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EDWARD O. WILSON

The Diversity of Life

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To my mother
Inez Linnette Huddleston
in love and gratitude

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Preface to the 2010 Printing

If any date can be fixed for the beginning of modern biodiversity studies, it would likely be September 21, 1986, when a National Forum on BioDiversity was held in Washington, D.C. Sponsored jointly by the National Research Council and the Smithsonian Institution, the three-day meeting brought together more than sixty leading biologists, economists, agricultural experts, philosophers, and representatives of assistance and leading agencies. When the contributions of this eclectic assemblage were published two years later under the title *BioDiversity,* the book became, by scientific publication standards at least, an international bestseller. As its editor, I had already adopted in other writings the unified word "biodiversity," and that is where the term settled.

The material covered in *BioDiversity,* which was focused primarily on biology and written for a broad readership, became the subject of the present book, *The Diversity of Life,* first published in 1992.

Biodiversity, short for biological diversity, is defined as the totality of inherited variation in all the organisms of a selected area. The area can be a woodland or a system of forests or a pond or an ocean. It can be a political unit, say a state or a country. Or it can be the whole world. Once the location is selected, researchers study biodiversity at one or the other or all three levels of biological organization: first ecosystems, such as a forest patch or a pond; then, next down, all the species, from microorganisms to trees and megafauna; and finally, at the third and lowest level, the genes that prescribe the traits of the species that make up the ecosystems.

It may well be asked at this point, what is so new about "modern" biodiversity studies? After all, record of humanity's attempt to identify all species of organisms dates back to Aristotle. The formalization of taxonomy to accomplish that goal was the consuming interest of Carl Linnaeus, one of the most influential scientists of the eighteenth century. Further, the discovery of the origin of species dates to

Charles Darwin. The process of speciation and the multiplication of species, as opposed to the change of individual species through time, had been worked out by Alfred Russel Wallace by 1865, and elaborated to the level of chromosomes and genes during the first half of the twentieth century. The same can be said of biogeography, the mapping of species, and the deduction of phylogenies begun by Wallace and Lamarck—also in the nineteenth century.

The full maturation of biodiversity studies, however, can be dated to the era begun in the 1980s, and is based upon two new developments. The first is the re-igniting of the great Linnaean enterprise, based upon the recognition that despite more than two centuries of taxonomic labor, most of the biodiversity of the world remains unknown. The second development is the extension of the boundary of biodiversity studies in order to unite them with other branches of science and technology.

To say that the fauna and flora of the world remains largely unknown is no exaggeration. At the present time (2010), the numbers of known species of all kinds of organisms, defined as those discovered, characterized, and given a scientific name, is approximately 1.9 million. The actual number in existence on Earth has been variously estimated to be between 5 and more than 50 million; if microorganisms are added, the number would have to be increased dramatically, albeit to an entirely unknown degree.

In 2006–2007, approximately 18,000 new species of all kinds of non-microbial organisms were being described each year. Of these species, about 75 percent were invertebrates, 7 percent were vertebrates, and 11 percent were plants.* If we accept 10 million species as the total global number, a figure most biodiversity experts find conservative, it follows that at the present rate of species discovery it will be half another millennium, well into the twenty-seventh century, before the census of life on Earth is complete.

Nor are the still largely unknown groups of organisms trivial in importance to the rest of life, including our own. The 100,000 species of fungi thus far discovered and named are but a tiny fraction of the roughly 1.5 million estimated to exist. Fewer than 25,000 species of nematodes, tiny wormlike creatures considered the most abundant animals on the planet, are known, whereas somewhat less than a half

*These estimates are from Arthur D. Chapman, ed., *Numbers of Living Species in Australia and the World,* 2nd ed. (Australian Biodiversity Information Services, Department of the Environment, Water, Heritage and the Arts, Australia, September 2009).

million have been estimated to await discovery. Some 14,000 known species of ants, the most abundant and ecologically dominant insects, probably represent no more than half of those in existence. The same rough figure—half or less—applies to the world's beetles and flies.

Science is at the dawn of a new age in the discovery of biodiversity. Yet it is clear that a much greater effort is needed from humanity if we wish to continue struggling along on a little-known planet. The technology exists to speed the effort to map the living world. DNA sequencing is now rapid enough for the mapping of complete genomes in days or even (in bacteria, for example) hours. Metagenomics, the sampling of DNA from assemblages of species in selected ecosystems, allows "quick and dirty" estimates of the amount of microbial diversity in soil and water. Once species of all kinds are separated and described by diagnostic traits, they can be quickly identified by DNA barcoding—the reading of selected parts of the genome.

As information accumulates, it is already being fed into databases available through single access on command. The most encompassing is the Encyclopedia of Life (http://www.eol.org), which was begun in 2005 and is well on its way to recording and making immediately accessible everything known about every species of organism, with updates on already known species and information on new species as they are discovered.

The first round of taxonomic discovery and archiving is only the beginning. Of the known species of organisms, only a very small fraction of the species, approximately 3 percent, have been studied well enough to evaluate their conservation status—whether they are abundant and widespread enough to be stable and safe, or liable in any degree to extinction. The 5,490 species of mammals and 9,998 species of birds thus far discovered have all been evaluated in this manner, but this knowledge is more than counterbalanced by our ignorance of plants (3.9 percent of 282,000 known species) and invertebrate animals (0.6 percent of 1.3 million species).*

Every species on Earth has been adapted by thousands to millions of years of evolution to the particularities of the environment in which it lives. Its genotype is different from that of all other species. The traits its genes prescribe are also unique, in biochemistry, anatomy, physiology, and behavior, and in the way it interacts with other

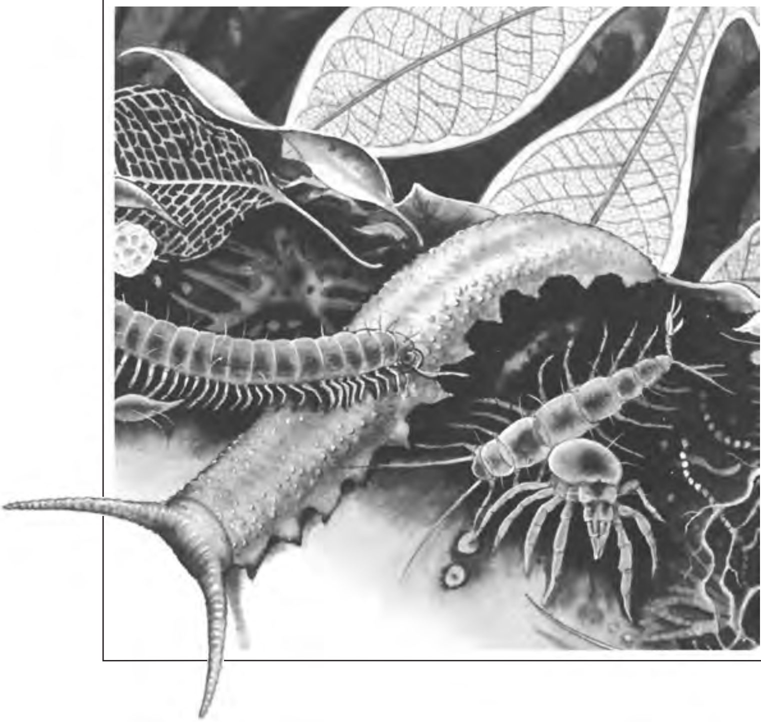
*These estimates are from S. N. Stuart, E. O. Wilson, J. A. McNeely, R. A. Mittermeier, and J. P. Rodríguez, "The barometer of life," *Science* 328:177 (9 April 2010).

species and serves the ecosystem it inhabits. Each species, in short, is a living encyclopedia of how to survive on planet Earth.

Humanity is in the very early stages of acquiring the knowledge biodiversity offers us. The impact of biodiversity studies on medicine, biotechnology, and agriculture is already substantial, and will in time become enormous. As the reach of general biology at all levels grows, the role of biodiversity studies will become disproportionately large. Its importance is foreordained by the fact that future biology as a whole is settling upon two laws. The first is that all living processes are ultimately obedient to the laws of physics and chemistry. This provides the foundation of molecular, cellular, and developmental biology. The second law is that all living processes have originated through evolution by natural selection. That perception is the foundation of evolutionary and environmental biology, much of which is devoted to biodiversity studies. In time, I believe, biology will be seen as a discipline that advances in coordinated manner along these two fronts.

Edward O. Wilson
20 May 2010

Violent Nature, Resilient Life



CHAPTER ONE

Storm over the Amazon

IN THE AMAZON BASIN the greatest violence sometimes begins as a flicker of light beyond the horizon. There in the perfect bowl of the night sky, untouched by light from any human source, a thunderstorm sends its premonitory signal and begins a slow journey to the observer, who thinks: the world is about to change. And so it was one night at the edge of rain forest north of Manaus, where I sat in the dark, working my mind through the labyrinths of field biology and ambition, tired, bored, and ready for any chance distraction.

Each evening after dinner I carried a chair to a nearby clearing to escape the noise and stink of the camp I shared with Brazilian forest workers, a place called Fazenda Dimona. To the south most of the forest had been cut and burned to create pastures. In the daytime cattle browsed in remorseless heat bouncing off the yellow clay and at night animals and spirits edged out onto the ruined land. To the north the virgin rain forest began, one of the great surviving wildernesses of the world, stretching 500 kilometers before it broke apart and dwindled into gallery woodland among the savannas of Roraima.

Enclosed in darkness so complete I could not see beyond my outstretched hand, I was forced to think of the rain forest as though I were seated in my library at home, with the lights turned low. The forest at night is an experience in sensory deprivation most of the time, black and silent as the midnight zone of a cave. Life is out there in expected abundance. The jungle teems, but in a manner mostly beyond the reach of the human senses. Ninety-nine percent of the animals find their way by chemical trails laid over the surface, puffs of odor released into the air or water, and scents diffused out of little hidden glands and into the air downwind. Animals are masters of this chemical channel, where we are idiots. But we are geniuses of the audiovisual channel, equaled in this modality only by a few odd groups (whales, monkeys, birds). So we wait for the dawn, while they wait for the fall of darkness; and because sight and sound are the evolutionary prerequisites of intelligence, we alone have come to reflect on such matters as Amazon nights and sensory modalities.

I swept the ground with the beam from my headlamp for signs of life, and found—diamonds! At regular intervals of several meters, intense pinpoints of white light winked on and off with each turning of the lamp. They were reflections from the eyes of wolf spiders, members of the family Lycosidae, on the prowl for insect prey. When spotlighted the spiders froze, allowing me to approach on hands and knees and study them almost at their own level. I could distinguish a wide variety of species by size, color, and hairiness. It struck me how little is known about these creatures of the rain forest, and how deeply satisfying it would be to spend months, years, the rest of my life in this place until I knew all the species by name and every detail of their lives. From specimens beautifully frozen in amber we know that the Lycosidae have survived at least since the beginning of the Oligocene epoch, forty million years ago, and probably much longer. Today a riot of diverse forms occupy the whole world, of which this was only the minutest sample, yet even these species turning about now to watch me from the bare yellow clay could give meaning to the lifetimes of many naturalists.

The moon was down, and only starlight etched the tops of the trees. It was August in the dry season. The air had cooled enough to make the humidity pleasant, in the tropical manner, as much a state of mind as a physical sensation. The storm I guessed was about an hour away. I thought of walking back into the forest with my headlamp to hunt for new treasures, but was too tired from the day's work. Anchored again to my chair, forced into myself, I welcomed a meteor's streak and the occasional courtship flash of luminescent click beetles among the nearby but unseen shrubs. Even the passage of a jetliner 10,000 meters up, a regular event each night around ten o'clock, I awaited with pleasure. A week in the rain forest had transformed its distant rumble from an urban irritant into a comforting sign of the continuance of my own species.

But I was glad to be alone. The discipline of the dark envelope summoned fresh images from the forest of how real organisms look and act. I needed to concentrate for only a second and they came alive as eidetic images, behind closed eyelids, moving across fallen leaves and decaying humus. I sorted the memories this way and that in hope of stumbling on some pattern not obedient to abstract theory of textbooks. I would have been happy with *any* pattern. The best of science doesn't consist of mathematical models and experiments, as textbooks make it seem. Those come later. It springs fresh from a more primitive mode of thought, wherein the hunter's mind weaves ideas from old facts and fresh metaphors and the scrambled crazy images of things recently seen. To move forward is to concoct new patterns of thought, which in turn dictate the design of the models and experiments. Easy to say, difficult to achieve.

The subject fitfully engaged that night, the reason for this research trip to the Brazilian Amazon, had in fact become an obsession and, like all obsessions, very likely a dead end. It was the kind of favorite puzzle that keeps forcing its way back because its very intractability makes it perversely pleasant, like an overly familiar melody intruding into the relaxed mind because it loves you and will not leave you. I hoped that some new image might propel me past the jaded puzzle to the other side, to ideas strange and compelling.

Bear with me for a moment while I explain this bit of personal esoterica; I am approaching the subject of central interest. Some kinds of plants and animals are dominant, proliferating new species and spreading over large parts of the world. Others are driven back until they become rare and threatened by extinction. Is there a single formula for this biogeographic difference, for all kinds of organisms? The process, if articulated, would be a law or at least a principle of dynastic succession in evolution. I was intrigued by the circumstance that social insects, the group on which I have spent most of my life, are among the most abundant of all organisms. And among the social insects, the dominant subgroup is the ants. They range 20,000 or more species strong from the Arctic Circle to the tip of South America. In the Amazon rain forest they compose more than 10 percent of the biomass of all animals. This means that if you were to collect, dry out, and weigh every animal in a piece of forest, from monkeys and birds down to mites and roundworms, at least 10 percent would consist of these insects alone. Ants make up almost half of the insect biomass overall and 70 percent of the individual insects found in the treetops. They are only slightly less abundant in grasslands, deserts, and temperate forests throughout the rest of the world.

It seemed to me that night, as it has to others in varying degrees of persuasion many times before, that the prevalence of ants must have something to do with their advanced colonial organization. A colony is a superorganism, an assembly of workers so tightly knit around the mother queen as to act like a single, well-coordinated entity. A wasp or other solitary insect encountering a worker ant on its nest faces more than just another insect. It faces the worker and all her sisters, united by instinct to protect the queen, seize control of territory, and further the growth of the colony. Workers are little kamikazes, prepared—eager—to die in order to defend the nest or gain control of a food source. Their deaths matter no more to the colony than the loss of hair or a claw tip might to a solitary animal.

There is another way to look at an ant colony. Workers foraging around their nest are not merely insects searching for food. They are a living web cast out by the superorganism, ready to congeal over rich food finds or shrink back from the most formidable enemies. Superorganisms can control and dominate the ground and treetops in competition with ordinary, solitary organisms, and that is surely why ants live everywhere in such great numbers.

I heard around me the Greek chorus of training and caution: *How can you prove that is the reason for their dominance? Isn't the connection just another shaky conclusion that because two events occur together, one causes the other? Something else entirely different might have caused both. Think about it—greater individual fighting ability? Sharper senses? What?*

Such is the dilemma of evolutionary biology. We have problems to solve, we have clear answers—too many clear answers. The difficult part is picking out the right answer. The isolated mind moves in slow circles and breakouts are rare. Solitude is better for weeding out ideas than for creating them. Genius is the summed production of the many with the names of the few attached for easy recall, unfairly so to other scientists. My mind drifted into the hourless night, no port of call yet chosen.

The storm grew until sheet lightning spread across the western sky. The thunderhead reared up like a top-heavy monster in slow motion, tilted forward, blotting out the stars. The forest erupted in a simulation of violent life. Lightning bolts broke to the front and then closer, to the right and left, 10,000 volts dropping along an ionizing path at 800 kilometers an hour, kicking a countersurge skyward ten times faster, back and forth in a split second, the whole perceived as a single flash and crack of sound. The wind freshened, and rain came stalking through the forest.

In the midst of chaos something to the side caught my attention. The lightning bolts were acting like strobe flashes to illuminate the wall of the rain forest. At intervals I glimpsed the storied structure: top canopy 30 meters off the ground, middle trees spread raggedly below that, and a lowermost scattering of shrubs and small trees. The forest was framed for a few moments in this theatrical setting. Its image turned surreal, projected into the unbounded wildness of the human imagination, thrown back in time 10,000 years. Somewhere close I knew spear-nosed bats flew through the tree crowns in search of fruit, palm vipers coiled in ambush in the roots of orchids, jaguars walked the river's edge; around them eight hundred species of trees stood, more than are native to all of North America; and a thousand species of butterflies, 6 percent of the entire world fauna, waited for the dawn.

About the orchids of that place we knew very little. About flies and beetles almost nothing, fungi nothing, most kinds of organisms nothing. Five thousand kinds of bacteria might be found in a pinch of soil, and about them we knew absolutely nothing. This was wilderness in the sixteenth-century sense, as it must have formed in the minds of the Portuguese explorers, its interior still largely unexplored and filled with strange, myth-engendering plants and animals. From such a place the pious naturalist would send long respectful letters to royal patrons about the wonders of the new world as testament to the glory of God. And I thought: there is still time to see this land in such a manner.

The unsolved mysteries of the rain forest are formless and seductive. They are like unnamed islands hidden in the blank spaces of old maps, like dark shapes glimpsed descending the far wall of a reef into the abyss. They draw us forward and stir strange apprehensions. The unknown and prodigious are drugs to the scientific imagination, stirring insatiable hunger with a single taste. In our hearts we hope we will never discover everything. We pray there will always be a world like this one at whose edge I sat in darkness. The rain forest in its richness is one of the last repositories on earth of that timeless dream.

That is why I keep going back to the forests forty years after I began, when I flew down to Cuba, a graduate student caught up in the idea of the "big" tropics, free at last to look for something hidden, as Kipling had urged, something lost behind the Ranges. The chances are high, in fact certain, of finding a new species or phenomenon within days or, if you work hard, hours after arrival. The hunt is also on for rare species already discovered but still effectively unknown—represented by one or two specimens placed in a museum drawer fifty or a hundred years ago, left with nothing but a locality and a habitat note handwritten on a tiny label ("Santarém, Brazil, nest on side of tree in swamp forest"). Unfold the stiff yellowing piece of paper and a long-dead biologist speaks: I was there, I found this, now you know, now move on.

There is still more to the study of biological richness. It is a microcosm of scientific exploration as a whole, refracting hands-on experience onto a higher plane of abstraction. We search in and around a subject for a concept, a pattern, that imposes order. We look for a way of speaking about the rough unmapped terrain, even just a name or a phrase that calls attention to the object of our attention. We hope to be the first to make a connection. Our goal is to capture and label a process, perhaps a chemical reaction or behavior pattern driving an ecological change, a new way of classifying energy flow, or a relation between predator and prey that preserves them both, almost anything at all. We will settle for just one good question that starts people thinking and talking: Why are there so many species? Why have mammals evolved more quickly than reptiles? Why do birds sing at dawn?

These whispering denizens of the mind are sensed but rarely seen. They rustle the foliage, leave behind a pug mark filling with water and a scent, excite us for an instant and vanish. Most ideas are waking dreams that fade to an emotional residue. A first-rate scientist can hope to capture and express only several in a lifetime. No one has learned how to invent with any consistent success the equations and phrases of science, no one has captured the metaformula of scientific research. The conversion is an art aided by a stroke of luck in minds set to receive them. We hunt outward and we hunt inward, and the value of the quarry on one side of that mental barrier is commensurate with the value of the quarry on the other side. Of this dual quality the great chemist Berzelius wrote in 1818 and for all time:

> All our theory is but a means of consistently conceptualizing the inward processes of phenomena, and it is presumable and adequate when all scientifically known facts can be deduced from it. This mode of conceptualization can equally well be false and, unfortunately, presumably is so frequently. Even though, at a certain period in the development of science, it may match the purpose just as well as a true theory. Experience is augmented, facts appear which do not agree with it, and one is forced to go in search of a new mode of conceptualization within which these facts can also be accommodated; and in this manner, no doubt, modes of conceptualization will be altered from age to age, as

experience is broadened, and the complete truth may perhaps never be attained.

The storm arrived, racing from the forest's edge, turning from scattered splashing drops into sheets of water driven by gusts of wind. It forced me back to the shelter of the corrugated iron roof of the open-air living quarters, where I sat and waited with the *mateiros.* The men stripped off their clothing and walked out into the open, soaping and rinsing themselves in the torrential rain, laughing and singing. In bizarre counterpoint, leptodactylid frogs struck up a loud and monotonous honking on the forest floor close by. They were all around us. I wondered where they had been during the day. I had never encountered a single one while sifting through the vegetation and rotting debris on sunny days, in habitats they are supposed to prefer.

Farther out, a kilometer or two away, a troop of red howler monkeys chimed in, their chorus one of the strangest sounds to be heard in all of nature, as enthralling in its way as the songs of humpback whales. A male opened with an accelerating series of deep grunts expanding into prolonged roars and was then joined by the higher-pitched calls of the females. This far away, filtered through dense foliage, the full chorus was machine-like: deep, droning, metallic.

Such raintime calls are usually territorial advertisements, the means by which the animals space themselves out and control enough land to forage and breed. For me they were a celebration of the forest's vitality: *Rejoice! The powers of nature are within our compass, the storm is part of our biology!*

For that is the way of the nonhuman world. The greatest powers of the physical environment slam into the resilient forces of life, and nothing much happens. For a very long time, 150 million years, the species within the rain forest evolved to absorb precisely this form and magnitude of violence. They encoded the predictable occurrence of nature's storms in the letters of their genes. Animals and plants have come to use heavy rains and floods routinely to time episodes in their life cycle. They threaten rivals, mate, hunt prey, lay eggs in new water pools, and dig shelters in the rain-softened earth.

On a larger scale, the storms drive change in the whole structure of the forest. The natural dynamism raises the diversity of life by means of local destruction and regeneration.

Somewhere a large horizontal tree limb is weak and vulnerable, covered by a dense garden of orchids, bromeliads, and other kinds of plants that grow on trees. The rain fills up the cavities enclosed by the axil sheaths of the epiphytes and soaks the humus and clotted dust around their roots. After years of growth the weight has become nearly unsupportable. A gust of wind whips through or lightning strikes the tree trunk, and the limb breaks and plummets down, clearing a path to the ground. Elsewhere the crown of a giant tree emergent above the rest catches the wind and the tree sways above the rain-soaked soil. The shallow roots cannot hold, and the entire tree keels over. Its trunk and canopy arc downward like a blunt ax, shearing through smaller trees and burying understory bushes and herbs. Thick lianas coiled through the limbs are pulled along. Those that stretch to other trees act as hawsers to drag down still more vegetation. The massive root system heaves up to create an instant mound of bare soil. At yet another site, close to the river's edge, the rising water cuts under an overhanging bank to the critical level of gravity, and a 20-meter front collapses. Behind it a small section of forest floor slides down, toppling trees and burying low vegetation.

Such events of minor violence open gaps in the forest. The sky clears again and sunlight floods the ground. The surface temperature rises and the humidity falls. The soil and ground litter dries out and warms up still more, creating a new environment for animals, fungi, and microorganisms of a different kind from those in the dark forest interior. In the following months pioneer plant species take seed. They are very different from the young shade-loving saplings and understory shrubs of the prevailing old-stand forest. Fast-growing, small in stature, and short-lived, they form a single canopy that matures far below the upper crowns of the older trees all around. Their tissue is soft and vulnerable to herbivores. The palmate-leaved trees of the genus *Cecropia*, one of the gap-filling specialists of Central and South America, harbor vicious ants in hollow internodes of the trunk. These insects, bearing the appropriate scientific name *Azteca*, live in symbiosis with their hosts, protecting them from all predators except sloths and a few other herbivores specialized to feed on *Cecropia.* The symbionts live among new assemblages of species not found in the mature forest.

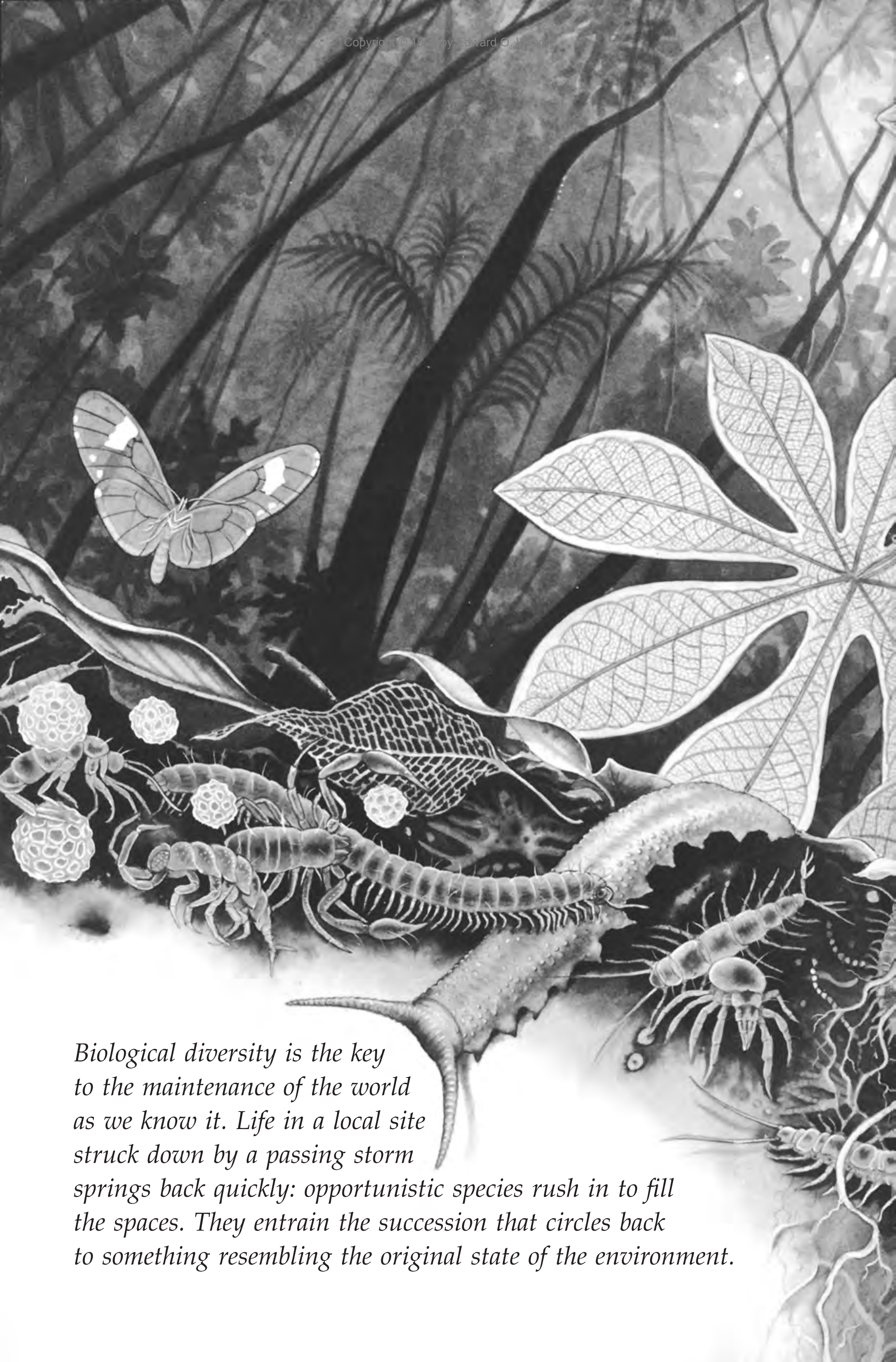
All around the second-growth vegetation, the fallen trees and branches rot and crumble, offering hiding places and food to a vast array of basidiomycete fungi, slime molds, ponerine ants, scolytid beetles, bark lice, earwigs, embiopteran webspinners, zorapterans, entomobryomorph springtails, japygid diplurans, schizomid arachnids, pseudoscorpions, real scorpions, and other forms that live mostly or exclusively in this habitat. They add thousands of species to the diversity of the primary forest.

Climb into the tangle of fallen vegetation, tear away pieces of rotting bark, roll over logs, and you will see these creatures teeming everywhere. As the pioneer vegetation grows denser, the deepening shade and higher humidity again favor old-forest species, and their saplings sprout and grow. Within a hundred years the gap specialists will be phased out by competition for light, and the tall storied forest will close completely over.

In the succession, pioneer species are the sprinters, old-forest species the long-distance runners. The violent changes and a clearing of space bring all the species briefly to the same starting line. The sprinters dash ahead, but the prolonged race goes to the marathoners. Together the two classes of specialists create a complex mosaic of vegetation types across the forest which, by regular tree falls and landslides, is forever changing. If square kilometers of space are mapped over decades of time, the mosaic turns into a riotous kaleidoscope whose patterns come and go and come again. A new marathon is always beginning somewhere in the forest. The percentages of successional vegetation types are consequently more or less in a steady state, from earliest pioneer species through various mixes of pioneer and deep-forest trees to stands of the most mature physiognomy. Walk randomly on any given day for one or two kilometers through the forest, and you will cut through many of these successional stages and sense the diversity sustained by the passage of storms and the fall of forest giants.

It is diversity by which life builds and saturates the rain forest. And diversity has carried life beyond, to the harshest environments on earth. Rich assemblages of animals swarm in the shallow bays of Antarctica, the coldest marine habitats on earth. Perch-like notothenioid fishes swim there in temperatures just above the freezing point of salt water but cold enough to turn ordinary blood to ice, because they are able to generate glycopeptides in their tissues as antifreeze and thrive where other fish cannot go. Around them flock dense populations of active brittlestars, krill, and other invertebrate animals, each with protective devices of its own.

Overleaf: **Seen from the level of soil-dwelling insects, a young cecropia tree grows upward within a gap created by a storm in the Brazilian rain forest.**



Biological diversity is the key to the maintenance of the world as we know it. Life in a local site struck down by a passing storm springs back quickly: opportunistic species rush in to fill the spaces. They entrain the succession that circles back to something resembling the original state of the environment.

In a radically different setting, the deep unlighted zone of caves around the world, blind white springtails, mites, and beetles feed on fungi and bacteria growing on rotting vegetable matter washed down through ground water. They are eaten in turn by blind white beetles and spiders also specialized for life in perpetual darkness.

Some of the harshest deserts of the world are home to unique ensembles of insects, lizards, and flowering plants. In the Namib of southwestern Africa, beetles use leg tips expanded into oarlike sandshoes to swim down through the shifting dunes in search of dried vegetable matter. Others, the swiftest runners of the insect world, race over the baking hot surface on bizarre stilt legs.

Archaebacteria, one-celled microorganisms so different from ordinary bacteria as to be candidates for a separate kingdom of life, occupy the boiling water of mineral hot springs and volcanic vents in the deep sea. The species composing the newly discovered genus *Methanopyrus* grow in boiling vents at the bottom of the Mediterranean Sea in temperatures up to 110°C.

Life is too well adapted in such places, out to the edge of the physical envelope where biochemistry falters, and too diverse to be broken by storms and other ordinary vagaries of nature. But diversity, the property that makes resilience possible, is vulnerable to blows that are greater than natural perturbations. It can be eroded away fragment by fragment, and irreversibly so if the abnormal stress is unrelieved. This vulnerability stems from life's composition as swarms of species of limited geographical distribution. Every habitat, from Brazilian rain forest to Antarctic bay to thermal vent, harbors a unique combination of plants and animals. Each kind of plant and animal living there is linked in the food web to only a small part of the other species. Eliminate one species, and another increases in number to take its place. Eliminate a great many species, and the local ecosystem starts to decay visibly. Productivity drops as the channels of the nutrient cycles are clogged. More of the biomass is sequestered in the form of dead vegetation and slowly metabolizing, oxygen-starved mud, or is simply washed away. Less competent pollinators take over as the best-adapted bees, moths, birds, bats, and other specialists drop out. Fewer seeds fall, fewer seedlings sprout. Herbivores decline, and their predators die away in close concert.

In an eroding ecosystem life goes on, and it may look superficially the same. There are always species able to recolonize the impoverished area and exploit the stagnant resources, however clumsily accomplished. Given enough time, a new combination of species—a reconstituted fauna and flora—will reinvest the habitat in a way that transports energy and materials somewhat more efficiently. The atmosphere they generate and the composition of the soil they enrich will resemble those found in comparable habitats in other parts of the world, since the species are adapted to penetrate and reinvigorate just such degenerate systems. They do so because they gain more energy and materials and leave more offspring. But the restorative power of the fauna and flora of the world as a whole depends on the existence of enough species to play that special role. They too can slide into the red zone of endangered species.

Biological diversity—"biodiversity" in the new parlance—is the key to the maintenance of the world as we know it. Life in a local site struck down by a passing storm springs back quickly because enough diversity still exists. Opportunistic species evolved for just such an occasion rush in to fill the spaces. They entrain the succession that circles back to something resembling the original state of the environment.

This is the assembly of life that took a billion years to evolve. It has eaten the storms—folded them into its genes—and created the world that created us. It holds the world steady. When I rose at dawn the next morning, Fazenda Dimona had not changed in any obvious way from the day before. The same high trees stood like a fortress along the forest's edge; the same profusion of birds and insects foraged through the canopy and understory in precise individual timetables. All this seemed timeless, immutable, and its very strength posed the question: how much force does it take to break the crucible of evolution?

C H A P T E R   T W O

Krakatau

KRAKATAU, earlier misnamed Krakatoa, an island the size of Manhattan located midway in the Sunda Strait between Sumatra and Java, came to an end on Monday morning, August 27, 1883. It was dismembered by a series of powerful volcanic eruptions. The most violent occurred at 10:02 A.M., blowing upward like the shaped explosion of a large nuclear bomb, with an estimated force equivalent to 100–150 megatons of TNT. The airwave it created traveled at the speed of sound around the world, reaching the opposite end of the earth near Bogotá, Colombia, nineteen hours later, whereupon it bounced back to Krakatau and then back and forth for seven recorded passages over the earth's surface. The audible sounds, resembling the distant cannonade of a ship in distress, carried southward across Australia to Perth, northward to Singapore, and westward 4,600 kilometers to Rodriguez Island in the Indian Ocean, the longest distance traveled by any airborne sound in recorded history.

As the island collapsed into the subterranean chamber emptied by the eruption, the sea rushed in to fill the newly formed caldera. A column of magma, rock, and ash rose 5 kilometers into the air, then fell earthward, thrusting the sea outward in a tsunami 40 meters in height. The great tidal waves, resembling black hills when first sighted on the horizon, fell upon the shores of Java and Sumatra, washing away entire towns and killing 40,000 people. The segments traversing the channels and reaching the open sea continued on as spreading waves around the world. The waves were still a meter high when they came ashore in Ceylon, now Sri Lanka, where they drowned one person, their last casualty. Thirty-two hours after the explosion, they rolled in to Le Havre, France, reduced at last to centimeter-high swells.

The eruptions lifted more than 18 cubic kilometers of rock and other material into the air. Most of this tephra, as it is called by geologists, quickly rained back down onto the surface, but a residue of sulfuric-acid aerosol and dust boiled upward as high as 50 kilometers and diffused through the stratosphere around the world, where for several years it created brilliant red sunsets and "Bishop's rings," opalescent coronas surrounding the sun.

Back on Krakatau the scene was apocalyptic. Throughout the daylight hours the whole world seemed about to end for those close enough to witness the explosions. At the climactic moment of 10:02 the American barque *W. H. Besse* was proceeding toward the straits 84 kilometers east northeast of Krakatau. The first officer jotted in his logbook that "terrific reports" were heard, followed by

> a heavy black cloud rising up from the direction of Krakatoa Island, the barometer fell an inch at one jump, suddenly rising and falling an inch at a time, called all hands, furled all sails securely, which was scarcely done before the squall struck the ship with terrific force; let go port anchor and all the chain in the locker, wind increasing to a hurricane; let go starboard anchor, it had gradually been growing dark since 9 A.M. and by the time the squall struck us, it was darker than any night I ever saw; this was midnight at noon, a heavy shower of ashes came with the squall, the air being so thick it was difficult to breathe, also noticed a strong smell of sulfur, all hands expecting to be suffocated; the terrible noises from the volcano, the sky filled with forked lightning, running in all directions and making the darkness more intense than ever; the howling of the wind through the rigging formed one of the wildest and most awful scenes imaginable, one that will never be forgotten by any one on board, all expecting that the last days of the earth had come; the water was running by us in the direction of the volcano at the rate of 12 miles per hour, at 4 P.M. wind moderating, the explosions had nearly ceased, the shower of ashes was not so heavy; so was enabled to see our way around the decks; the ship was covered with tons of fine ashes resembling pumice stone, it stuck to the sails, rigging and masts like glue.

In the following weeks, the Sunda Strait returned to outward normality, but with an altered geography. The center of Krakatau had been replaced by an undersea crater 7 kilometers long and 270 meters deep. Only a remnant at the southern end still rose from the

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