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ABSTRACT

Concerns associated with biological diversity and the extinction of species are addressed in this report. Major topic areas examined include: (1) historical records of extinctions; (2) conservation biology and tropical ecology; (3) human-management regeneration potentials; (4) restoration ecology; (5) experimental restoration efforts; (6) governmental programs and policies; (7) global environmental priorities; and (8) the need for environmental sustainability. Bibliographic notes are also provided. (ML)

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On the Brink of Extinction: Conserving the Diversity of Life

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When the Kumawa Mountains of Indonesian New Guinea were designated as a biological diversity reserve early in the eighties, no scientist had ever visited the area. The plants and animals of Kumawa's forests were completely unknown; even the elevation of the peaks remained unmeasured. But the government, which had decided to protect 20 percent of the forests of Irian Jaya state in biological sanctuaries, was anxious to open the island's other forests to logging to help pay interest on the country's $35 billion debt and to resettle families from the overpopulated islands of Java and Sumatra. If Kumawa's unique ecosystems were not protected, they would not long remain undisturbed.[1]

Biologists recommended protecting the Kumawa Mountains based on little more than guesswork. The mountains were remote; there was a good chance that in such isolation, plants and animals found nowhere else had evolved. When the park's boundaries were finally set and a survey was conducted in 1983, biologists' expectations were confirmed. Kumawa's unique diversity was saved by an educated guess. Ecologist Jared Diamond writes that "the reserve could not have been set aside at all unless a decision had been taken in the total absence of specific knowledge."[2]

The protection of the Kumawa Mountains was a minor victory in what has become a global battle for the biological future of the earth. Because of such pressures as acid rain and air pollution in industrial countries, and the indiscriminate destruction of tropical forest throughout much of the Third World, the forests and wetlands that support most of earth's nonhuman species are increasingly at risk. The capacity of natural habi-

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tats to sustain their myriad plants, animals, and microorganisms is today being eroded so rapidly that biologists warn we are on the brink of a "mass extinction."

Extinction is the eventual destiny of all species, but at most times in earth's history, widespread extinctions have been infrequent. The disappearance of a few species per million years constitutes what scientists call a "background" rate. When the rate of extinction more than doubles for many different groups of plants and animals at the same time, a mass extinction is under way; the usual rules that dictate biological survival have been suspended.

Peter Raven, Director of the Missouri Botanical Garden, estimates that the harvesting of forests and clearing of land are already causing the disappearance of several unique plant and animal species each day. As ecosystems are converted to farms and pasture in ill-planned development schemes in tropical countries, that rate is likely to reach several hundred extinctions per day in the next 20 to 30 years—millions of times higher than background levels. More species of earth's flora and fauna may disappear in our lifetime than were lost in the mass extinction that included the disappearance of the dinosaurs 65 million years ago.[3]

Loss of diversity has implications beyond the extinction of species. When local populations of plants or animals are wiped out, the genetic diversity within each species that provides the capacity to adapt to environmental changes is diminished. Eventually, entire species, whether California condors or rare tropical orchids, reach the brink of extinction. And as species disappear, the intricate links between species—their biological and behavioral associations—are sundered. Even ecosystem processes such as the cycling of water and nutrients that link each habitat to global chemical and geological processes can be affected. But the consequences of changes in diversity cannot be forecast because our knowledge of earth's biological fabric is uneven and incomplete.

The extent of our ignorance of biological diversity is imposing. From existing scientific surveys, we know that insects and plants together account for four out of five species identified so far. (See Table 1.)

Table 1: Known and Estimated Diversity of Life on Earth

Form of Life	Known Species	Estimated Total Species
Insects and other arthropods	874,161	30 million insect species, extrapolated from surveys in forest canopy in Panama; most believed unique to tropical forests.
Higher Plants	248,400	Estimates of total plant species range from 275,000 to as many as 400,000; at least 10-15 percent of all plants are believed undiscovered.
Invertebrates[1]	116,873	True invertebrate species may number in the millions; nematodes, eelworms, and roundworms each may comprise more than 1 million species.
Lower Plants[2]	73,900	Not available.
Microorganisms	36,600	Not available.
Fish	19,056	21,000, assuming that 10 percent of fish remain undiscovered; the Amazon and Orinoco rivers alone may account for 2,000 additional species.
Birds	9,040	Known species probably account for 98 percent of all birds.
Reptiles and Amphibians	8,962	Known species of reptiles, amphibians, and mammals probably comprise over 95 percent of total diversity.
Mammals	4,000	
Total	1,390,992	10 million species considered a conservative estimate; if insect estimates are accurate the total exceeds 30 million.

[1]Excludes arthropods, includes 1,273 miscellaneous chordates.
[2]Fungi and algae.

Sources: Edward O. Wilson, Museum of Comparative Zoology, Harvard University, Cambridge, Mass., private communications, February 22, March 19, and March 20, 1987; Peter H. Raven, "The Significance of Biological Diversity" (unpublished), Missouri Botanical Garden, St. Louis, Mo., 1987; insect figures from Terry Erwin, National Museum of Natural History, Smithsonian Institution, Washington, D.C., private communication, February 13, 1987.

Mammals, including humans, comprise just three-tenths of 1 percent of all known organisms. All vertebrates together account for less than 3 percent.

Until just a few years ago, biologists believed that earth sustained 3 to 5 million species of all living organisms. Currently, studies in tropical forests suggest that there may be 30 *million* kinds of insects alone—or 34 undiscovered insects for every one known today. Ten to 40 percent of all flowering plants and 10 percent of the fish have yet to be discovered and described.

Faced with such vast uncertainty, compiling a thorough inventory of life on earth is not of interest solely to specialists hunched over beetle collections in dusty laboratories. Biologist Edward O. Wilson of Harvard University argues that "the magnitude and control of biological diversity is not just a central problem of evolutionary biology; it is one of the key problems of science as a whole."[4]

Many of the species at risk in a mass extinction are completely unknown—their biological importance a mystery and their potential value to society an open question. The causes of extinction, however, are more straightforward. Conspicuous species, like Africa's black rhino, may be driven to extinction by overhunting. Even more numerous, however, are extinctions that are the unintended result of human activities. One isolated ridgetop in the Andean foothills of western Ecuador, only 20 square kilometers in size, lost as many as 90 unique plant species when the last of its forest was cleared to plant subsistence crops. Such unintentional extinctions are by far the rule, not the exception.[5]

As intact ecosystems are isolated from one another, the risk to remaining species increases. When sea levels rose as the glaciers melted at the end of the ice ages about 10,000 years ago, for instance, areas that had once been linked to the continents were cut off by rising waters. Studies of these "land bridge islands" have shown that when a chunk of once-contiguous ecosystem is isolated or fragmented, some of its plants and animals die out in a process scientists call "faunal collapse." The number of species lost depends in part on the area of remaining habitat. Today faunal collapse is occurring in regions far removed from rising

"Many of the species at risk are completely unknown—their biological importance a mystery and their potential value to society an open question."

seas. Farming, grazing, and road-building in formerly remote areas like the vast Amazon Basin are turning continuous ecosystems into islands amid a sea of annual crops, pastures, and degraded lands. The biological consequences are as irrevocable as floodwaters; plant and animal species are confined to an island world, and the inevitable extinctions have only begun.[6]

The regional and global consequences of human activities may undermine the ability of natural ecosystems to recover from this fragmentation. Air and water pollution can poison species and hinder their reproduction. The global warming trend expected to result from rising atmospheric carbon dioxide levels will alter the distribution of plants and the animals that depend on them. A depletion of stratospheric ozone, induced by the use of chlorofluorocarbons in industrial countries, could permit enough damaging ultraviolet light to reach earth's surface to damage plant leaves and cause skin cancers and immune system problems among animals and humans alike. The cumulative effects of such changes can alter ecosystems in ways that increase the vulnerability of plant and animal species to extinction. Scientists call the process "biotic impoverishment"—a series of changes that leave soils less fertile and vegetation less productive, favor outbreaks of pests and diseases, and require costly adjustments from humans trying to raise food in the midst of a biologically depleted landscape.[7]

Conservation of biological diversity has long been seen as a matter of creating parks and reserves free from human interference. Today, 425 million hectares of land in some 3,500 areas worldwide enjoy various degrees of protection. UNESCO's Man and the Biosphere Program administers a global network of 252 "Biosphere Reserves" in 66 countries. Sites are chosen to protect an intact example of each of earth's ecological zones, called biogeographic provinces, and to reconcile their preservation with the economic needs of surrounding communities.[8]

But designating parks—a static solution to a dynamic problem—is not itself enough to avert a mass extinction. Perhaps as much as 1.3 billion hectares would have to be set aside to conserve representative samples of all the earth's ecosystems. In addition to preserving land, more scientific investigations of unprotected areas must be undertaken to find out what species remain at risk. Degraded lands should be rehabilitated in an effort to reconstitute the diversity they have lost. An innovative strategy, encompassing both preservation and active management of species and ecosystems, will be needed to counter biotic impoverishment. The research that can underpin this strategy is still in its infancy.[9]

A Biologically Depleted World

Plant and animal species have arisen and disappeared throughout life's 3.5-billion-year history, but fossil evidence attests that occasionally numerous species of many kinds of animals have disappeared simultaneously. Apparently the conditions for life have repeatedly become hostile. Whole suites of organisms, from trilobites to dinosaurs, exited the evolutionary stage long before human activities began to reshape the earth's surface.

Yet scientists are only beginning to apply the lessons of the evolutionary past to the present crisis. By comparing past mass extinctions with the current threat to diversity, we may be able to widen our options in responding to it. Estimates of the magnitude of current extinctions provide a point of departure.

British environmental consultant Norman Myers pioneered a method to relate deforestation and habitat destruction to species diversity in order to estimate contemporary extinctions. Myers begins with the conservative estimate that 5 million species of all kinds of organisms live on earth. Existing inventories suggest that two-thirds of all species (3.3 million) live in the tropics, and in turn two-thirds of these are unique to tropical forests. Rounding the figures, Myers estimates that at least 2 million species live in the rich mosaic of tropical forests that cover just 7 percent of earth's land area.[10]

A survey of estimates of the rate at which tropical forests are being cleared leads Myers to conclude that "by the end of the century we can expect that somewhere between one-third and one-half of all our remaining tropical moist forests will be so grossly disturbed or depleted as to have lost much of their capacity to support their current

"One million species—out of a total of 5 million—are at risk of extinction by the end of this century."

huge array of species."[11] Linking the known abundance of species to these rates, Myers estimates that two-thirds to three-quarters of a million species are at risk in tropical forests alone. Pressures on other species-rich habitats such as coral reefs and wetlands raise the ante: One million species—out of a total of 5 million—are at risk of extinction by the end of this century. The loss of one-fifth of earth's diversity, already under way, is only the leading edge of a far larger contraction if the clearing of tropical forests accelerates.

Myers' admittedly rough calculation has been challenged on many counts. Uncertainties plague estimates of total species richness, the distribution of diversity, and rates of forest clearing. Some critics use these uncertainties to dismiss warnings about widespread extinction.[12] In response, biologists have begun to construct more precise estimates combining data on known species with ecological theories that relate species diversity to the area of available habitat. The results support Myers' basic conclusion.

Ecologists agree that there is a direct relationship between the area of a natural habitat and the number of species it can sustain. The short mathematical equation that describes this species-area relationship is a key concept of "the equilibrium theory of island biogeography." This theory, based originally on species changes observed on islands, is being tested in many different ecosystems. From their investigations, scientists have confirmed that reducing habitat size increases species' risk of extinction.[13]

Although each ecosystem has a characteristic complement of species, within any ecosystem—a forest, for example—more plant and animal species will be found in 100 hectares than in 10 hectares. The same relationship holds on islands, with small islands containing fewer species than large islands. But an island the size of Puerto Rico holds fewer species than a patch of forest the size of Puerto Rico in the Amazon Basin. As the Amazon forest is reduced to isolated fragments by farmers and ranchers, the effect is the same as if the surrounding land were flooded. The fragments gradually lose species until a new biological equilibrium is reached.

Daniel Simberloff of Florida State University chose to apply the theory to plant and bird species in the Latin American tropics, since reasonably thorough lists of both have been compiled. His study combines the effects of a shrinkage in total forest area and the creation of islandlike patches of forest.

If Latin American forests contract to 52 percent of their original extent by the end of this century, as is consistent with current estimates of population growth and forest clearing, the species-area equation forecasts that 15 percent of the forest plant species—about 13,600 kinds of plants—will be lost before a new biological equilibrium is reached. (See Table 2.) If the worst case unfolds and only the intact stands of forest in established parks and protected areas remain, Simberloff predicts the eventual loss of 66 percent of the plant species in the Latin American tropics. The most likely scenario falls somewhere between these cases. Extending the analysis to the bird species in the Amazon Basin, Simberloff found that Amazon forest likely to remain just 13 years from now would support 12 percent fewer bird species, and ultimately nearly 70 percent of the Basin's birds could be lost as intact forest shrinks.[14]

Table 2: Projected Plant Extinctions in Latin American Rain Forests

	Estimate of Forest Area	Equilibrium Number of Species	Share of Species Lost
	(million hectares)		(percent)
Original Forest Area	693.0	92,128	—
End of Century	366.0	78,534	15
Worst Case[1]	9.7	31,662	66

[1]Assuming only areas currently designated as parks and reserves remain intact.

Source: Adapted from Daniel Simberloff, "Are We on the Verge of a Mass Extinction in Tropical Rain Forests?" in David K. Elliott, ed., *Dynamics of Extinction* (New York: John Wiley & Sons, 1986).

Such biological losses are not confined to the tropics. A number of studies confirm that the same biological rules apply in temperate latitudes as well. Some of the losses in industrial countries will be especially visible, since the species at risk are far more conspicuous.

In North America, for example, national parks considered the last refuge for some of the continent's most distinctive wildlife are proving inadequate to the task. Ecologist William Newmark surveyed the mammals in national parks and found an alarming percent of mammal species lost in all but the largest parks. (See Table 3.) Just like the fragments of forest in tropical latitudes, habitats in temperate zones may lose species even when they are protected from the direct pressures of hunting or poaching. Many parks are simply too small to

Table 3: Habitat Area and Loss of Large Animal Species in North American National Parks, Assessed in 1986

Park	Area	Share of Original Species Lost
	(square kilometers)	(percent)
Bryce Canyon	144	36
Lassen Volcano	426	43
Zion	588	36
Crater Lake	641	31
Mount Rainier	976	32
Rocky Mountain	1,049	31
Yosemite	2,083	25
Sequoia-Kings Canyon	3,389	23
Glacier-Waterton	4,627	7
Grand Teton-Yellowstone	10,328	4
Kootenay-Banff-Jasper-Yoho	20,736	0

Source: Based on William D. Newmark, "A Land-Bridge Island Perspective on Mammalian Extinctions in Western North American Parks," *Nature*, January 29, 1987.

maintain populations large enough to ensure species survival. Although large predators like grizzly bears have proved most vulnerable to extinction, even foxes and jackrabbits have disappeared from some parks. As ecological theory predicts, the smallest parks have lost the greatest share of their original mammal species, but even very large parks such as Rocky Mountain and Yosemite have already lost between a quarter and a third of their native mammals.[15]

The loss of native mammals in national parks occurred so slowly that local extinctions went unnoticed by park rangers. It is not clear how long species loss will continue, or to what extent smaller and less conspicuous bird and plant species will eventually be affected. According to Newmark, "The big question now is how many species can we expect to disappear and what is the time period."[16]

Although faunal collapse has begun, the species at risk are not numerous enough in the temperate zones and the process not far enough advanced in Latin American forests to merit the label "mass extinction" quite yet. For some large areas in the tropics that are still in the early stages of development or exploitation, such as large parts of the Amazon or Zaire basins, time remains in which to document species diversity and map out detailed conservation strategies.

The projected loss of two-thirds of Latin America's plants or the birds of Amazonia, however, is comparable to the extinctions revealed in the fossil record. And Latin American forests, particularly those in the Amazon Basin, have so far sustained much less pressure and exploitation than those of Asia or Africa. Parts of Central America, Southeast Asia, and West Africa have already reached the point at which 10 percent or less of their original forests remain—thousands of native species of insects, plants, and animals have undoubtedly been lost, and tens of thousands more are immediately at risk.[17]

Simberloff's model and Newmark's study of faunal collapse support Myers' exploratory estimates. Simberloff concludes, "Myers was remarkably close to the mark. The imminent catastrophe in tropical forests *is* commensurate with all the great mass extinctions except for that at the end of the Permian."[18]

"Idiosyncracies of the fossil record make comparisons with the present provisional and incomplete."

The Permian extinction, 250 million years ago, is one of a series of prehistoric events that has been exhaustively studied by paleontologists, scientists who comb the fossil record for its lessons. The cause of prehistoric extinctions has proved one of the liveliest and most controversial topics in biology in recent years. Until recently, study of the fossil evidence contributed little to our understanding of the biological changes the earth faces today. But interest in mass extinctions, past, present, and future, has begun to draw paleontologists into the dialogue.[19]

Idiosyncracies of the fossil record make comparisons with the present provisional and incomplete. A time span of roughly 600 million years was recorded imperfectly in the rocks as seas advanced and receded, mountains rose and eroded once again to plains. Our picture of the history of life is really a mosaic of earth's fauna and flora at times and places that favored the formation of fossils.

The lessons of the past are clearest on the seafloor; hard-shelled marine organisms have left the best continuous record. One of the most complete long-term records of changes in marine life was assembled by evolutionary biologists John Sepkoski and David Raup. They analyzed the fossil remains of marine animals preserved in 82 adjacent sedimentary layers to construct a large-scale picture of evolutionary changes spanning 270 million years.[20]

Sepkoski and Raup's study of marine fossils reveals eight extinction episodes that stand out against the slow pace of background extinctions; five were unusually wide-ranging. They have argued that widespread extinctions seem to recur at regular intervals of 26 million years. Unfortunately, although scientists have searched for an event that could cause extinctions to recur like clockwork, no one has yet produced a conclusive explanation.[21]

Scientists have proposed a variety of causes to account for abrupt changes in the character and diversity of life at the end of the Permian period and in other "extinction spasms." Some say falling sea levels caused the marine extinctions. Others emphasize the changes in global temperature caused by climate shifts. The advance of glaciers seems to have had a more disastrous effect on biological diversity than their retreat when the earth warmed up.[22]

16 At the end of a geological age known as the Cretaceous Period about 65 million years ago, dinosaurs and a variety of other organisms disappeared in a complex episode of extinctions. Some scientists argue that an asteroid struck the earth, lofting a worldwide layer of dust and smoke that blocked sunshine and temporarily disrupted life-support systems. Discovery of a rare form of iridium, a mineral more common in meteorites than on earth, in sediments deposited at about the time dinosaurs became extinct supports this claim. This extraterrestrial-impact hypothesis has generated lively controversy among scientists and aroused the curiosity of the public.[23]

An alternative explanation proposed to account for the disappearance of the dinosaurs holds more ominous implications. Writing in the journal *Nature*, Charles B. Officer and his coauthors argue that a period of intense worldwide volcanic activity coincided with the late Cretaceous extinctions. They contend that "volatile emissions from this volcanism would lead to acid rain, reduction in the alkalinity and pH of the surface ocean, global atmospheric temperature changes, and ozone layer depletion." They suggest that these environmental effects, acting in tandem, best account for the pattern and timing of extinctions. This scenario is remarkably similar to the "biotic impoverishment" driven by human activities today.[24]

There is no simple way to compare the rates and magnitude of extinctions in prospect with those of the distant past. Most of the evidence about past extinctions concerns collections of related species called families; the gaps and inconsistencies in the fossil record make it easier to analyze patterns of extinction at the family level. Because families persist when some of their constituent species are wiped out, family-level extinctions typically understate species losses. The Permian extinction, for example, in which 52 percent of marine families disappeared, may have involved the demise of as many as 96 percent of all marine species. Simberloff has estimated that the prospective extinction of 66 percent of Latin America's plants or 69 percent of the birds of the Amazon Basin would correspond to a loss of 14 percent of plant families and 26 percent of bird families for those regions. By contrast, the late Cretaceous extinction involved 11 percent of marine animal families, 57 percent of reptile families, and 32 percent of the mammal families then extant. The magnitude of impending extinctions clearly falls within the range of prehistoric extinctions.[25]

All mass extinctions suspend the Darwinian rules that prevail at other times. The fittest no longer survive; the weak and obscure are as likely to prevail as the strong and abundant. David Jablonski of the University of Chicago suggests that "the victims of mass extinction . . . might easily include groups that were dominant during normal times, whereas survivors might include groups normally vulnerable to extinction."[26]

Extinction's survivors, the record shows, tend to be ecological opportunists. They reproduce quickly, eat indiscriminately, and tolerate a wide range of conditions—characteristics we associate with pests. Plankton that bloom uncontrolled after a marine extinction, birds like house sparrows and starlings, and the rats, cockroaches, and weedy plants that flourish in disturbed environments all suppress the recovery of diversity by their prolific reproduction and intense competition for resources. Myers writes, "It is possible, even probable, that within 50 years, when many current species disappear and their places begin to be taken by others, we will have a disproportionate number of species we would characterize as 'pest' or weed species. That is the kind of biological world our children are going to have to contend with."[27]

The study of mass extinctions points again and again to the special role the tropics have played throughout the history of life. The fossil record shows that tropical species have been disproportionately vulnerable to extinction, but the region has also been a reservoir from which diversity is reconstituted. When climate altered during the great eras of glaciation, for example, plant species retreated into pockets of diversity in a few areas of the tropics, from which they spread once again when the ice sheets retreated. Some scientists believe that these "Pleistocene refuges," which even today contain unusually diverse collections of species, then held the species that recolonized the tropics when climates became warmer and wetter.[28]

Whatever resilience the tropics formerly possessed will likely be surpassed by the changes now unfolding in earth's most species-rich regions. Tropical ecosystems today face pressures of many dimensions, including climate change, clearing by farmers and loggers, and the biological consequences of isolation and fragmentation. The distinctive collections of species in some areas cannot remain intact much longer.

Just as tropical environments have played a unique role in the course of evolution, tropical studies are critical to our understanding of how evolution unfolds. Theories of how flowering plants evolved, for example, are based in part on botanical studies in today's tropical forests.[29] Rapid destruction of these threatened ecosystems is hindering our comprehension of the past at the same time it undermines our biological future. Extinctions will accelerate unless the fate of the tropics becomes a global concern.

Exploring Terra Incognita

Charles Darwin knew nothing about rain forests when he sailed out of Devonport, England, aboard HMS *Beagle* in 1831. The four-year voyage, though it included the visit to the Galapagos Islands that catalyzed Darwin's thinking about evolution, skirted some of earth's greatest theaters of natural selection. But when Darwin and his shipmates travelled briefly into a Latin American rain forest from their coastal moorings, the biological richness left a lasting impression. Near Bahia, Brazil, Darwin wrote: "Delight . . . is a weak term to express the feelings of a naturalist who, for the first time, has wandered by himself into a Brazilian forest. The elegance of the grasses, the novelty of the parasitical plants, the beauty of the flowers, the glossy green of the foliage, but above all the general luxuriance of the vegetation, filled me with admiration."[30]

Darwin's successors have done much to augment that awe with knowledge. Yet a century and a half after the *Beagle's* voyage, vast areas of ignorance remain. Only 500,000 of the 1.4 million identified species of plants, animals, and other organisms are native tropical species. Tropical ecosystems remain terra incognita, and correcting

"A hectare of Peruvian forest can yield 41,000 species of insects, more than a quarter of them beetles."

this ignorance is the necessary first step toward averting a human-induced mass extinction.[31]

Less than 10 percent of the Brazilian coastal forest that Darwin admired remains today. Barely 2 percent of the tropical dry forest that once cloaked the Pacific Coast from Central America to the Gulf of California still stands. In the Amazon and Zaire basins, coastal West Africa, Central America, and the archipelagos of Southeast Asia, closed tropical forests have already been cut back 28 percent from their original climatic range of 1.6 billion hectares, according to the U.N. Food and Agriculture Organization (FAO). Many biologists believe that these official statistics vastly understate the extent of forest clearing. And even FAO's numbers imply that by the end of the century, fewer than 1.1 billion hectares of intact forest will remain, and a great many tropical regions, including much of Central America, will be essentially treeless.[32]

Comprehensive efforts are needed to identify and describe tropical species in the natural environment that remains to them. From a purely numerical standpoint, this means more extensive cataloging of neglected lifeforms such as insects, invertebrates, and plants. The larger animals—mammals, amphibians, reptiles, birds, and fish—are better known and far less numerous. But even conspicuous animals can escape notice in poorly studied regions. A large species of peccary, a piglike mammal believed extinct for millennia, was discovered not long ago in the Chaco region of Paraguay and Argentina.[33]

Entomologist Terry Erwin, director of the Biological Diversity Program of the Smithsonian Institution, has devoted his career to studying the insects of Central America and the Amazon Basin. Because most forest insects live in the treetops, Erwin developed new techniques to sample and record the nearly inaccessible canopy life. The diversity he uncovered is astonishing. One hectare of Peruvian forest can yield 41,000 species of insects, more than a quarter of them beetles. In fact, studies of beetles in lowland tropical forests in Panama led Erwin to estimate that there may be as many as 30 million types of insects. Insect collections from the tangled canopy of the Tambopata Wildlife Reserve in the Peruvian Amazon reveal that tropical insects are often highly localized: Four out of five of the species collected live exclusively in a particular type of forest, and 13 percent are confined to one species of tree. It is this specialization that makes tropical insects so vulnerable to extinction.[34]

The Tambopata Reserve dramatizes both the stunning diversity and the vulnerability of many tropical parks. The 26-square-kilometer reserve encompasses seven distinct forest types, and is home to 528 species of birds, at least 1,122 kinds of butterflies, and rare animals including the jaguar, black caiman, and harpy eagle. Despite its location on a remote tributary of the Amazon, land clearing for pasture and farming approaches the boundary of the reserve. Yet Tambopata is not among the areas the Peruvian government protects against incursions.[35]

History's most ambitious biological census was conducted in 1985 on the Indonesian island of Sulawesi. The British Royal Entomological Society, in cooperation with the Indonesian Institute of Science, assembled 160 scientists from 17 countries to study and identify the insects in Dumoga-Bone National Park. Even the British Army was along to provide logistical support. The scientists of Project Wallace, as the effort was called, collected bugs from the canopy and forest floor throughout 1985, and devoted the following year to species identification and lab work.[36]

The forests of Dumoga-Bone act as a giant sponge controlling the water supply for a large rice irrigation project downstream. The park itself was created with the help of a World Bank loan in order to protect the watershed that feeds the irrigated fields. Although the Bank's primary concern was the stability of water supplies, Project Wallace revealed intricate ecological connections between farm and forest that could shape Sulawesi's agricultural future as decisively as water availability.

Green leafhoppers, for example, carry viruses that can decimate rice harvests. Since leafhoppers' natural habitat is treetops, scientists looked there to study their behavior and find natural predators. Biological controls based on these predators might keep the leafhoppers in check and sustain rice harvests without incurring the risks and costs of chemical pesticides.[37]

Other researchers examined the subtle interactions between insects and trees to establish the role insects play in forest regeneration. Successful reforestation with native species depends on harnessing this biological interdependence, but in most tree-planting projects, the role of insects in promoting regeneration is overlooked.[38]

To sample species diversity in the intricate lacework of tropical treetops, biologists have developed radically new research techniques. Erwin and his colleagues spray through the canopy a mist of pyrethrum, a biodegradable pesticide that knocks out insects without harming birds, mammals, or plants. The insects are collected on a tarpaulin as they fall to the ground. Once they are counted and identified, the percentage of new species is calculated. Scientists in Sulawesi used the same "bug bomb" technique to collect their samples. In the lowland rain forests of Costa Rica, biologist Donald Perry has adapted the slings and ropes used by mountaineers to allow him to move freely in the canopy itself. Fixed ropes strung between the giant trees are Perry's gateway to the aerial zone where most photosynthesis occurs and the vast majority of rain forest species live. Techniques that open tropical treetops to study for the first time are a scientific advance as dramatic as the use of scuba equipment to explore coral reefs, or submarines to probe the bizarre communities of the seafloor.[39]

As unknown species are discovered and named, and new findings flood the few journals devoted to tropical biology, scientists must piece observations together like a jigsaw puzzle to form a coherent picture of conservation priorities. Conservation biology, a discipline less than a decade old, has emerged to fill this role. This "science of scarcity and diversity" is an eclectic blend of genetics, ecology, and natural resource management designed to guide conservation decision-making. How should captive populations of an endangered primate like Brazil's golden lion tamarin be bred to retain genetic diversity and allow reintroduction to the wild? Where can nature reserves be sited on the island of New Guinea to maximize the conservation of biological diversity consistent with government development plans? What happens to forest birds and animals when cattle ranchers cut an irregular patchwork of pastures in the midst of once-continuous timber?[40]

Unlike most scientific fields, conservation biology rests on an explicit ethical principle: Biological diversity is valuable in itself, irrespective of economic or practical value. A corollary is that untimely extinction of populations or species is bad. The highest priority of conservation biology is to design and establish viable parks in the tropics, where options for preserving biological diversity are quickly being foreclosed.

Some pioneering projects in conservation biology are already reshaping scientists' ideas about extinction and its consequences. In the Amazon Basin near Manaus, Brazil, the World Wildlife Fund and Brazil's National Institute for Amazonian Research launched the "Minimum Critical Size of Ecosystems" project in 1979. Brazilian law requires that 50 percent of the land in new cattle ranches remains forested; researchers worked with local ranchers as they cleared grazing land to create a set of forest reserves ranging in size from 1 to 10,000 hectares. This huge experiment allows biologists to observe the process of extinction and species change when forest patches are isolated from once-continuous forest.

The Minimum Critical Size project will reveal for the first time the rates and patterns of species loss as the ecosystem approaches new equilibrium populations of plants and animals. Researchers refer to this loss of diversity as "ecosystem decay." Studies in the various reserves focus on two key questions: Are species lost in any predictable order? Will fragments of the same size end up with the same array of species? Measurable changes have already occurred in the smaller reserves; as observations from the large fragments begin to fill in the picture, the studies will help scientists and policymakers collaborate on the design and location of preserves that can best protect the Amazon's spectacular diversity.[41]

Although the Minimum Critical Size project is dramatic in scale and significance, results from the Amazon Basin may not be transferable to other areas in the tropics. Similar studies are needed in every type of habitat on every continent—a goal beyond the present capacity of the scientific community. Furthermore, project researchers face a dilemma that troubles all conservation biologists. Once the biological changes in the largest forest fragments have been analyzed to the

"Regeneration potential seems to depend on the scale of the disturbance; the smaller the disturbance, the quicker and more complete the recovery."

point that firm conclusions can be drawn, perhaps decades down the road, it may be too late to prevent comparable species losses in many areas.

Another vital knowledge gap is how tropical forests recover after human disturbance. What happens when pasture or cropland is abandoned? Can the recovery of forest be managed and accelerated? What species will return? In late 1984, the Royal Society in Britain established the South-East Asian Rain Forest Research Programme in Malaysian Borneo to answer these questions. In a conservation area bordered by commercial timber concessions in the Danum Valley, scientists are conducting a species census as they compare the recovery of lowland rain forest after natural tree falls with recovery from logging and other human clearing. In the forests of Southeast Asia, regeneration potential seems to depend on the scale of the disturbance; the smaller the disturbance, the quicker and more complete the recovery.[42]

If such studies are to influence conservation decisions throughout the tropics, they will have to be done on more than a piecemeal basis. The scientific community is beginning to recognize the need for large-scale, integrated studies of earth's life-support systems, and tropical biology offers a promising starting point for such programs. Edward O. Wilson proposes that the United States, the largest funder of tropical research, declare an "International Decade for the Study of Life on Earth" to focus scientific and financial resources on the pressing problems of biological diversity.[43] Though such a high-profile initiative has yet to take shape, an ambitious program, "Decade of the Tropics," now enjoys broad international support.

Decade of the Tropics was launched with little fanfare in 1982 by the International Union of Biological Sciences (IUBS), consisting of 47 national academies of science and 66 professional societies. Research began two years later. The program was prompted as much by the economic and social disparities that divide tropical and temperate countries as by the uncatalogued biological variety of the tropics. Much of the IUBS-sponsored research aims to develop ways to tap this biological abundance for the benefit of local populations without destabilizing tropical ecosystems.[44]

Since IUBS has no resources of its own to support a major research program, Decade of the Tropics research depends on collaboration among participants to share results from existing national research efforts. Separate studies of tropical savannas, soil biology and fertility, mountain environments, human adaptations to tropical conditions, and species diversity constitute the program. Project leaders in Australia, Zimbabwe, Venezuela, England, and the United States manage the contributions of dozens of participating scientists and research stations.

Such decentralized science contrasts with the "mission-oriented" research that led to the Green Revolution in Third World agriculture two decades ago. Unlike that work, which was an unusually successful but limited example of technology transfer from industrial to developing countries, the Decade of the Tropics research seeks to discover and unleash the productivity latent in tropical ecosystems. Green Revolution scientists combined new seeds, irrigation, and artificial fertilizer to coax up to 4 tons of grain from a hectare of tropical cropland, doubling previous yields; the Decade of the Tropics teams want to know how a hectare of leached soils, scorching sunshine, and seasonal rains can support 300 tons or more of tropical forest. Answers to that question could eventually help millions of Third World households that never shared in Green Revolution advances.

Despite new initiatives in conservation biology and tropical ecology, they remain the poor relatives of better-funded, more prestigious research fields. A Society for Conservation Biology has been established, departments are springing up at universities, and a new journal, *Conservation Biology*, charts research progress, but the field still remains outside the mainstream of science. The U.S. National Science Foundation, for example, has no program to fund work in conservation biology, which it considers an "applied" discipline, beyond the bounds of the "basic" research the Foundation's $1.6 billion budget supports.[45]

In 1980, tropical biology research worldwide received about $35 million, excluding work in applied areas of agriculture and forestry. With increasing attention to tropical environmental problems, biologist

Peter Raven of the Missouri Botanical Garden estimates that the total may have risen to the $50 to $75 million range by 1986.[46]

Unfortunately, there is no systematic way to monitor this spending. Tropical biology is a fragmented field, and researchers in a variety of disciplines receive funding through many different agencies and programs. Five programs within the National Science Foundation's Division of Biotic Systems and Resources encompass tropical studies, but only 15 to 18 percent of the $60 million Division budget—$9 to $11 million—funds tropical research. The Smithsonian Institution, which maintains a research station in Panama, spent $17 million on tropical activities in 1986. The National Academy of Sciences, which does not fund research directly but helps set the national scientific agenda, recently created a Program on Biodiversity that may give tropical studies the visibility needed to attract more generous support.[47]

One way to strengthen research in critical tropical areas is to use development aid funds to train Third World students in conservation biology and help pay for national parks, species inventories, and natural resource management. But in the United States, development aid for scientific research faces an uncertain future. Pressures to use foreign aid to promote political objectives, and budget constraints resulting from the federal deficit, have reduced science and technology programs in the U.S. Agency for International Development (AID) more than 22 percent over the last two years—a cut of $63 million. Even the budget for agricultural research, which enjoys widespread support, has been cut by 30 percent. According to AID Assistant Administrator for Science and Technology Nyle Brady, the projects that bear the brunt of these cutbacks "tend to deal more with the future." Unless Japan or the European Community steps in to offset shrinking U.S. support for overseas science, applied tropical studies could languish.[48]

Given the enormous significance of tropical studies in helping nations come to terms with an era of biological change, the question of how to attract sufficient resources is an important one. Stanford University biologist Paul Ehrlich proposes quadrupling the level of funding for research in ecology, taxonomy, and tropical studies through the

National Science Foundation. Even at this level—roughly $200 million per year— tropical biology would remain a modest national priority beside multibillion dollar programs in biomedical research.[49]

Tropical biology, the essential foundation for a response to the biological diversity crisis, is constrained by a legacy of neglect. The tropics and earth's biosphere face profound changes in the course of the next human lifetime. Research agendas and science budgets should reflect this challenge. Reweaving the fabric of biological diversity can scarcely begin as long as the strands remain uncounted and unknown.

Reweaving the Web of Life

On August 26, 1883, the Indonesian island of Krakatau exploded in the largest volcanic eruption ever recorded, devastating the island's ecosystems. Slopes once cloaked with verdant tropical forest were transformed into a sterile landscape buried in cinders and lava. But Krakatau's explosion was not the island's biological epitaph. The remnant island of Rakata now supports a surprising diversity of insects, birds, plants, and forest trees that have gradually recolonized the site. To outward appearances, Rakata's ecosystems are flourishing once more. Despite a century of recovery, however, only one tree species now found on the island is characteristic of mature rain forest. Scientists predict that "progression . . . to the taller, richer, primary forest could take another 100 years or much longer."[50]

As if to mark Krakatau's centennial, the largest forest fire in history coursed across East Kalimantan, Indonesia, in the spring of 1983. Drought, logging practices, and slash-and-burn farming combined to turn the usually fire-resistant rain forest into tinder. Ultimately, 3.5 million hectares of forest, an area nearly the size of Taiwan, were burned. Scientists are studying the plants, vines, and *Euphorbia* trees pushing up amid the charred trunks of the former forest to learn how the forest heals. As with Rakata, a diverse ecosystem will return, but the process will take centuries.[51]

"In the Amazon Basin, at least 15 to 17 million hectares of forest have been converted to pasture and cropland, and roughly half of this area is now abandoned."

Natural catastrophes like these are now dwarfed by the cumulative effects of everyday human activities. In the Amazon Basin, at least 15 to 17 million hectares of forest have been converted to pasture and cropland, and roughly half of this area is now abandoned. The thin, lateritic soils that underlie these Amazon forests often sustain crops or cattle for no more than four to eight years. This land, worthless to conventional agriculture, is now a deduction from earth's reservoir of diversity.[52]

But even such severely degraded tropical land need not be written off as a total biological loss. Pennsylvania State University biologist Christopher Uhl believes nearly all of the land deforested so far in the Amazon has the capacity to regenerate. If tropical forests can be restored to once-cleared land, the implications for conservation are enormous.

Tropical forests are known to have expanded and contracted in response to past climatic swings. But scientists question whether human interventions might help accelerate the natural recovery of forests, grasslands, and wetlands, and in the process reconstitute some of the diversity of degraded land. According to William R. Jordan of the University of Wisconsin Arboretum, "The quality of the environment in the long run is going to depend not so much on the amount of land we are able to set aside and protect from disturbance as on our ability to achieve an equilibrium between the forces of degradation on the one hand and of regeneration on the other."[53]

The potential for human-managed regeneration is suggested by studies of how natural ecosystems repair themselves. Uhl has been studying tropical forest recovery in southern Venezuela and in Brazil's Pará state in the Amazon Basin for more than a decade. In the San Carlos de Rio Negro region just north of the equator, Uhl documented the way forests return to small agricultural clearings. Saplings spring up in the abundant sunshine, roots and stumps sprout new growth, buried seeds poke through the soil, and birds and animals leave seeds behind in their droppings. One measure of forest recovery is the total biomass—the cumulative weight of living plant matter on a forested site. Uhl studied farm sites in Venezuela that had been abandoned from 2 to 60 years and concluded that at least 150 years would be needed for complete forest recovery after slash-and-burn farming.[54]

Recovery is slowed dramatically when disturbances are large and prolonged—for example, when forests are converted to pasture and then abandoned. As intact forests recede toward a distant horizon, fewer birds and mammals stray far enough from their forest refuge to bring seeds of the main forest trees. Leaf-cutter ants and mice devour the few seeds that arrive. Natural regeneration is slowed to an imperceptible pace. More severe disruption could bring recovery to a grinding halt; on a site laid bare by a bulldozer, Uhl concluded that "close to 1,000 years may pass before biomass levels reach those of mature forest."[55]

Human disruptions can have a synergistic effect, further retarding the natural regenerative mechanisms. Uhl has found, for instance, that when ranchers use fire to clear their pastures and then selectively harvest timber from adjacent forests, destructive forest fires occur more frequently. Fires cannot be set to control the growth of shrubs or promote the growth of pasture grasses without jeopardizing standing timber in the formerly fire-resistant forests. And aside from destroying timber that ranchers would prefer to sell, the fires reduce the biological diversity of the remaining forest stands. Thus ranching and timber production are in some areas incompatible.[56]

While tropical forests can reclaim cropland and pasture, or, for that matter, even land scorched by lava, the process is painfully slow. And from the standpoint of biological diversity, slow isn't good enough. Once a tract of forest is reduced to isolated pockets, each of the fragments begins to lose species. Extinctions occur fairly quickly. If the fragments, particularly those amid abandoned lands, can be rejoined into larger areas quickly enough, at least some extinctions could be prevented.

Researchers are creating a new discipline of ecological restoration, based on lessons from the study of natural ecosystem recovery, that can speed the repair of damaged environments. Restoration aims to reestablish viable communities of plants and animals in all their natural diversity. Advocates of restoration argue that the successful con-

"The successful conservation of biological diversity depends less on keeping humans out of fragile ecosystems than on making sure they do the right things when they are there."

servation of biological diversity depends less on keeping humans out of fragile ecosystems than on making sure they do the right things when they are there.

Refcrestation with economically valuable tree species has been practiced for millennia. Reclamation of mined lands to protect streams and hold the soil in place has a long history. But deliberate restoration patterned on ecosystems that occur naturally has only recently begun to attract wide attention. Restoring healthy ecosystems cannot be done haphazardly. Just as modern medicine rests on a scientific foundation encompassing physiology, microbiology, and biochemistry, healing the land can draw on the emerging scientific field of restoration ecology.

Like conservation biology, restoration ecology falls somewhere between basic and applied science. Putting ecosystems together is a good way to go about asking scientific questions about them. Restoration offers opportunities to test ecological theories as well as new ways to correct environmental damage.[57]

Restoration also has an intimate tie to more traditional conservation practices. While conservationists have tended to focus on preserving intact ecosystems before diversity has been lost, restoration ecologists seek to recover diversity *after* it has been lost. But restoration requires natural ecosystems as models and seed sources. As essayist Wendell Berry has observed, "We cannot know what we are doing until we know what nature would be doing if we were doing nothing."[58]

The most extensive restoration research so far has focused on North American prairies. The nearly 300 million hectares of tallgrass prairies that once blanketed the midwestern United States have now been reduced by farming, grazing, and the invasion of exotic plants to a tiny remnant—less than one-tenth of 1 percent—of their original expanse.[59]

Wildlife ecologist Aldo Leopold conceived of prairie restoration in 1934 at the University of Wisconsin Arboretum. Leopold, then director of the Arboretum, sought to recreate the native plant communities that original settlers had encountered in Wisconsin. As he suspected, the process is far more intricate than simply broadcasting seeds and hoping for the best. Native species have to be reintroduced in a pattern and sequence that sets natural succession in motion. The work is complicated by the presence of tenacious alien species that have been inadvertently introduced to the United States. "You do not get a prairie . . . today by fencing off a piece of land and waiting for the grass to grow back," writes Walter Truett Anderson in *To Govern Evolution*. "If you do that you get an interesting collection of weeds from all over the world."[60]

Perhaps the largest and most rapidly expanding restored prairie is at the Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois. Prairie has been restored to 180 hectares over 12 years, and the goal is a prairie that completely blankets the 240 hectare site. Unlike other restoration projects, the Fermilab site is large enough to sustain native animals as well as a flourishing array of native grasses and flowers. Managers at the site have already introduced trumpeter swans to "pothole" ponds in the prairie, and they plan to reintroduce sandhill cranes, Franklin's ground squirrels, and a variety of native prairie insects.[61]

Fire, so destructive of species-rich forests in the tropics, defines the biological possibilities of the prairie, and managing fire is a key theme in prairie restoration. Once wildfires are suppressed, as they were when the first settlers began to plow the prairie sod, oak forest invades. This subtle biological change illustrates the delicate counterpoint of opposing forces that ecosystem restorers must perceive and manage. As William Jordan writes, "Remove the fires caused by lightning or set by Indians, and you have to replace them, or the prairie will quietly vanish, not in a roar of machinery but into the shadows of a forest."[62]

At the 3,500 hectare Konza prairie near Manhattan, Kansas, researchers have found that the diversity of prairie plant and animal life depends on the frequency of fires. Burning every four to six years results in more grass, taller flowering plants, and more insects than other schedules. Scientists have also reintroduced bison, elk, and pronghorn antelope to part of the prairie to compare the impact of their grazing with that of domestic livestock. Though Konza is not a *restored* prairie, lessons learned there will guide efforts to reestablish tallgrass elsewhere. New insights may be applied, for example, to the effort to bring bluestem, switchgrass, and Indiangrass back to two former cattle ranches for the proposed National Tallgrass Prairie Preserve in Osage County, Oklahoma.[63]

Restoration of coastal and freshwater wetlands is also widely practiced in the United States, particularly on the Eastern seaboard. Marshes, swamps, and seagrass beds, though they typically contain just a few native plant species, play a critical biological role by providing spawning and feeding grounds for many fish species, and by acting as a living filter for wastewater. Natural wetlands have been polluted, drained, and buried by various forms of industrial and urban development. U.S. environmental law provides the incentive for restoration by requiring developers to replace degraded habitat with natural habitat equivalent in size and character. Environmentalists charge that restoration seldom achieves this equivalence, and reports of poorly supervised restoration with inappropriate species are common. Though restoring wetlands remains controversial, the legal and economic aspects of this work may hold lessons for other ecosystems.[64]

The restoration of forests—as opposed to the planting of single species in reforestation—is limited. Forests pose unusual problems to restoration: They take far longer to reach maturity, and are more complex in structure and composition than other ecosystems. Few reforestation projects have aimed specifically at restoring a diversity of species. Notable exceptions include the effort to recreate redwood forest on 14,500 hectares of logged land adjacent to Redwood National Park, and the volunteer effort to expand redwood and fir forest in Big Basin State Park, both in California.[65]

As air pollution and acid rain continue to kill trees in Central Europe and eastern North America, forest restoration is likely to receive more attention in industrial countries. Where forests are already under stress, as in Central Europe, scientists must find ways to create a functioning community of trees and wildlife that can survive on the acid-laden soils that are likely to persist for decades even if pollution sources are curbed.[66]

The greatest challenge for forest restoration, however, lies in the tropics, where a panoply of forest types is being converted to farmland and pasture, or degraded by poorly managed logging operations. Current estimates of deforestation suggest that at least 10 hectares are cleared for each hectare newly planted worldwide. Moreover, almost all reforestation in the tropics consists of single-species plantations rather than diverse natural assemblages of forest species.

The most ambitious tropical restoration project yet undertaken is in the dry tropical forest of northwest Costa Rica. Dry forest, like rain forest, is unimaginably rich in species; unlike rain forest, its trees are deciduous and shed their leaves during the dry season. When Spanish conquistadores first reached Central America, dry tropical forest covered the Pacific Coast from Panama to northern Mexico. Today less than 1 hectare in 50 remains. While poor soils underlie many rain forests, the soils over much of the range of former dry forest are eminently suited to farming and grazing. Corn, cotton, and cattle have replaced the forest's rich web of plants, animals, and microorganisms. Like North America's tallgrass prairies, dry forests in Central America were quickly plowed under.

University of Pennsylvania biologist Daniel Janzen believes that dry tropical forest can be grown from scratch. Janzen works in the 10,500 hectare Santa Rosa National Park, in Costa Rica's Guanacaste Province. He plans to use the few intact stands of tropical dry forest in Santa Rosa, the largest that remain in Central America, as a graft to restore the surrounding lands to their pre-Columbian ecological health. The expanded dry forest will be renamed Guanacaste National Park. With support from the Costa Rican government, the Nature Conservancy, and private donors, Janzen intends to purchase enough land from adjacent landowners to expand the park to 70,000 hectares. At that size, the park will be large enough for its ecological communities to become self-sustaining once again.[67]

Reestablishing this forest requires much more than replanting trees. To recreate the ecosystems that preceded the Spanish conquest will take centuries. By controlling fires, managing livestock, regulating hunting, and reintroducing animal species, Janzen intends to give seedlings and forest wildlife a second chance. Eventually, natural regeneration will supplant human management as an intact community of plants and animals takes shape.[68]

Despite the most aggressive conservation policy in the tropics, Costa Rica has been unable to slow the pace of deforestation outside the country's parks and preserves. Against the daunting array of pressures on forests, Janzen's project appears quixotic at best. But the Guanacaste project reflects an overdue shift in thinking about how natural resources and ecosystems can be managed in the tropics. If successful, it will confirm that even intricate tropical forest ecosystems can be reassembled.[69]

Researchers at the University of Wisconsin's Center for Restoration Ecology have proposed an ambitious tropical restoration project on the Caribbean islands visited by Columbus in the late fifteenth century. This "Bosques Colon" (Forests of Columbus) project is intended to coincide with the 500th anniversary of Columbus' first landfall in the West Indies. The project's primary goal is to recreate dry forest characteristic of the Caribbean islands essentially from scratch by reassembling constituent species that have survived only in small threatened stands.[70]

Bosques Colon would take advantage of several unique ecological attributes of Caribbean islands. Island ecosystems, somewhat less complex than their tropical mainland counterparts, may prove considerably easier to restore. Because they have borne human pressures longer and are more densely populated than other parts of the tropics, successful island restoration could offer a promising precedent for continental areas. Some of the species needed to reconstruct pre-Columbian ecosystems still exist in scattered refuges; restoration will improve their chances of long-term survival.

Ecological restoration, with demonstrated potential in North American prairies and wetlands, faces key tests in Costa Rica's dry forests and the Caribbean islands. Ultimately, it must be attempted in the most species-rich tropical ecosystems: the rain forests. Basic research like Uhl's studies of natural forest regeneration could provide a point of departure.

Land for restoration is not scarce; the challenge will be deciding where to begin. The 8 million hectares of abandoned, unproductive pasture in the Amazon Basin suggest the dimensions of the opportunities, but every country contains eroded wasteland that could be used to test restoration's potential. The Indian government, for example, estimates that 175 million hectares—nearly half the country's land mass—is degraded land that produces far below its biological potential and sustains few of its native species. Indian Prime Minister Rajiv Gandhi established a National Wastelands Development Board in early 1985 to promote reforestation of 5 million hectares of this land each year. Though the action plan emphasizes plantations of fuelwood and fodder trees to supply subsistence needs of India's poor, the Board's mission of "greening wastelands" could easily be broadened to include experimental ecological restoration on a small scale. As with fuelwood and fodder plantations, the key to sustained success would be the participation of local communities.[71]

Until experimental restoration is extended to a variety of ecosystems, it will not be possible to estimate the cost of large-scale efforts. Since most restoration projects so far have been small-scale and labor intensive, costs appear high. In the United States, full reassembly of fragile semi-arid grassland with native species can cost $500 to $2,000 per hectare—with most of the expense in propagation and hand-planting of native species. The more disturbed the original site, the more expensive restoration will be. Janzen intends to use natural seed sources and seed dispersal by wildlife and domestic livestock in the Guanacaste project. His big financial hurdle is to raise an estimated $5 million to purchase 16,000 hectares for the dry forest restoration. The more natural regenerative processes can be initiated and managed, the cheaper restoration is likely to be.[72]

Eventually, restoration will have to grow beyond pilot projects if it is to make a significant impact on conserving biological diversity. One opportunity to test restoration on a large scale lies in the United States. The Conservation Reserve mandated by the 1985 Food Security Act aims to convert 16 million hectares of land now in the cropland base to grass or trees by 1990 in an effort to curb soil erosion and restrain surplus production. Farmers have already enrolled nearly 8 million hectares in the program, well ahead of schedule. Although

"Restoration will have to grow beyond pilot projects if it is to make a significant impact on conserving biological diversity."

this land is not all in adjacent parcels, it includes acreage on which restoration could reinforce other conservation efforts. Tallgrass prairie restoration, with its proven track record, would be a good place to start.[73]

On the restored prairie at Fermilab, scientists have found that soil structure and water-holding capacity recovered dramatically compared with adjacent land that had been planted to pasture grasses. Native prairie might prove the best long-term rotation crop for some farm areas suffering erosion, soil compaction, and other consequences of intensive crop production. The scientists who studied Fermilab's soils write: "Incorporating prairie into agriculture suggests an incentive for returning prairie to the landscape on a large scale, and so a major force for restoration. Perhaps before too long strips of prairie will again flourish on the gentle hills of Iowa and Illinois, a vision of the past pointing the way to our future."[74]

Although it is not yet realistic to launch large-scale tropical forest restoration programs, indigenous peoples in many tropical countries have traditions of artificial forest regeneration that could provide a place to begin. A team of Mexican researchers led by Arturo Gomez-Pompa found that descendants of the Maya living on Mexico's Yucatan Peninsula protect and cultivate useful forest trees in managed stands called *pet kot*. The tended forests, composed of a variety of fruit and nut-bearing trees, are so similar in structure and appearance to surrounding rain forests that Gomez-Pompa and his colleagues remark that they "in many cases are indistinguishable from them."[75]

Such tended rain forests are not unique to the Yucatan. Researchers have found and documented similar practices in Brazil, Colombia, Java, Sumatra, Tanzania, and Venezuela. People in every tropical forest region have developed traditions of forest restoration and management. But such traditional practices have not yet been systematically examined as a basis for sustainable development for growing populations, let alone as a promising tool for conservation. Unfortunately, in the Yucatan and elsewhere, the traditional *pet kot* forests seem to be dying out. Few farmers in the region start new stands, and some existing stands have been cut in recent years. The loss of this cultural knowledge about restoration and management of tropical forests could prove as costly as the loss of species.[76]

36 Restoration may prove to be the key to conserving biological diversity and averting extinctions in a time of climate change. The concentration of carbon dioxide in the atmosphere has been climbing for two centuries due to the burning of fossil fuels and deforestation, and some data suggest that the long-expected global warming is now under way. Natural ecological communities are not indifferent to climate change; plants and animals vary in their preferences for temperature, moisture, and seasonal alternations. As these factors vary, living organisms respond by expanding, contracting, or shifting their distribution to follow optimal climate conditions. A national park, surrounded by farmland, pasture, or any sort of development, cannot pick up its boundaries and move when conditions no longer favor the array of organisms it was designed to protect. Restoration may help add habitat to existing parks and reserves, or help establish species and ecosystems outside their previous range to buffer the biological uncertainties that will come with a CO_2-induced warming.[77]

Restoration is not a substitute for vigorous efforts to preserve natural areas. It cannot be expected to recover the full range of natural diversity on converted lands. But by enhancing areas that border parks, biosphere reserves, and other remaining wildlands, restoration can help conserve their array of plant and animal species. Restoration may help slow the effects of habitat fragmentation, and expand habitat to allow some animal species now maintained in captivity to be reintroduced to the wild. It will surely be needed to manage plant communities as they are affected by changing climate. Lessons from early restoration projects may also help scientists design more sustainable farming and forestry practices patterned on natural ecosystems.

The practice of ecological restoration on a large scale could mark a turning point in efforts to arrest extinctions. New questions are arising as restoration projects proceed in prairies and forests, honing the theory and practice of applied ecology. Researchers working to restore tropical ecosystems can benefit from these temperate zone lessons. The challenges of ecological restoration can give conservation efforts worldwide a new creative spirit.

Evolutionary Responsibility

For 3.5 billion years, evolution has unfolded without our conscious guidance. Today, human activities seem destined to shape earth's biological future as inexorably as a geological process. But as the distinguished Australian geneticist O. H. Frankel has observed, "We are *not* the equivalent of an ice age or a rise in sea level: we are capable of prediction and control. We have acquired evolutionary responsibility."[78]

The next decade will be especially crucial in determining the ultimate severity of the extinctions that we have already set in motion. Should deforestation unfold according to projections, biotic impoverishment proceed unchecked, and human populations double from 5 billion today to the 10 billion now forecast for the year 2028, future choices will be foreclosed.[79] "No generation in the past has faced the prospect of mass extinction within its lifetime," writes Norman Myers, "the problem has never existed before. No generation in the future will ever face a similar challenge: if this present generation fails to get to grips with the task, the damage will have been done and there will be no 'second try.'"[80]

The exercise of evolutionary responsibility is largely a political problem, but our present political vocabulary is inadequate. The first step toward "evolutionary governance" is recognition that present priorities and institutions, far from being neutral as far as the biosphere is concerned, entail evolutionary consequences. While two dominant political philosophies vie for influence in the community of nations, the biosphere consistently proves that one set of rules applies everywhere. Political scientist Walter Truett Anderson believes that decisionmakers can no longer escape this reality. "Politics is about evolution," he writes. "Governance is inextricably connected with the growing human responsibility for all the things the word 'evolution' implies: the survival and extinction of species, the changing ecology of the planet, the biological (and cultural) condition of the human species itself."[81]

Embarking on a path away from mass extinction will require a radical departure from deeply embedded policies and land-use practices. The necessary changes, if they are to come at all, must come from within existing institutions: Evolutionary responsibility will have to be accepted by the present set of agencies, international bodies, and nongovernmental organizations. Since the challenge is disproportionately severe in the Third World, development assistance from the industrial countries is today among the most important means of putting the preservation of diversity on government agendas.

In the United States, initiatives to conserve biological diversity at the international level have been pursued as part of foreign policy, and the main instrument has been AID. A series of amendments to the Foreign Assistance Act broadened AID's mandate to conserve biological diversity and reverse tropical deforestation in the 60 developing countries with AID missions. In 1981, AID joined a number of other U.S. government agencies to cosponsor a Strategy Conference on Biological Diversity. Two years later, Congress passed a landmark amendment to the Foreign Assistance Act that established the conservation of biological diversity as an explicit objective of U.S. foreign assistance. AID delivered a U.S. strategy for conserving biological diversity to the Congress in 1985, recommending 67 ways government agencies and private organizations could help developing countries to reconcile conservation with their economic needs.

By 1986, however, intentions collided with economics. AID suffered severe budget cuts under the Gramm-Rudman-Hollings Deficit Reduction Act. AID's environmental programs were not well financed to begin with, but these programs have received disproportionate cuts under Gramm-Rudman. For example, in fiscal year 1986 AID's total budget was cut 4.3 percent. But the Office of Forestry, Natural Resources, and the Environment, which helps administer activities related to biological diversity, was cut by 25 percent to maintain funding for other development assistance programs.[82]

"Environment and natural resource activities remain among the lowest of foreign aid priorities."

Congressional sponsors of biodiversity initiatives, displeased by the cuts, earmarked $2.5 million of AID's appropriation for fiscal year 1987 to support conservation projects, and $4.5 million may be designated for biological diversity in fiscal year 1988. Although this level of support is small in relation to conservation needs, it represents the first Congressional commitment to biodiversity and a precedent for more aggressive programs. But aid for the conservation of biological diversity, like the humanitarian assistance intended to combat poverty and illiteracy, remains vulnerable to shifts in public opinion and political agendas.[83]

Environment and natural resource activities remain among the lowest of foreign aid priorities. Foreign aid spending, though it accounts for less than 2 percent of the U.S. government budget, still amounted to $12.9 billion in fiscal year 1987. But roughly 70 percent of this was earmarked for international security assistance—programs that help foreign governments with military assistance or direct cash outlays. The U.S. government pays more to maintain American troops in Honduras, among the countries where deforestation is proceeding fastest, than it devotes to cataloging and managing biological diversity worldwide. Until basic aid priorities are reordered, real progress on biological diversity is likely to remain elusive.[84]

Few other industrial nations have yet elevated biological diversity among their foreign aid priorities. But major producers and consumers of tropical hardwoods are beginning to address the loss of tropical forests through the International Tropical Timber Agreement, ratified in 1985. The Agreement reflects an unprecedented consensus among sponsor countries about escalating pressures on forest ecology and the risks to timber production. As a report from Friends of the Earth points out, "It is the first time that a commodity agreement, or indeed any international trade agreement, has built the goal of environmental sustainability into its economic strategy." At the inaugural meeting of the International Tropical Timber Organization in April 1987, Japan led other donor countries in pledging $2 million for research on reforestation and sustainable management of tropical forests. Japan, the largest importer of tropical hardwoods, has long been criticized for ignoring the environmental consequences of irresponsible logging. A change in Japan's attitude, backed up with expanded financial support for innovative forest management, could brighten the outlook for Southeast Asia's threatened forests.[85]

The World Bank, an institution with 150 member countries and an avowedly global role, has gradually begun to recognize the links between biological diversity and economic development. In 1986, the Bank adopted a new wildlands policy that for the first time establishes its role in the preservation of natural areas. Virtually all Bank-funded projects have an impact on the environment, but to date fewer than 1 percent have included an explicit effort to conserve natural areas.[86]

The Bank's new policy acknowledges that intact natural areas are under severe pressure, and that remaining wildlands can contribute more to economic development in their natural state than if converted to some other use. The policy is explicitly intended to "greatly reduce current extinction rates to much lower (perhaps almost 'natural') levels, without slowing the pace of economic progress"—the first development policy justified on the basis of its effect on extinction rates.[87]

The policy directs Bank officials to refuse to finance projects that would require converting biologically unique natural areas—a tendency for which the Bank has been widely criticized by environmental groups. Projects like land settlement in the Amazon, Indonesia's transmigration program, or the Narmada hydroelectric and irrigation scheme in India—all of which affect vast and unique natural areas—will prove more difficult to fund in the future. Second, it specifies that new projects should be sited on lands already converted or degraded, rather than virgin lands, a requirement that could focus attention on the economic potential of abandoned land. Third, when a project requires the clearing of virgin land, an area of natural habitat equal in size and biological value must be protected. Thus the Bank will begin partly to compensate for the biological losses incurred by conventional development schemes.[88]

In May 1987, World Bank President Barber Conable announced the creation of an environment department that will contribute to the design and direction of development policies at the Bank's top level. New environmental offices in the four regional divisions will monitor Bank projects and promote innovative resource management. Acknowledging the Bank's past failures in the environmental area, Conable noted that "sustained development depends on managing resources, not exhausting them." The wildlands policy stands a better chance of aggressive implementation with this kind of institutional support. The African, Asian, and Inter-American development banks, which together with the World Bank lend $6.5 billion annually for agricultural projects that can put natural diversity at risk, should join this effort to reconcile conservation and development.[89]

The "greening" of international finance illustrates a significant trend in development assistance. The objectives of development agencies and nongovernmental conservation groups are converging in a way that few conservationists or development economists could have foreseen even a few years ago. While the World Bank is considering "wildland financing," some of the major international conservation groups now aim their activities squarely at economic development. The World Wildlife Fund, for example, recently launched a program called "Wildlands and Human Needs," which seeks to base small-scale rural development projects on the ecosystems that supply fodder, fuelwood, and fresh water supplies to local communities. Projects include an effort to provide secure land titles to small farmers in eastern Costa Rica to reduce the pressure to clear remaining forest, and a program to involve Zambian villagers in sustainable wildlife harvests for local needs from land adjacent to South Luangwa National Park. The program will expand to more ambitious efforts in Africa, Asia, and Latin America with support from AID.[90]

Data collected and analyzed by conservation groups are increasingly used to plan development. The U.S.-based Nature Conservancy's International Program has helped found Conservation Data Centers in Colombia, Costa Rica, the Dutch Antilles, Peru, and Puerto Rico, and plans to establish centers in Bolivia, Brazil, Chile, Ecuador, Guatemala, Mexico, Panama, Paraguay, and Venezuela by the end of 1987. The centers, staffed by national scientists rather than visiting foreign researchers, are created to gather, organize, and disseminate information on national biological diversity in a form useful to national policymakers. Other information networks, like the Conservation Monitoring Centre created by the International Union for the Conservation of Nature and Natural Resources, also serve development agencies as well as conservation groups.[91]

At least 38 countries are preparing comprehensive national conservation strategies to identify environmental priorities and integrate sustainable management of natural resources into country development plans. The strategies are patterned on the World Conservation Strategy, prepared by the International Union for the Conservation of Nature in 1980. Indonesia, Malaysia, and Venezuela, countries especially rich in biological diversity, are on the list; Brazil, Zaire, and the countries of West Africa that contain that continent's most valuable remaining tropical forests are not. Though strategies are not binding, the attempt to integrate conservation plans into political and economic decision-making signifies that some developing countries have begun to address their long-standing neglect of conservation.[92]

Local institutions that assume global responsibilities play an increasingly significant role in averting extinctions. Most zoos, for example, created for the education and entertainment of local communities, now recognize that they are in the business of "genetic management" as increasing numbers of the species they house face extinction in the wild. In the late seventies, Species Survival Plans were drafted for a few animals and circulated among North American zoos to provide a comprehensive blueprint for captive breeding programs, and to maintain the genetic diversity of captive animal populations. The International Species Inventory System, set up to maintain records on captive populations, now tracks 2,500 species of mammals and birds kept by 223 zoos in Europe and North America.[93]

Species Survival Plans aim not just to maintain popular animals like pandas or siberian tigers in captivity, but to keep species genetically fit enough to consider reintroduction to the wild. The managed population of about 400 golden lion tamarins is now large enough to permit some of these animals to be reintroduced to Brazil's heavily threatened Atlantic Forest. The tamarin is the first primate bred in captivity with the goal of returning it to natural habitat. But unless remaining forest is protected and fragmented areas restored and re-

"Zoos have become a kind of 'millennium ark' between the natural conditions of the past and the time that human demands on the biosphere stabilize."

connected, there is no chance the tamarins will become self-sustaining. "We are just holding the fort genetically while allowing the habitat to regenerate," says James Dietz of Washington, D.C.'s National Zoo.[94]

Biologists estimate that as many as 2,000 species of mammals, reptiles, and birds will, like the tamarins, have to be bred in captivity to escape extinction. Zoos, the key to this task, have become a kind of "millennium ark" between the natural conditions of the past and the time that human demands on the biosphere stabilize.[95]

There are clear limits to the ability of zoos to exercise evolutionary responsibility. Zoos have a carrying capacity defined by budgets no more forgiving than the carrying capacity of natural environments. William Conway, Director of the New York Zoological Society, estimates that if existing zoos aim to maintain viable populations, they probably can protect no more than 900 species of birds and animals—less than 50 percent of the 2,000 species believed unlikely to survive in the wild over the long term. And zoos can do almost nothing for the hundreds of thousands of insects and invertebrates threatened with extinction.[96]

Like zoos, botanical gardens could complement ecological restoration by maintaining threatened plant species and strategically restoring them to natural settings. Botanical gardens in the United States now coordinate efforts to preserve threatened species in a program managed and funded by the Center for Plant Conservation in Jamaica Plain, Massachusetts. But the global effectiveness of botanical gardens is limited by the difficulty of conserving the full genetic range of threatened plant species. "Although it may be theoretically possible for the botanic gardens of the world to grow the estimated 25,000 to 40,000 threatened species of flowering plants, cultivating sufficient populations to maintain diversity is unrealistic," warns the U.S. Office of Technology Assessment. "Consequently, protecting a diversity of wild species will rest on maintaining them in the wild."[97]

The well-publicized plight of single species like the California condor or the Bengal tiger can attract attention to the pressures on biological diversity. But species-based efforts will certainly be insufficient to counter the risk of a mass extinction. There are neither enough trained biologists nor enough sources of financial support even to decide which species merit preservation. More important, the interactions among wild species in natural assemblages give ecosystems their integrity. Only ecosystem-based conservation and restoration can preserve interactions.[98]

The ongoing fragmentation and isolation of natural habitats, and the prevalence of the "living dead"—species that temporarily persist in modified habitats in which they can no longer successfully reproduce—shape the world's biological future as directly and inexorably as nations' balance of payments shape their economic future. These fundamental realities of the living world must become better known if policymakers are to make the conceptual shift from the conservation of species to the conservation of ecosystems, and attempt to reconcile conservation with national economic needs and aspirations.[99]

Existing initiatives can be building blocks for a strategy to avert a mass extinction. By coordinating efforts to study tropical ecosystems that remain, systematically investigating the potential to restore degraded forests and grasslands, and integrating the management of biological diversity with agricultural and development policies, policymakers will dictate the outlines of future biological equilibrium.

Decisions made over the next decade—the "Decade of the Tropics"—will establish the terms of humanity's coexistence with the millions of species with which we share the planet. Though the consequences of evolutionary negligence loom large, the tools with which to exercise evolutionary responsibility are more numerous and more powerful than ever. To the extent humans learn to protect and restore tropical dry forests and savannas, and to expand the rain forests and prairies, these ecosystems—and the species saved from extinction—may one day be seen as *cultural* achievements. Reweaving the web of life could prove a lasting measure of our civilization.

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