What Is Nature Worth?

There's a powerful economic argument for preserving our living natural environment: The biosphere promotes the long-term material prosperity and health of the human race to a degree that is almost incalculable. But moral reasons, too, should compel us to take responsibility for the natural world.

by Edward O. Wilson

In the early 19th century, the coastal plain of the southern United States was much the same as in countless millenniums past. From Florida and Virginia west to the Big Thicket of Texas, primeval stands of cypress and flatland hardwoods wound around the corridors of longleaf pine through which the early Spanish explorers had found their way into the continental interior. The signature bird of this wilderness, a dweller of the deep bottomland woods, was the ivory-billed woodpecker, *Campephilus principalis*. Its large size, exceeding a crow's, its flashing white primaries, visible at rest, and its loud nasal call—*kent!* . . . *kent!* . . . *kent!*—likened by John James Audubon to the false high note of a clarinet, made the ivory-bill both conspicuous and instantly recognizable. Mated pairs worked together up and down the boles and through the canopies of high trees, clinging to vertical surfaces with splayed claws while hammering their powerful, off-white beaks through dead wood into the burrows of beetle larvae and other insect prey. The hesitant beat of their strikes—*tick tick* . . . *tick tick tick* . . . *tick tick*—heralded their approach from a distance in the dark woods. They came to the observer like spirits out of an unfathomed wilderness core.

Alexander Wilson, early American naturalist and friend of Audubon, assigned the ivorybill noble rank. Its manners, he wrote in *American Ornithology* (1808–14), "have a dignity in them superior to the common herd of woodpeckers. Trees, shrubbery, orchards, rails, fence posts, and old prostrate logs are all alike interesting to those, in their humble and indefatigable search for prey; but the royal hunter before us scorns the humility of such situations, and seeks the most towering trees of the forest, seeming particularly attached to those prodigious cypress swamps whose crowded giant sons stretch their bare and blasted or moss-hung arms midway to the sky."

A century later, almost all of the virgin bottomland forest had been replaced by farms, towns, and second-growth woodlots. Shorn of its habitat, the ivorybill declined precipitously in numbers. By the 1930s, it was down to scattered pairs in the few remaining primeval swamps of South Carolina, Florida, and Louisiana. In the 1940s, the only verifiable sightings were in the Singer Tract of northern Louisiana. Subsequently, only rumors of sightings persisted, and even these faded with each passing year.

The final descent of the ivorybill was closely watched by Roger Tory Peterson, whose classic *A Field Guide to the Birds* had fired my own interest in birds when I was a teenager. In 1995, the year before he died, I met Peterson, one of my heroes, for the first and only time. I asked him a question common in conversations among American naturalists: What of the ivory-billed woodpecker? He gave the answer I expected: "Gone."


Ivory-billed Woodpecker *(1840–44),*
by John James Audubon

I thought, surely not gone *everywhere*, not *globally*! Naturalists are among the most hopeful of people. They require the equivalent of an autopsy report, cremation, and three witnesses before they write a species off, and even then they would hunt for it in séances if they thought there were any chance of at least a virtual image. Maybe, they speculate, there are a few ivorybills in some inaccessible cove, or deep inside a forgotten swamp, known only to a few close-mouthed cognoscenti. In fact, several individuals of a small Cuban race of ivorybills were discovered during the 1960s in an isolated pine forest of Oriente Province. Their current status is unknown. In 1996, the Red List of the World Conservation Union reported the species to be everywhere extinct, including Cuba. I have heard of no further sightings, but evidently no one at this writing knows for sure.

Why should we care about *Campephilus principalis*? It is, after all, only one of 10,000 bird species in the world. Let me give a simple and, I hope, decisive answer: because we knew this particular species, and knew it well. For reasons difficult to understand and express, it became part of our culture, part of the rich mental world of Alexander Wilson and all those afterward who cared about it. There is no way to make a full and final valuation of the ivorybill or any other species in the natural world. The measures we use increase in number and magnitude with no predictable limit. They rise from scattered, unconnected facts and elusive emotions that break through the surface of the subconscious mind, occasionally to be captured by words, though never adequately.

We, *Homo sapiens*, have arrived and marked our territory well. Winners of the Darwinian lottery, bulge-headed paragons of organic evolution, industrious bipedal apes with opposable thumbs, we are chipping away the ivorybills and other miracles around us. As habitats shrink, species decline wholesale in range and abundance. They slide down the Red List ratchet, and the vast majority depart without special notice. Over the past half-billion years, the planet lost perhaps one species per million species each year, including everything from mammals to plants. Today, the annual rate of extinction is 1,000 to 10,000 times faster. If nothing more is done, one-fifth of all the plant and animal species now on earth could be gone or on the road to extinction by 2030. Being distracted and self-absorbed, as is our nature, we have not yet fully understood what we are doing. But future generations, with endless time to reflect, will understand it all, and in painful detail. As awareness grows, so will their sense of loss. There will be thousands of ivory-billed woodpeckers to think about in the centuries and millenniums to come.

Is there any way now to measure even approximately what is being lost? Any attempt is almost certain to produce an underestimate, but let me start anyway with macroeconomics. In 1997, an international team of economists and environmental scientists put a dollar amount on all the ecosystems services provided to humanity free of charge by the living natural environment. Drawing from multiple databases, they estimated the contribution to be $33 trillion or more each year. This amount is nearly twice the 1997 combined gross national product (GNP) of all the countries in the world—$18 trillion. *Ecosystems services* are defined as the flow of materials, energy, and information from the biosphere that support human existence. They include the regulation of the atmosphere and climate; the purification and retention of fresh water; the formation and enrichment of the soil; nutrient cycling; the detoxification and recirculation of waste; the pollination of crops; and the production of lumber, fodder, and biomass fuel.

The 1997 megaestimate can be expressed in another, even more cogent, manner. If humanity were to try to replace the free services of the natural economy with substitutes of its own manufacture, the global GNP would have to be

>Edward O. Wilson *is Pellegrino University Research Professor and Honorary Curator in Entomology at Harvard University's Museum of Comparative Zoology. His books include* Sociobiology: The New Synthesis *(1975),* Consilience: The Unity of Knowledge *(1998), and two Pulitzer Prize winners,* On Human Nature *(1978) and* The Ants *(1990, with Burt Holldobler). This essay is taken from his latest book,* The Future of Life *(2002). Published by arrangement with Alfred A. Knopf, a division of Random House, Inc.*

increased by at least $33 trillion. The exercise, however, cannot be performed except as a thought experiment. To supplant natural ecosystems entirely, even mostly, is an economic—and even physical—impossibility, and we would certainly die if we tried. The reason, ecological economists explain, is that the *marginal value,* defined as the rate of change in the value of ecosystems services relative to the rate of decline in the availability of these services, rises sharply with every increment in the decline. If taken too far, the rise will outpace human capacity to sustain the needed services by combined natural and artificial means. Hence, a much greater dependence on artificial means—in other words, environmental prostheses—puts at risk not just the biosphere but humanity itself.

Most environmental scientists believe that the shift has already been taken too far, lending credit to the folk injunction "Don't mess with Mother Nature." The lady is our mother all right, and a mighty dispensational force as well. After evolving on her own for more than three billion years, she gave birth to us a mere million years ago, the blink of an eye in evolutionary time. Ancient and vulnerable, she will not tolerate the undisciplined appetite of her gargantuan infant much longer.

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Abundant signs of the biosphere's limited resilience exist all around. The oceanic fish catch now yields $2.5 billion to the U.S. economy and $82 billion worldwide. But it will not grow further, simply because the amount of ocean is fixed and the number of organisms it can generate is static. As a result, all of the world's 17 oceanic fisheries are at or below sustainable yield. During the 1990s, the annual global catch leveled off around 30 million tons. Pressed by ever-growing global demand, it can be expected eventually to drop. Already, fisheries of the western North Atlantic, the Black Sea, and portions of the Caribbean have largely collapsed. Aquaculture, or the farming of fish, crustaceans, and mollusks, takes up part of the slack, but at rising environmental cost. This "fin-and-shell revolution" necessitates the conversion of valuable wetland habitats, which are nurseries for marine life. To feed the captive populations, fodder must be diverted from crop production. Thus, aquaculture competes with other human activities for productive land while reducing natural habitat. What was once free for the taking must now be manufactured. The ultimate result will be an upward inflationary pressure across wide swaths of the world's coastal and inland economies.

Another case in point: Forested watersheds capture rainwater and purify it before returning it by gradual runoffs to the lakes and sea, all for free. They can be replaced only at great cost. For generations, New York City thrived on exceptionally clean water from the Catskill Mountains. The watershed inhabitants were proud that their bottled water was once sold throughout the

Passion Flowers and Humming Birds ***(c. 1875–85), by Martin Johnson Heade***

Northeast. As their population grew, however, they converted more and more of the watershed forest into farms, homes, and resorts. Gradually, the sewage and agricultural runoff adulterated the water, until it fell below Environmental Protection Agency standards. Officials in New York City now faced a choice: They could build a filtration plant to replace the Catskill watershed, at a $6 billion to $8 billion capital cost, followed by $300 million annual running costs, or they could restore the watershed to somewhere near its original purification capacity for $1 billion, with subsequently very low maintenance costs. The decision was easy, even for those born and bred in an urban environment. In 1997, the city raised an environmental bond issue and set out to purchase forested land and to subsidize the upgrading of septic tanks in the Catskills. There is no reason the people of New York City and the Catskills cannot enjoy the double gift from nature in perpetuity of clean water at low cost and a beautiful recreational area at no cost.

There is even a bonus in the deal. In the course of providing natural water management, the Catskill forest region also secures flood control at very little expense. The same benefit is available to the city of Atlanta. When 20 percent of the trees in the metropolitan area were removed during its rapid development, the result was an annual increase in stormwater runoff of 4.4 billion cubic feet. If enough containment facilities were built to capture this volume, the cost would be at least $2 billion. In contrast, trees replanted along streets and in yards, and parking area are a great deal cheaper than concrete drains and revetments. Their maintenance cost is near zero, and, not least, they are more pleasing to the eye.

In conserving nature, whether for practical or aesthetic reasons, diversity matters. The following rule is now widely accepted by ecologists: The more numerous the species that inhabit an ecosystem, such as a forest or lake, the more productive and stable is the ecosystem. By “production,” the scientists mean the amount of plant and animal tissue created in a given unit of time. By “stability,” they mean one or the other, or both, of two things: first, how narrowly the summed abundances of all species vary through time; and, second, how quickly the ecosystem recovers from fire, drought, and other stresses that perturb it. Human beings understandably wish to live in the midst of diverse, productive, and stable ecosystems. Who, if given a choice, would build a home in a wheat field instead of a parkland?

Ecosystems are kept stable in part by the insurance principle of biodiversity: If a species disappears from a community, its niche will be more quickly and effectively filled by another species if there are many candidates for the role instead of few. Example: A ground fire sweeps through a pine forest, killing many of the understory plants and animals. If the forest is biodiverse, it recovers its original composition and production of plants and animals more quickly. The larger pines escape with some scorching of their lower bark and continue to grow and cast shade as before. A few kinds of shrubs and herbaceous plants also hang on and resume regeneration immediately. In some pine forests subject to frequent fires, the heat of the fire itself triggers the germination of dormant seeds genetically adapted to respond to heat, speeding the regrowth of forest vegetation still more.

A second example of the insurance principle: When we scan a lake, our macroscopic eye sees only relatively big organisms, such as eelgrass, pondweeds, fishes, water birds, dragonflies, whirligig beetles, and other things big enough to splash and go bump in the night. But all around them, in vastly greater numbers and variety, are invisible bacteria, protistans, planktonic single-celled algae, aquatic fungi, and other microorganisms. These seething myriads are the true foundation of the lake’s ecosystem and the hidden agents of its stability. They decompose the bodies of the larger organisms. They form large reservoirs of carbon and nitrogen, release carbon dioxide, and thereby damp fluctuations in the organic cycles and energy flows in the rest of the aquatic ecosystem. They hold the lake close to a chemical equilibrium, and, to a point, they pull it back from extreme perturbations caused by silting and pollution.

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In the dynamism of healthy ecosystems, there are minor players and major players. Among the major players are the ecosystems engineers, which add new parts to the habitat and open the door to guilds of organisms specialized to use them. Biodiversity engenders more biodiversity, and the overall abundance of plants, animals, and microorganisms increases to a corresponding degree.

By constructing dams, beavers create ponds, bogs, and flooded meadows. These environments shelter species of plants and animals that are rare or absent in free-running streams. The submerged masses of decaying wood forming the dams draw still more species, which occupy and feed on them.

Elephants trample and tear up shrubs and small trees, opening glades within forests. The result is a mosaic of habitats that, overall, contains larger numbers of resident species.

Florida gopher tortoises dig 30-foot-long tunnels that diversify the texture of the soil, altering the composition of its microorganisms. Their retreats are also shared by snakes, frogs, and ants specialized to live in the burrows.

Euchondrus snails of Israel's Negev Desert grind down soft rocks to feed on the lichens growing inside. By converting rock to soil and releasing the nutrients photosynthesized by the lichens, the snails multiply niches for other species.

Overall, a large number of independent observations from differing kinds of ecosystems point to the same conclusion: The greater the number of species that live together, the more stable and productive the ecosystems these species compose. On the other hand, mathematical models that attempt to describe the interactions of species in ecosystems show that the apparent opposite also occurs: High levels of diversity can reduce the stability of individual species. Under certain conditions, including random colonization of the ecosystem by large numbers of species that interact strongly with one another, the separate but interlocking fluctuations in species populations can become more volatile, thus making extinction more likely. Similarly, given appropriate species traits, it is mathematically possible for increased diversity to lead to decreased production.

> TO EVALUATE INDIVIDUAL SPECIES SOLELY BY THEIR KNOWN PRACTICAL VALUE AT THE PRESENT TIME IS BUSINESS ACCOUNTING IN THE SERVICE OF BARBARISM.

When observation and theory collide, scientists turn to carefully designed experiments for resolution. Their motivation is especially strong in the case of biological systems, which are typically far too complex to be grasped by observation and theory alone. The best procedure, as in the rest of science, is first to simplify the system, then to hold it more or less constant while varying the important parameters one or two at a time to see what happens. In the 1990s a team of British ecologists, in an attempt to approach these ideal conditions, devised the *ecotron*, a growth chamber in which artificially simple ecosystems can be assembled as desired, species by species. Using multiple ecotrons, they found that productivity, measured by the increase of plant bulk, rose with an increase in species numbers. Simultaneously, ecologists monitoring patches of Minnesota grassland—outdoor equivalents of ecotrons—during a period of drought found that patches richer in species diversity underwent less decline in productivity and recovered more quickly than patches with les diversity.

These pioneering experiments appeared to uphold the conclusion drawn earlier from natural history, at least with reference to production. Put more precisely, ecosystems tested thus far do not possess the qualities and starting conditions allowed by theory that can reduce production and produce instability as a result of large species numbers.

But—how can we be sure, the critics asked (pressing on in the best tradition of science), that the increase in production in particular is truly the result of just an increase in the number of species? Maybe the effect is due to some other factor that just happens to be correlated with species numbers. Perhaps the result is a statistical artifact. For example, the larger the number of plant species present in a habitat, the more likely it is that at least one kind among them will be extremely productive. If that occurs, the increase in the yield of plant tissue—and in the number of the animals feeding on it—is only a matter of luck of the draw, and not the result of some pure property of biodiversity itself. At its base, the distinction made by this alternative hypothesis is semantic. The increased likelihood of acquiring an outstandingly productive species can be viewed as just one means by which the enrichment of biodiversity boosts productivity. (If you draw on a pool of 1,000 candidates for a basketball team, you are more likely to get a star than if you draw on a pool of 100 candidates.)

Still, it is important to know whether other consequences of biodiversity enrichment play an important role. In particular, do species interact in a manner that increases the growth of either one or both? This is the process called *overyielding*. In the mid-1990s, a massive study was undertaken to test the effect of biodiversity on productivity that paid special attention to the presence or absence of overyielding. Multiple projects of BIODEPTH, as the project came to be called, were conducted during a two-year period by 34 researchers in eight European countries. This time, the results were more persuasive. They showed once again that productivity does increase with biodiversity. Many of the experimental runs also revealed the existence of overyielding.

Over millions of years, nature's ecosystems engineers have been especially effective in the promotion of overyielding. They have coevolved with other species that exploit the niches they build. The result is a harmony within ecosystems. The constituent species, by spreading out into multiple niches, seize and cycle more materials and energy than is possible in similar ecosystems. *Homo sapiens* is an ecosystems engineer too, but a bad one. Not having coevolved with the majority of life forms we now encounter around the world, we eliminate far more niches than we create. We drive species and ecosystems into extinction at a far higher rate than existed before, and everywhere diminish productivity and stability.

I will grant at once that economic and production values at the ecosystem level do not alone justify saving every species in an ecosystem, especially those so rare as to be endangered. The loss of the ivory-billed woodpecker has had no discernible effect on American prosperity. A rare flower or moss could vanish from the Catskill forest without diminishing the region's filtration capacity. But so what? To evaluate individual species solely by their known practical value at the present time is business accounting in the service of barbarism. In 1973, the economist Colin W. Clark made this point persuasively in the case of the blue whale, *Balaenopterus musculus*. A hundred feet in length and 150 tons in weight at maturity, the species is the largest animal that ever lived on land or sea. It is also among the easiest to hunt and kill. More than 300,000 blue whales were harvested during the 20th century, with a peak haul of 29,649 in the 1930-31 season. By the early 1970s, the population had plummeted to several hundred individuals. The Japanese were especially eager to continue the hunt, even at the risk of total extinction. So Clark asked, What practice would yield the whalers and humanity the most money: Cease hunting and let the blue whales recover in numbers, then harvest them sustainably forever, or kill the rest off as quickly as possible and invest the profits in growth stocks? The disconcerting answer for annual discount rates over 21 percent: Kill them all and invest the money.

Now, let us ask, what is wrong with that argument?

Clark's implicit answer is simple. The dollars-and-cents value of a dead blue whale was based only on the measures relevant to the existing market—that is, on the going price per unit weight of whale oil and meat. There are many other values, destined to grow along with our knowledge of living *Balaenopterus musculus* and as science, medicine, and aesthetics grow and strengthen, in dimensions and magnitudes still unforeseen. What was the value of the blue whale in A.D. 1000? Close to zero. What will be its value in A.D. 3000? Essentially limitless—to say nothing of the measure of gratitude the generation then alive will feel to those who in their wisdom saved the whale from extinction.

No one can guess the full future value of any kind of animal, plant, or microorganism. Its potential is spread across a spectrum of known and as yet unimagined human needs. Even the species themselves are largely unknown. Fewer than two million are in the scientific register, with a formal Latinized name, while an estimated five to 100 million—or more—await discovery. Of the species known, fewer than one percent have been studied beyond the sketchy anatomical descriptions used to identify them.

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Agriculture is one of the vital industries most likely to be upgraded by attention to the remaining wild species. The world's food supply hangs by a slender thread of biodiversity. Ninety percent is provided by slightly more than 100 plant species out of a quarter-million known to exist. Twenty species carry most of the load, of which only three—wheat, maize, and rice—stand between humanity and starvation. For the most part, the premier 20 are those that happened to be present in the regions where agriculture was independently invented some 10,000 years ago, namely the Mediterranean perimeter and southwestern Asia; Central Asia; the Horn of Africa; the rice belt of tropical Asia; and the uplands of Mexico, Central America, and Andean South America. Yet some 30,000 species of wild plants, most occurring outside these regions, have edible parts consumed at one time or other by hunter-gatherers. Of these species, at least 10,000 can be adapted as domestic crops. A few, including the three species of New World amaranths, the carrotlike arracacha of the Andes, and the winged bean of tropical Asia, are immediately available for commercial development.

In a more general sense, all the quarter-million plant species—in fact, all species of organisms—are potential donors of genes that can be transferred by genetic engineering into crop species in order to improve their performance. With the insertion of the right snippets of DNA, new strains can be created that are, variously, cold resistant, pest resistant, perennial, fast growing, highly nutritious, multipurpose, sparing in their consumption of water, and more easily sowed and harvested. And compared with traditional breeding techniques, genetic engineering is all but instantaneous.

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The method, a spinoff of the revolution in molecular genetics, was developed in the 1970s. During the 1980s and 1990s, before the world quite realized what was happening, it came of age. A gene from the bacterium *Bacillus thuringiensis*, for example, was inserted into the chromosomes of corn, cotton, and potato plants, allowing them to manufacture a toxin that kills insect pests. No need to spray insecticides; the engineered plants now perform this task on their own. Other transgenes, as they are called, were inserted from bacteria into soybean and canola plants to make them resistant to chemical weed killers. Agricultural fields can now be cheaply cleared of weeds with no harm to the crops growing there. The most important advance of all, achieved in the 1990s, was the creation of golden rice. This new strain is laced with bacterial and daffodil genes that allow it to manufacture beta-carotene, a precursor of vitamin A. Because rice, the principal food of three billion people, is deficient in vitamin A, the addition of beta-carotene is no mean humanitarian feat. About the same time, the almost endless potential of genetic engineering was confirmed by two circus tricks of the trade: A bacterial gene was implanted into a monkey, and a jellyfish bioluminescence gene into a plant.

But not everyone was dazzled by genetic engineering, and inevitably it stirred opposition. For many, human existence was being transformed in a fundamental and insidious way. With little warning, genetically modified organisms (GMOs) had entered our lives and were all around us, changing incomprehensibly the order of nature and society. A protest movement against the new industry began in the mid-1990s and exploded in 1999, just in time to rank as a millennial event with apocalyptic overtones. The European Union banned transgenic crops, the Prince of Wales compared the methodology to playing God, and radical activists called for a global embargo of all GMOs. "Frankenfoods," "superweeds," and "Farmageddon" entered the vocabulary: GMOs were, according to one British newspaper, the "mad forces of genetic darkness." Some prominent environmental scientists found technical and ethical reasons for concern.

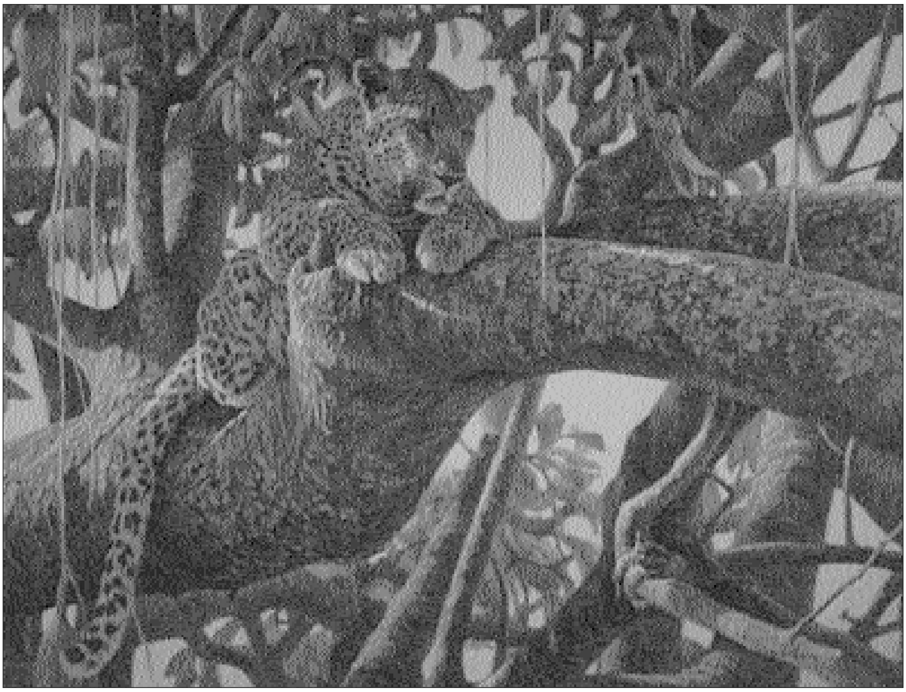
As I write, public opinion and official policy toward genetic engineering have come to vary greatly from one country to the next. France and Britain are vehemently opposed. China is strongly favorable, and Brazil, India, Japan, and the United States cautiously so. In the United States particularly, the public awoke to the issue only after the transgenie (so to speak) was out of the bottle. From 1996 to 1999, the amount of U.S. farmland devoted to genetically modified crops had rocketed from 3.8 million to 70.9 million acres. As the century ended, more than half the soybeans and cotton grown, and nearly a third (28 percent) of the corn, were engineered.

There are, actually, several sound reasons for anxiety over genetic engineering, which I will now summarize and evaluate.

Many people, not just philosophers and theologians, are troubled by the ethics of transgenic evolution. They grant the benefits but are unsettled by the reconstruction of organisms in bits and pieces. Of course, human beings have been creating new strains of plants and animals since agriculture began, but never at the sweep and pace inaugurated by genetic engineering. And during the era of traditional plant breeding, hybridization was used to mix genes almost always among varieties of the same species or closely similar species. Now it is used across entire kingdoms, from bacteria and viruses to plants and animals. How far the process should be allowed to continue remains an open ethical issue.

The effects on human health of each new transgenic food are hard to predict, and certainly never free of risk. However, the products can be tested just like any other new food products on the market, then certified and labeled. There is no reason at this time to assume that their effects will differ in any fundamental way. Yet scientists generally agree that a high level of alertness is essential, and for the following reason: All genes, whether original to the organism or donated to it by an exotic species, have multiple effects. Primary effects, such as the manufacture of a pesticide, are the ones sought. But destructive secondary effects, including allergenic or carcinogenic activity, are also at least a remote possibility.

Transgenes can escape from the modified crops into wild relatives of the crop where the two grow close together. Hybridization has always occurred widely in agriculture, even before the advent of genetic engineering. It has been recorded at one or another time and place in 12 of the 13 most important crops used worldwide. However, the hybrids have not overwhelmed their wild parents. I know of no case in which a hybrid strain outcompetes wild



Leopard in a Sausage Tree *(1979), by Robert Bateman*

strains of the same or closely related species in the natural environment. Nor has any hybrid turned into a superweed, in the same class as the worst wild nonhybrid weeds that afflict the planet. As a rule, domesticated species and strains are less competitive than their wild counterparts in both natural and human-modified environments. Of course, transgenes could change the picture. It is simply too early to tell.

Genetically modified crops can diminish biological diversity in other ways. In a now famous example, the bacterial toxin used to protect corn is carried in pollen by wind currents for distances of 60 meters or more from the cultivated fields. Then, landing on milkweed plants, the toxin is capable of killing the caterpillars of monarch butterflies feeding there. In another twist, when cultivated fields are cleared of weeds with chemical sprays against which the crops are protected by transgenes, the food supply of birds is reduced and their local populations decline. These environmental secondary effects have not been well studied in the field. How severe they will become as genetic engineering spreads remains to be seen.

Many people, having become aware of the potential threats of genetic engineering in their food supply, understandably believe that yet another bit of their freedom has been taken from them by faceless corporations (who can even name, say, three of the key players?) using technology beyond their control or even understanding. They also fear that an industrialized agriculture dependent on high technology can by one random error go terribly wrong. At the heart of the anxiety is a sense of helplessness. In the realm of public opinion, genetic engineering is to agriculture as nuclear engineering is to energy.

The problem before us is how to feed billions of new mouths over the next several decades and save the rest of life at the same time—without being trapped in a Faustian bargain that threatens freedom and security. No one knows the exact solution to this dilemma. Most scientists and economists who have studied both sides of it agree that the benefits outweigh the risks. The benefits must come from an evergreen revolution that has as its goal to lift food production well above the level attained by the green revolution of the 1960s, using technology and regulatory policy more advanced, and even safer, than that now in existence.

Genetic engineering will almost certainly play an important role in the evergreen revolution. Energized by recognition of both its promise and its risk, most countries have begun to fashion policies to regulate the marketing of transgenic crops. The ultimate driving force in this rapidly evolving process is international trade. More than 130 countries took an important first step in 2000 to address the issue by tentatively agreeing to the Cartagena Protocol on Biosafety, which provides the right to block imports of transgenic products. The protocol also sets up a joint "biosafety clearing house" to publish information on national policy. About the same time, the U.S. National Academy of Sciences, joined by the science academies of five other countries (Brazil, China, India, Mexico, and the United Kingdom) and the Third World Academy of Sciences, endorsed the development of transgenic crops. They made recommendations for risk assessment and licensing agreements and stressed the needs of the developing countries in future research programs and capital investment.

Medicine is another domain that stands to gain enormously from the world's store of biodiversity, with or without the impetus of genetic engineering. Pharmaceuticals in current use are already drawn heavily from wild species. In the United States, about a quarter of all prescriptions dispensed by pharmacies are substances extracted from plants. Another 13 percent originate from microorganisms, and three percent more from animals—making a total of about 40 percent derived from wild species. What's even more impressive is that nine of the 10 leading prescription drugs originally came from organisms. The commercial value of the relatively small number of natural products is substantial. The over-the-counter cost of drugs from plants alone was estimated in 1998 to be $20 billion in the United States and $84 billion worldwide.

But only a tiny fraction of biodiversity has been utilized in medicine, despite its obvious potential. The narrowness of the base is illustrated by the dominance of ascomycete fungi in the control of bacterial diseases. Although only about 30,000 species of ascomycetes—two percent of the total known species of organisms—have been studied, they have yielded 85 percent of the antibiotics in current use. The underutilization of biodiversity is still greater than these figures alone might suggest—because probably fewer than 10 percent of the world's ascomycete species have even been discovered and given scientific names. The flowering plants have been similarly scanted. Although it is likely that more than 80 percent of the species have received scientific names, only some three percent of this fraction have been assayed for alkaloids, the class of natural products that have proved to be among the most potent curative agents for cancer and many other diseases.

There is an evolutionary logic in the pharmacological bounty of wild species. Throughout the history of life, all kinds of organisms have evolved chemicals needed to control cancer in their own bodies, kill parasites, and fight off predators. Mutations and natural selection, which equip this armamentarium, are processes of endless trial and error. Hundreds of millions of species, evolving by the life and death of astronomical numbers of organisms across geological stretches of time, have yielded the present-day winners of the mutation-and-selection lottery. We have learned to consult them while assembling a large part of our own pharmacopoeia. Thus, antibiotics, fungicides, antimalarial drugs, anesthetics, analgesics, blood thinners, blood-clotting agents, agents that prevent clotting, cardiac stimulants and regulators, immunosuppressive agents, hormone mimics, hormone inhibitors, anticancer drugs, fever suppressants, inflammation controls, contraceptives, diuretics and antidiuretics, antidepressants, muscle relaxants, rubefacients, anticongestants, sedatives, and abortifacients are now at our disposal, compliments of wild biodiversity.

Revolutionary new drugs have rarely resulted from the pure insights of molecular and cellular biology, even though these sciences have grown very sophisticated and address the causes of disease at the most fundamental level. Rather, the pathway of discovery has usually been the reverse: The presence of the drug is first detected in whole organisms, and the nature of its activity subsequently tracked down to the molecular and cellular levels. Then the basic research begins.

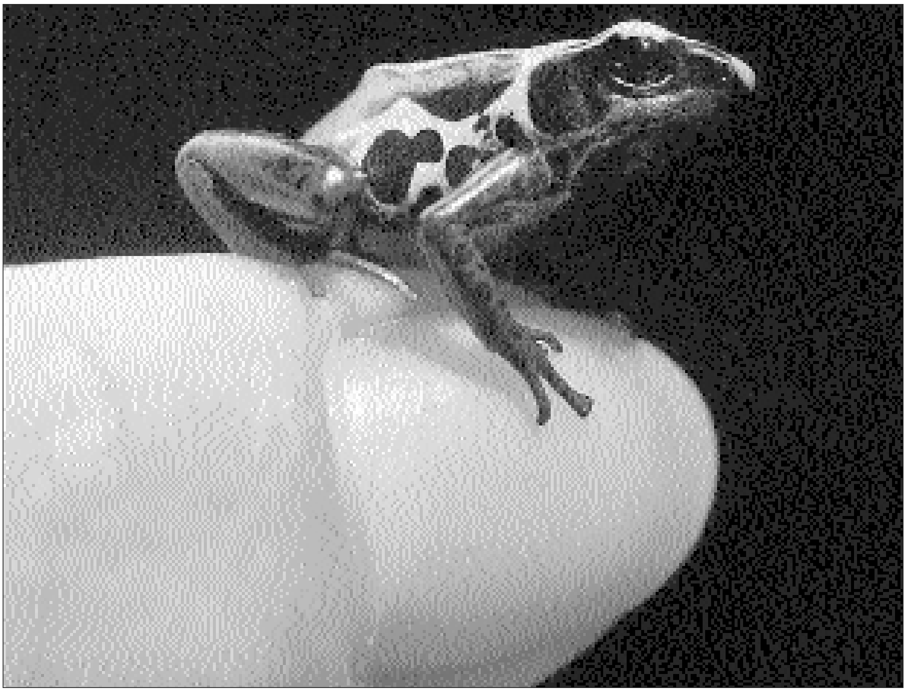
> THE PROBLEM BEFORE US IS HOW TO FEED BILLIONS OF NEW MOUTHS OVER THE NEXT SEVERAL DECADES AND SAVE THE REST OF LIFE AT THE SAME TIME.

The first hint of a new pharmaceutical may lie among the hundreds of remedies of Chinese traditional medicine. It may be spotted in the drug-laced rituals of an Amazonian shaman. It may come from a chance observation by a laboratory scientist unaware of its potential importance for medicine. More commonly nowadays, the clue is deliberately sought by the random screening of plant and animal tissues. If a positive response is obtained—say, a suppression of bacteria or cancer cells—the molecules responsible can be isolated and tested on a larger scale, using controlled experiments with animals and then (cautiously!) human volunteers. If the tests are successful, and the atomic structure of the molecule is also in hand, the substance can be synthesized in the laboratory, then commercially, usually at lower cost than by extraction from harvested raw materials. In the final step, the natural chemical compounds provide the prototype from which new classes of organic chemicals can be synthesized, adding or taking away atoms and double bonds here and there. A few of the novel substances may prove more efficient than the natural prototype. And of equal importance to the pharmaceutical companies, these analogues can be patented.

Serendipity is the hallmark of pharmacological research. A chance discovery can lead not only to a successful drug but to advances in fundamental science, which in time yield other successful drugs. Routine screening, for example, revealed that an obscure fungus growing in the mountainous interior of Norway produces a powerful suppressor of the human immune system. When the molecule was isolated from the fungal tissue and identified, it proved to be a complex molecule of a kind never before encountered by organic chemists. Nor could its effect be explained by the contemporary principles of molecular and cellular biology. But its relevance to medicine was immediately obvious, because when organs are transplanted from one person to another, the immune system of the host must be prevented from rejecting the alien tissue. The new agent, named cyclosporin, became an essential part of the organ transplant industry. It also served to open new lines of research on the molecular events of the immune response itself.

The surprising events that sometimes lead from natural history to medical breakthrough would make excellent science fiction—if only they were untrue. The protagonists of one such plot are the poison dart frogs of Central and South America, which belong to the genera *Dendrobates* and *Phyllobates* in the family Dendrobatidae. Tiny, able to perch on a human fingernail, they are favored as terrarium animals for their beautiful colors: The 40 known species are covered by various patterns of orange, red, yellow, green, or blue, usually on a black background. In their natural habitat, dendrobatids hop about slowly and are relatively unfazed by the approach of potential predators. For the trained naturalist their lethargy triggers an alarm, in observance of the following rule of animal behavior: If a small and otherwise unknown animal encountered in the wild is strikingly beautiful, it is probably poisonous, and if it is not only beautiful but also easy to catch, it is probably deadly. And so it is with dendrobatid frogs, which, it turns out, secrete a powerful toxin from glands on their backs. The potency varies according to species. A single individual of one (perfectly named) Colombian species, *Phyllobates horribilis*, for example, carries enough of the substance to kill 10 men. Indians of two tribes living in the Andean Pacific slope forests of western Colombia, the Emberá Chocó and the Noanamá Chocó, rub the tips of their blowgun darts over the backs of the frogs, very carefully, then release the little creatures unharmed so they can make more poison.

In the 1970s a chemist, John W. Daly, and a herpetologist, Charles W. Myers, gathered material from a similar Ecuadorian frog, *Epipedobates tricolor*, for a closer look at the dendrobatid toxin. In the laboratory, Daly found that very small amounts administered to mice worked as an



A South American poison dart frog is deadly out of all proportion to its thumbnail size.

opiumlike painkiller, yet otherwise lacked the properties of typical opiates. Would the substance also prove nonaddictive? If so, it might be turned into the ideal anesthetic. From a cocktail of compounds taken from the backs of the frogs, Daly and his fellow chemists isolated and characterized the toxin itself, a molecule resembling nicotine, which they named epibatidine. This natural product proved 200 times more effective in the suppression of pain than opium, but was also too toxic, unfortunately, for practical use. The next step was to redesign the molecule. Chemists at Abbott Laboratories synthesized not only epibatidine but hundreds of novel molecules resembling it. When tested clinically, one of the products, code-named ABT-594, was found to combine the desired properties: It depressed pain like epibatidine, including pain from nerve damage of a kind usually impervious to opiates, and it was nonaddictive. ABT-594 had two additional advantages: It promoted alertness instead of sleepiness, and it had no side effects on respiration or digestion.

The full story of the poison dart frogs also carries a warning about the conservation of tropical forests. The destruction of much of the habitat in which populations of *Epipedobates* live almost prevented the discovery of epibatidine and its synthetic analogues. By the time Daly and Myers set out to collect enough toxin for chemical analysis, after their initial visit to Ecuador, one of the two prime rainforest sites occupied by the frogs had been cleared and replaced with banana plantations. At the second site, which fortunately was still intact, they found enough frogs to harvest just one milligram of the poison. From that tiny sample, chemists were able, with skill and luck, to identify epibatidine and launch a major new initiative in pharmaceutical research.

It is no exaggeration to say that the search for natural medicinals is a race between science and extinction, and will become critically so as more forests fall and coral reefs bleach out and disintegrate. Another adventure dramatizing this point began in 1987, when the botanist John Burley collected samples of plants from a swamp forest near Lundu in the Malaysian state of Sarawak, on the northwestern corner of the island of Borneo. His expedition was one of many launched by the National Cancer Institute (NCI) to search for new natural substances to add to the fight against cancer and AIDS. Following routine procedure, the team collected a kilogram of fruit, leaves, and twigs from each kind of plant they encountered. Part was sent to the NCI laboratory for assay, and part was deposited in the Harvard University Herbarium for future identification and botanical research.

> Collecting samples of valuable species from rich ecosystems and cultivating them in bulk elsewhere is not only profitable but the most sustainable of all.

One such sample came from a small tree at Lundu about 25 feet high. It was given the voucher code label Burley-and-Lee 351. Back at the NCI laboratories, an extract made from it was tested routinely against human cancer cells grown in culture. Like the majority of such preparations, it had no effect. Then it was run through screens designed to test its potency against the AIDS virus. The NCI scientists were startled to observe that Burley-and-Lee 351 gave, in their words, "100 percent protection against the cytopathic effects of HIV-I infection," having "essentially halted HIV-I replication." In other words, while the substance the sample contained could not cure AIDS, it could stop cold the development of disease symptoms in HIV-positive patients.

The Burley-and-Lee 351 tree was determined to belong to a species of *Calophyllum*, a group of species belonging to the mangosteen family, or Guttiferae. Collectors were dispatched to Lundu a second time to obtain more material from the same tree, with the aim of isolating and chemically identifying the HIV inhibitor. The tree was gone, probably cut down by local people for fuel or building materials. The collectors returned home with samples from other *Calophyllum* trees taken in the same swamp forest, but their extracts were ineffective against the virus.

Peter Stevens, then at Harvard University, and the world authority on *Calophyllum*, stepped in to solve the problem. The original tree, he found, belonged to a rare strain named *Calopsyllum lanigerum*, variety *austrocoriaceum*. The trees sampled on the second trip were another species, which explained their inactivity. No more specimens of *austrocoriaceum* could be found at Lundu. The search for the magic strain widened, and finally a few more specimens were located in the Singapore Botanic Garden. Thus supplied with enough raw material, chemists and microbiologists were able to identify the anti-HIV substance as (+)-calanolide A. Soon afterward the molecule was synthesized, and the synthetic proved as effective as the raw extract. Additional research revealed calanolide to be a powerful inhibitor of reverse transcriptase, an enzyme needed by the HIV virus to replicate itself within the human host cell. Studies are now underway to determine the suitability of calanolide for market distribution.

The exploration of wild biodiversity in the search for useful resources is called *bioprospecting*. Propelled by venture capital, it has in the past 10 years grown into a respectable industry within a global market hungry for new pharmaceuticals. It is also a means for discovering new food sources, fibers, petroleum substitutes, and other products. Sometimes bioprospectors screen many species of organisms in search of chemicals with particular qualities, such as antisepsis or cancer suppression. On other occasions bioprospecting is opportunistic, focusing on one of a few species that show signs of yielding a valuable resource. Ultimately, entire ecosystems will be prospected as a whole, and all of the species assayed for most or all of the products they can yield.

The extraction of wealth from an ecosystem can be destructive or benign. Dynamiting coral reefs and clearcutting forests yield fast profits but are unsustainable. Fishing coral reefs lightly and gathering wild fruit and resins in otherwise undisturbed forest are sustainable. Collecting samples of valuable species from rich ecosystems and cultivating them in bulk elsewhere, in biologically less favored areas, is not only profitable but the most sustainable of all.

Bioprospecting with minimal disturbance is the way of the future. Its promise can be envisioned with the following matrix for a hypothetical forest: To the left, make a list of the thousands of plant, animal, and microbial species, as many as you can, recognizing that the vast majority have not yet been examined, and many still lack even a scientific name. Along the top, prepare a horizontal row of the hundreds of functions imaginable for all the products of these species combined. The matrix itself is the combination of the two dimensions. The spaces filled within the matrix are the potential applications, whose nature remains almost wholly unknown.

The richness of biodiversity's bounty is reflected in the products already extracted by native peoples of the tropical forests, using local knowledge and low technology of a kind transmitted solely by demonstration and oral teaching. Here, for example, is a small selection of the most common medicinal plants used by tribes of the upper Amazon, whose knowledge has evolved from their combined experience with the more than 50,000 species of flowering plants native to the region: motelo sanango, *Abuta grandifolia* (snakebite, fever); dye plant, *Arrabidaea chica* (anemia, conjunctivitis); monkey ladder, *Bauhinia guianensis* (amoebic dysentery); Spanish needles, *Bidens alba* (mouth sores, toothache); firewood tree, or capirona, species of *Calycophyllum* and *Capirona* (diabetes, fungal infection); wormseed, *Chenopodium ambrosioides* (worm infection);

caimito, *Chrysophyllum cainito* (mouth sores, fungal infection); toad vine, *Cissus sicyoides* (tumors); renaquilla, *Clusia rosea* (rheumatism, bone fractures); calabash, *Crescentia cujete* (toothache); milk tree, *Couma macrocarpa* (amoebic dysentery, skin inflammation); dragon's blood, *Croton lechleri* (hemorrhaging); fer-de-lance plant, *Dracontium loretense* (snakebite); swamp immortelle, *Erythrina fusca* (infections, malaria); wild mango, *Grias neuberthii* (tumors, dysentery); wild senna, *Senna reticulata* (bacterial infection).

Only a few of the thousands of such traditional medicinals used in tropical forests around the world have been tested by Western clinical methods. Even so, the most widely used already have commercial value rivaling that of farming and ranching. In 1992 a pair of economic botanists, Michael Balick and Robert Mendelsohn, demonstrated that single harvests of wild-grown medicinals from two tropical forest plots in Belize were worth $726 and $3,327 per hectare (2.5 acres) respectively, with labor costs thrown in. By comparison, other researchers estimated per hectare yield from tropical forest converted to farmland at $228 in nearby Guatemala and $339 in Brazil. The most productive Brazilian plantations of tropical pine could yield $3,184 per hectare from a single harvest.

In short, medicinal products from otherwise undisturbed tropical forests can be locally profitable, on condition that markets are developed and the extraction rate is kept low enough to be sustainable. And when plant and animal food products, fibers, carbon credit trades, and ecotourism are added to the mix, the commercial value of sustainable use can be boosted far higher.

Examples of the new economy in practice are growing in number. In the Petén region of Guatemala, about 6,000 families live comfortably by sustainable extraction of rainforest products. Their combined annual income is $4 million to $6 million, more than could be made by converting the forest into farms and cattle ranches. Ecotourism remains a promising but largely untapped additional resource.

Nature's pharmacopoeia has not gone unnoticed by industry strategists. They are well aware that even a single new molecule has the potential to recoup a large capital investment in bioprospecting and product development. The single greatest success to date was achieved with extremophile bacteria living in the boiling-hot thermal springs of Yellowstone National Park. In 1983 Cetus Corporation used one of the organisms, *Thermus aquaticus*, to produce a heat-resistant enzyme needed for DNA synthesis. The manufacturing process, called *polymerase chain reaction* (PCR), is today the foundation of rapid genetic mapping, a stanchion of the new molecular biology and medical genetics. By enabling microscopic amounts of DNA to be multiplied and typed, PCR also plays a key role in crime detection and forensic medicine. Cetus's patents on PCR technology, which have been upheld by the courts, are immensely profitable, with annual earnings now in excess of $200 million—and growing.

Bioprospecting can serve both mainstream economics and conservation when put on a firm contractual basis. In 1991, Merck signed an agreement with Costa Rica's National Institute of Biodiversity (INBio) to assist the search for new pharmaceuticals in Costa Rica's rainforests and other natural habitats. The first deposit was $1 million dispensed over two years, with two similar consecutive grants to follow. During the first period, the field collectors concentrated on plants, in the second on insects, and in the third on microorganisms. Merck is now working through the immense library of materials it gathered during the field program and testing and refining chemical extracts made from them.

Also in 1991, Syntex signed a contract with Chinese science academies to receive up to 10,000 plant extracts a year for pharmaceutical assays. In 1998, Diversa Corporation signed on with Yellowstone National Park to continue bioprospecting the hot springs for biochemicals from thermophilic microbes. Diversa pays the park $20,000 yearly to collect the organisms for study, as well as a fraction of the profits generated by commercial development. Funds returning to Yellowstone will be used to promote conservation of the unique microbes and their habitat, as well as basic scientific research and public education.

Still other agreements have been signed between NPS Pharmaceuticals and the government of Madagascar, between Pfizer and the New York Botanical Garden, and between the international company GlaxoSmithKline and a Brazilian pharmaceutical company, with part of the profits pledged to the support of Brazilian science.

Perhaps it is enough to argue that the preservation of the living world is necessary to our long-term material prosperity and health. But there is another, and in some ways deeper, reason not to let the natural world slip away. It has to do with the defining qualities and self-image of the human species. Suppose, for the sake of argument, that new species can one day be engineered and stable ecosystems built from them. With that distant prospect in mind, should we go ahead and, for short-term gain, allow the original species and ecosystems to be lost? Yes? Erase Earth's living history? Then also burn the art galleries, make cordwood of the musical instruments, pulp the musical scores, erase Shakespeare, Beethoven, and Goethe, and the Beatles too, because all these—or at least fairly good substitutes—can be re-created.

The issue, like all great decisions, is moral. Science and technology are what we can do; morality is what we agree we should or should not do. The ethic from which moral decisions spring is a norm or standard of behavior in support of a value, and value in turn depends on purpose. Purpose, whether personal or global, whether urged by conscience or graven in sacred script, expresses the image we hold of ourselves and our society. A conservation ethic is that which aims to pass on to future generations the best part of the nonhuman world. To know this world is to gain a proprietary attachment to it. To know it well is to love and take responsibility for it. ❑