest areas that have already been cut over, and get sustained yield out of them possibly in a cost-effective way.

In addition, ways have been suggested of taking the financial pressure off Third World countries, and at least one has been implemented. The one that has been implemented, by a complex trading of credits and debt units, picks up part of the foreign debt of Third World countries at a considerable discount. And many of the lending agencies and major banks are willing to do this at the present time, at perhaps 30 cents on the dollar, using this to buy credits through long-term incremental banking institutions in the country itself, getting matching money from outside, and using those credits to buy land for conservation purposes. That has been put into effect now on a small scale, but large enough to indicate that it has been a promising model in Brazil and Costa Rica. I think if world opinion were to grow strong enough in favor of halting the destruction of tropical forests, and since, after all, these do not cover very much of the land anymore in these tropical countries, that one could pretty well halt the destruction of tropical forests and in a way that actually might come out on the plus side economically for these Third World countries.

Question: *About two years ago you wrote an article, I think it was in* Bioscience Magazine, *called "The Biodiversity Crisis." In that article you called for an all-out effort to build up the discipline of taxonomy and to make the cataloguing of life a premier effort for looking at biological diversity and trying to conserve it. I wonder, in view of the fact that the resources available for conservation in developing countries are so minuscule and so thinly spread, if that is an effort that might divert scarce resources from broader attempts at conservation and ecosystem study.*

Wilson: I am very much in favor of a world biotic survey. I think it is past time that we revived systematics, using modern techniques of course, molecular techniques, techniques in cladism, and so on; but using those only as tools and going back to primary-purpose systematics, which is to describe and map the biotic diversity of the world. This is a task that we are only a small way through. We have to do it because if you do not have a data base and if you do not have the experts out there on each group of organisms in turn to serve as stewards to bring the knowledge of that group or the research of that group into the mainstream of science and to represent that group of organisms in the councils of conservation and government and the like, then you are flying blind. It is incredible to me that one could hope to do effective ecosystem surveys or call the shots with anywhere near optimum efficiency on recommending conservation measures—where to save environments, how much, and the like—without that fundamental knowledge. That is the most cost-efficient mode of research I know. It is labor intensive, and requires relatively little instrumentation. And the reason that it is not being prosecuted now to any significant extent is that it has gone completely out of fashion.

I think that we needed some kind of a jolt like the one I have been talking about to show the relevance of mapping world diversity to human welfare. And I think once we understand that fully, we will get going on a world biotic survey and find that it is quite cheap to do out of this country, out of the Soviet Union, out of Western Europe, if you will, compared with the big science projects already well advanced. I do not know the exact figures at the moment but I think we are putting somewhere between $3 billion and $4 billion at the present time into health-related research in this country. I do not know the exact amount being put into tropical biology but I think that it is about $100 million a year. And that includes all aspects: ecology, behavior, systematics, and the like. If this country were able to shift just a little bit of its funds into a world biotic survey—I am speaking now on the order of tens of millions to undertake this great enterprise—it would still be a drop in the bucket compared with most major big-science efforts under way. I think it would be far more beneficial for humanity than most of those and it would have very considerable returns to scale. That is, each absolute increment in funding would represent a very large percentage increase with reference to what is being supported before. Because it is cost-effective, not requiring (at this time, anyway) major instrumentation, it would pay off.

And then in the Third World countries—most Third World countries are very ambitious scientifically, as they should be—we are going to see rapid advances, particularly in those that are becoming industrialized by direct technology transfer. But in many areas of basic research they will never catch up until they have gone through quite an enormous per-capita income growth. They cannot afford the space stations and the advanced scanning electron microscopes and so on that require the day-to-day research. But one thing they *can* do, and they can do with excellence, is the systematic and ecological survey work that is so badly needed. Those surveys would be labor-intensive—and they, after all, have that resource. We do not have that, but they have it right there in their backyard. Once that gets a bit more prestige, as I think it should just from human necessity, then I believe that many Third World countries with a little bit of aid from the developed countries could mount this scientific effort without subtracting significantly from their other needed scientific and technological enterprises.