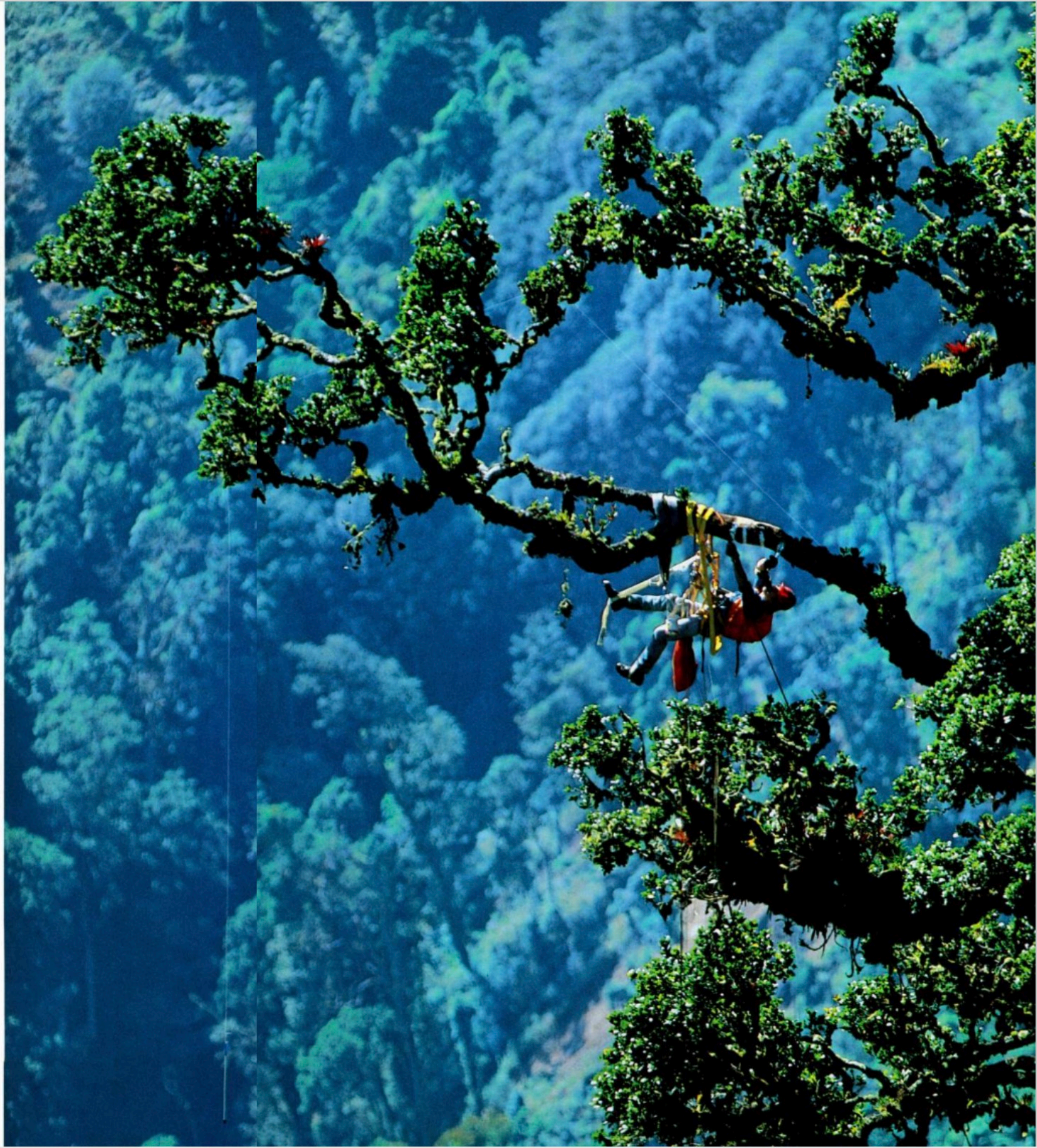
Rain Forest Canopy
The High Frontier

A new breed of scientist risks life and limb to probe the great unexplored world at the top of tropical rain forests. On a steep slope in Costa Rica, ecologist Pierre O. Berner paints rings to monitor the growth of an oak branch.

By EDWARD O. WILSON

Photographs by MARK W. MOFFETT



THE TROPICAL RAIN FOREST I had entered was a shadowed world broken by beams and nuances of greenish sunlight. I had come home to my favorite habitat, the one before which naturalists stand in awe. I was on Barro Colorado, an island in Gatún Lake halfway along the Panama Canal. My visit rekindled a simile that had come to mind in other places and other times: Seen on foot, a rain forest is like the nave of a cathedral, a thing of reverential beauty yet with much of its splendor out of reach in the towers and illuminated clerestories high above.

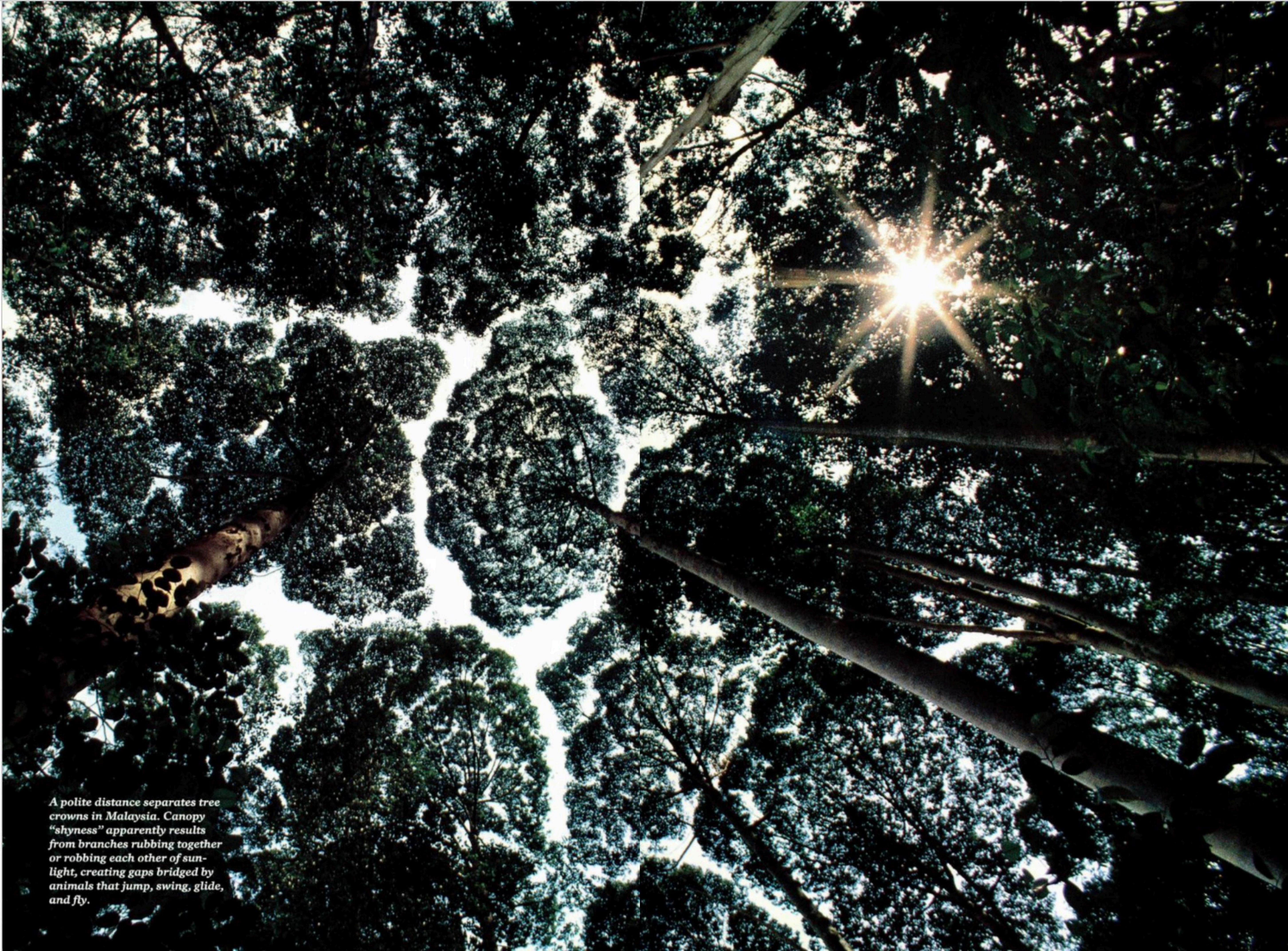
There was no lack of life around me on the ground. It teemed in the patchwork of light and dark. My attention was pulled to eye level and downward by the closeness of plants and animals in the soil and undergrowth. But I remained aware of a wholly different world a hundred feet above, where brilliant sunlight drenched sprays of vegetation and Babylonian gardens, an errant wind soughed throughout the day, and legions of birds, insects, and other animals specialized for high arboreal life flew and leaped back and forth. This high layer is the powerhouse of the forest, where more than 90 percent of photosynthesis takes place and, in the fullest sense, life begins.

Given a few grains of soil, baby bromeliads spring from seeds on a leaf of the mother plant (above). Bromeliads and other epiphytes—plants that grow atop other plants—thrive in the rain forest canopy, often taking root on mats of wind-deposited soil and decaying vegetation. In Costa Rica botanist Nalini Nadkarni peels a thick mat from a branch (facing page) to study how fast the layers accumulate.

The crown foliage of most tree species grows year-round, to be consumed by animals or to die and rot. The dead material thus produced rains steadily to the ground, bearing the remnants of energy to sustain the kinds of plants and animals among which I now stood. It brings nitrogen, phosphorus, and other nutrients back to the earth, to be sucked up by tree roots and returned to the canopy to restart the cycle of life.

The rain forest canopy, an undiscovered continent as naturalist William Beebe called it, is achingly close to the earthbound observer (map, page 84). But it is almost inaccessible and has remained largely unexplored. During 35 years of visits to tropical forests, I have made repeated attempts to study insects in the canopy. I once followed a logging operation in Papua New Guinea, climbing into the upper branches almost as soon as the trees fell to capture ants, beetles, and other specimens and to take notes. I worked the margin of a forest on the South Pacific island of Espiritu Santo, where the canopy bent down to the shore. On the edge of a ravine in the Brazilian Amazon, I peered for days through binoculars into tree crowns a few yards away. I learned little from these efforts. I was forced to stay with the ground and undergrowth.

Now I walked through the forest of Barro Colorado Island to a 138-foot tower, maintained by the Smithsonian Tropical Research Institute to assist long-term studies of the canopy. Climbing to the top, I could look out over the crowns of all but the highest trees, and peer at foliage close enough to touch.

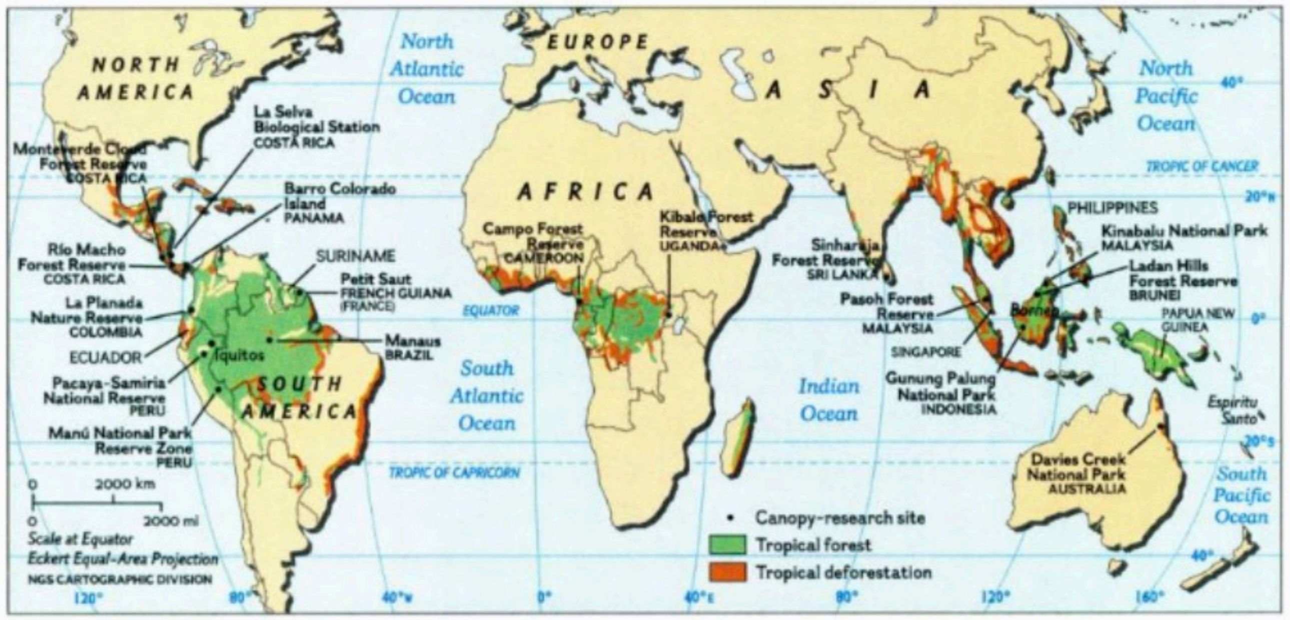


A polite distance separates tree crowns in Malaysia. Canopy "shyness" apparently results from branches rubbing together or robbing each other of sunlight, creating gaps bridged by animals that jump, swing, glide, and fly.

At my fingertips, literally, as I reached out and pulled a tree branch closer, were squadrons of ants gathered around treehoppers, thorn-shaped insects busily sucking the juices of the tender leaf shoots. The ants were not attacking these strange creatures. They were protecting them from spiders, wasps, and other enemies. In exchange, I knew, the treehoppers deposited sugar-laced excrement for the ants to eat. Such are the bonds of symbiosis that hold the rain forest community together.

Another image soon replaced the cathedral as I looked out and away: It now seemed I was floating atop a life-filled sea. All around me the bright green tree crowns of the upper story billowed like waves in a gentle breeze. Arboreal dragonflies soared and darted over the surface in search of insect prey, just as other dragonflies patrol the surfaces of ponds and lakes. Beautiful brown-and-blue charaxine butterflies swirled around one another in territorial dogfights. A pair of toucans glided into a nearby emergent tree, calling noisily. Ants scurried everywhere, hunting for food.

I could look straight down, as though peering into a crystal-clear water column, all the way to the ground. Thirty feet below, hundreds of small flies danced in a midair mating swarm alongside tree crowns of the lower story. Below them giant morpho butterflies sailed by, flashing brilliant blue points of light as they opened their wings, then almost disappearing as they flicked their wings back up, the alternation sending a signal in metronomic rhythm. On the ground, far below and hard to see in the deep shade, logs and fallen tree branches lay scattered on a thin blanket of dead leaves.



Like an undiscovered continent encircling the globe, tropical rain forests shelter an astonishing abundance of organisms—probably more than half the earth's plant and animal species. Heart of the forest is the canopy, the thick upper foliage where more than 90 percent of photosynthesis takes place. At canopy study sites around the world, scientists race to discover new organisms. With tropical forests being cut at a rate of 55,000 square miles a year, untold numbers of species perish before they can be identified, much less studied.

Well, I made it to the treetops, I thought, and here I am, born a few years too early, a slightly creaky field biologist now cast in the role of spectator instead of participant, but happy to be that much. A new generation of scientists have begun a serious assault on the mysteries of the canopy, and it will be a pleasure to travel with them vicariously. In addition to towers, they use a wide range of imaginative and daring methods to reach and study this part of the forest. Various teams of hard-muscled young men and women around the world lean booms into the upper branches, travel out in gondolas suspended from building cranes, ascend on ropes, lower supporting nets from dirigibles, nail ladders onto tree trunks, and travel along walkways suspended across the crowns of trees.*

Month by month, at an accelerating rate, their efforts have begun to disclose the remarkable and unique traits of the canopy and its inhabitants.

THEY ARE REVEALING unimagined worlds in the foliage of the rain forest, where chunk-headed snakes with catlike eyes feast on frogs and lizards; where an ant known as *Daceton armigerum*, armed with jaws like a bear trap, rotates its head vertically to snatch flies from the air; and where earthworms wriggle through foot-thick soil on tree branches—ten stories in the air. How do the worms and soil get there? That's one of the questions scientists are exploring. In the process, they are turning up thousands of new species, as yet undescribed by science. They've found a poisonous caterpillar in Peru that looks like a miniature dust mop, and in Papua New Guinea giant weevils that carry miniature gardens of mosses and lichens on their backs. So many new species are being found that it is hardly news any more.

The big news is, quite simply, that life is more diverse and more plentiful than anyone had previously known. Of the roughly 1.4 million species of organisms given a scientific name to the present time and those remaining to be studied, many biologists believe the majority are to be found in tropical rain forests.

Wincing in the face of gale-force winds, ecologist Ken Clark mans his weather station in Costa Rica's Monteverde Cloud Forest Reserve. As moist air whips in from the Atlantic Ocean, water condenses on Teflon filaments. Clark later measures nitrogen and other waterborne nutrients to determine how much the atmosphere adds to canopy soil mats and the rest of the ecosystem.

In an endless cycle, rain forest trees shed leaves that fall to the ground, thus enriching the soil tapped by the trees as they produce more leaves.

In just one 25-acre tract in Malaysia, Peter Ashton of Harvard University found 750 species of trees. In another record-breaking survey, Alwyn Gentry of the Missouri Botanical Garden identified 283 tree species in only 2.5 acres near Iquitos, Peru. By contrast, about 700 species make up the entire native tree flora of the United States and Canada.

Animal diversity is equally mind-boggling. From a single tree in Amazonia, I identified 43 ant species, approximately the same number as occur in all the British Isles. At some places in the upper Amazon basin, 1,200 kinds of butterflies occur, about 7 percent of the world's known species.

Yet even these figures pale in comparison with recent estimates of the total diversity of insects, (Continued on page 92)

*See "A Raft Atop the Rain Forest," by Francis Hallé, in the October 1990 NATIONAL GEOGRAPHIC.

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Stairways to the roof of the forest

How to get to the top? Enterprising scientists always find a way, simple or otherwise. Nalini Nadkarni (below) uses climbing rope and stamina as she gives her son Gus a look at the view in Costa Rica. From a

tower on Panama's Barro Colorado Island (far left), the author reaches out to collect ants, a lifelong passion. Erected by the Smithsonian Institution, the 138-foot-tall structure provides access to a high but narrow study area.

Near Panama City, a construction crane (top) enables researchers in a gondola to explore a 118-foot radius anywhere from ground level to a hundred feet high. After reaching the canopy in Sri Lanka by a succession of ladders (left), scientists built a bamboo platform for pollination studies.

Some Asian tree communities stand barren for several years, then burst into fruit over a large area, an unpredictable phenomenon called "masting." When it happens, scientists need to get into the canopy fast, with equipment such as a lightweight aluminum boom used in Malaysia (second from top).

Layers of life at the top

The profusion of life in the canopy may seem chaotic, but beneath it all lies an ordered pattern of relationships based on the struggle to survive. Plants live on other plants; animals eat other animals. And animals both exploit the plants for food and cover, and aid them by pollinating them and dispersing their seeds.

Four views of the same limb of a fig tree in Costa Rica (above) isolate major plant groupings and an array of animals, revealing the complex inner workings of canopy life.

Canopy animals

Stripped of its foliage, the branch reveals residents and visitors: a snake in naked pursuit of a tree frog, birds and small mammals feasting on worms and insects.

Hovering near their nest, shown hanging at center in the bottom view, paper wasps add their buzz to birdsongs and the whir of katydids—sounds drowned out by the screech of a white-faced monkey alarmed by a rival troop. Meanwhile, the canopy's silent armies, the ants, scurry to meet their mysterious imperatives.

Vascular plants

In a riot of leaves and roots, bromeliads, ferns, and other epiphytes add to the canopy's biomass. Some plants, or their relatives, are also found in temperate climates, either as natives or exotic imports: orchids, philodendrons, ericads (of the same family as blueberries and azaleas), columneas (of the African violet family), and peperomias, kin to the plant that yields black pepper.

Nonvascular plants

Among the first plants to colonize the limb are mosses, lichens, and other lower epiphytes that spread like carpets, gaining a foothold on areas with the least soil.

These canopy dwellers show distinct preferences. Some species grow only on branches, some only on dead surfaces, like the stubs of broken-off branches. Others, known as epiphylls, grow only on leaves.

Soil and detritus

Gravity lays life's foundation on the topside of branches. Wind-borne dust mingles with fallen leaves, animal droppings, and plant and animal remains. This mixture, a kind of bog, is especially deep at the fork, where a bromeliad flourishes, second view from top. From the lower branch hangs a nest fashioned by paper wasps. At the end of the branches, *Azteca* ants maintain football-shaped gardens, where they literally grow plants for food.

The bromeliad: a microhabitat

A small universe of interdependent creatures live in and around a large bromeliad, a member of the pineapple family, and the branch that supports it.

A nectar- and fruit-eating bat, *Anoura geoffroyi* **1**, homes in to feed, pollinating the bromeliad blossoms in the process. Going to and from their nest, *Myrmelachista* ants **2**, smaller than grains of rice, use a tunnel in the branch's core, where they swarm over the new, winged daughter queens **3**.

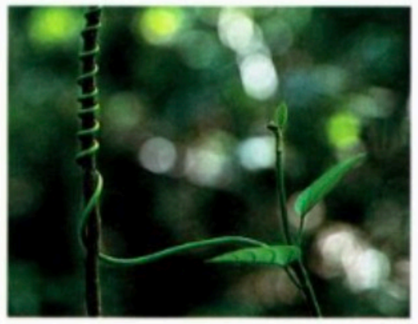
Known as a tank bromeliad for its water-collecting capacity, the plant is also home to creatures that utilize the water: tree frogs **4**, salamanders **5**, beetles **6**, flatworms **7**, flies **8**, katydids **9**, and spiders **10**.

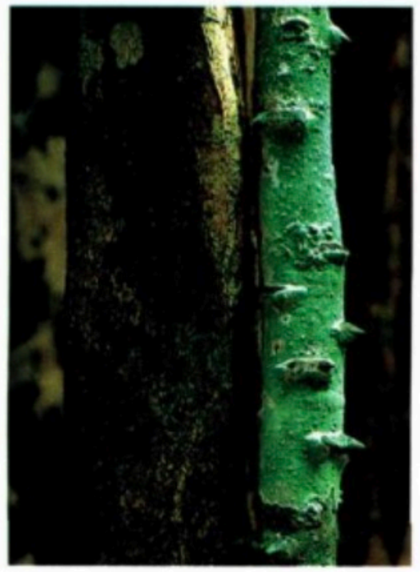
A coin-shaped close-up shows the bromeliad's reservoir to be alive with mosquito larvae **11** and the larva **12** and pupa **13** of a wood gnat.

Orchids **14** and a staghorn fern **15** share the nutrients of the soil mat. Mistletoe **16**, a parasite, sinks roots into the branch itself.

PAINTINGS BY JOHN D. DAWSON

Yearning for sunlight, earthbound vines called lianas (below) ride piggyback to reach the canopy. One reaches out with a stem that spirals like a corkscrew. Another grabs bark with three-pronged tendrils, while a third hangs on with stout spines. But the bully of the forest, the strangler fig (facing page), isn't content to coexist. After sprouting in the canopy from seeds dropped by birds and bats, it sends roots to the ground that envelop the host tree, which dies and rots away.





(Continued from page 85) spiders, and other arthropods living in the canopy. The discovery of the superabundance has been made by enveloping tree crowns with fogs of rapidly acting biodegradable insecticides and collecting the arthropods that fall dying, in the tens of thousands, to the ground.

How many kinds of arthropods live in the canopy? In a celebrated study published in 1982, Terry L. Erwin of the Smithsonian's National Museum of Natural History arrived at a figure of 20 million for the world as a whole, using the following procedure. He first identified 1,200 species of beetles from canopies of the tree *Luehea seemannii* in Panamanian rain forest. Of these beetle species, 163 were believed to be limited to this tree species. There are about 50,000 tropical tree species worldwide, so that if *L. seemannii* is typical, the total number of canopy-dwelling tropical beetle species is 8.15 million. These beetles represent 40 percent of the tropical canopy species of all arthropods, which, therefore, come to about 20 million. The rain forest canopy contains about twice as many arthropod species as the ground, so that the total number of species—in the canopy and on the ground combined—might well be 30 million. Nigel E. Stork of the Museum of Natural History in London independently evaluated his own counts from the forests of Borneo to produce a possible range of five million to ten million tropical forest arthropods.

Why this huge variation in the estimates of rain forest diversity? A great deal depends on the degree to which insect and other arthropod species are limited to one or at most a very few kinds of trees. Because research in the canopy has been so sparse to date, this key factor remains largely unknown. If the arthropod species turn out to be very restricted in the kinds of trees on which they live, their true numbers may approach 30 million or more. On the other hand, if they are able to exist on a wide range of species, the number will prove to be closer to five million.

Whatever the exact amount of diversity in the rain forest treetops, it must run into the millions of species. The few biologists who can identify rain forest organisms are swamped with new species now pouring in from collections in the canopy and on the ground.

MY OWN EXPERIENCE is typical. Every time I enter a previously unstudied stretch of rain forest, I find a new species of ant within a day or two, sometimes during the first hour. I search the ground and low vegetation, dig into rotting logs and stumps with a gardener's trowel, break open dead twigs and branches lying on the ground, and pull at ferns and other epiphytes growing on tree trunks and newly fallen tree limbs. On a typical day, the first 40 or 50 colonies encountered might be species already known to science, some very familiar to me, some rare and requiring later study under a microscope at higher magnification back home. Then a new species. Then another 20 colonies of established species, and one more new species, and so on in a continuing adventure for many days in a row.

One day Stefan Cover, a curatorial assistant at Harvard University's Museum of Comparative Zoology, returned from the rain forests of northeastern Costa Rica and presented me with a large ant of the genus *Pheidole* strikingly different from anything I'd seen before. I had to have more specimens! Cover drew me a map

A fog of biodegradable insecticide sprayed by Smithsonian's Terry Erwin in Peru will soon bring a rain of spiders, insects, and other invertebrates. Gathered on sheets, such collections show a superabundance of species in the canopy—far more than previously believed.

Mining a trove of invertebrates, Michael Pogue of the Smithsonian sorts specimens collected by fogging in Peru. A single Amazonian tree typically yields more than three pounds of specimens comprising 1,700 species, mostly ants and beetles. From such humble origins come medical and other scientific breakthroughs.

Woe to the novice field scientist who picks up this fluffy moth caterpillar (above). When grabbed, hidden spines break off and release an irritating venom. In the insect equivalent of a wash-and-wax job, one Daceton ant grooms another (center, right), cleaning it while possibly spreading protective antibiotic substances.

Colors send signals, say canopy scientists. The orange and black of a young unidentified grasshopper (center, left) probably mimics stinging or foul-tasting insects; its vivid blue trim may also indicate that it tastes bad.

showing the exact spot where he had found the species, near the crossing of two trails and just to the side of an adjacent fallen tree. I went there soon afterward and searched the area carefully and without success. But close by, nesting in the clay soil of one of the trails, I discovered two *more* new species of large, striking *Pheidole* ants, an unexpected gift for a biologist who prospects for ants as others dig for diamonds or gold.

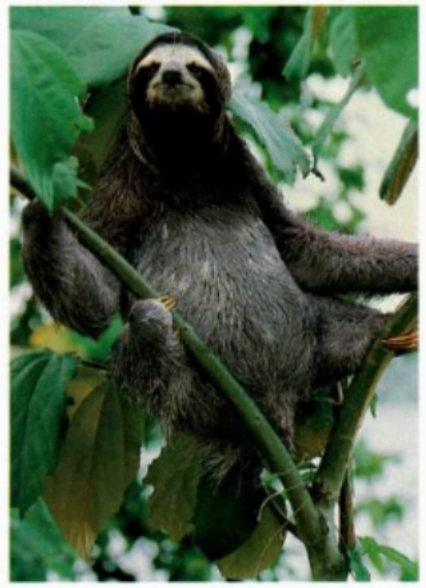
These biological treasures seem endless. I am currently laboring on the classification of more than 300 new species of rain forest ants in the Harvard collection. These represent only a fraction of those already collected and awaiting study.

THE BEST PLACE TO SEE the complete profile of a tropical rain forest and to put the canopy in perspective is, I am sorry to report, where it is being cleared and destroyed. As the forest is sliced along its side and peeled back, and the intervening second growth bulldozed and burned, the trees can be seen to vary greatly in height. A nearly continuous upper canopy is the dominant feature, composed mostly of trees with flattened crowns, nearly horizontal branches, and trunks free of branches for the first 60 feet or so. The term canopy, meaning an overarching cover, is entirely appropriate. Yet rising even above this layer are a few scattered emergents, giants that tower to heights of 200 feet or more. Lower down are trees with narrower trunks and vertically elongated crowns. Some are young individuals of upper-story species struggling their way to the top. Others are mature trees of species specialized for this intermediate, twilight region. Still lower, mostly at the height of a human being or less, are saplings and herbaceous plants.

All this exuberant, multilayered growth is supported by rain, lots of it. Rain forests grow in areas with more than 80 inches of rainfall annually, which allows the growth of broad-leaved evergreen trees. The leaves are typically smooth to the point of slickness and in many species are strongly narrowed at the end. Both features, smoothness of surface and tapered form, promote the rapid runoff of water during torrential rains and help prevent the leaves and branches from breaking because of waterlogging.

Two continents of life do indeed exist as layers in the tropical rain forest. The ground is a dark factory of decomposition, where bacteria, fungi, millipedes, and termites and other wood-feeding insects degrade the fallen plant debris into nutrient molecules. These substances are quickly absorbed by the omnipresent rootlets of the trees, so that little material is present on the ground. The air is still and humid, saturated with the odors of healthy decay.

The canopy is a brilliantly lit, noisy, three-dimensional world. Wind rakes the tree crowns, evaporating moisture away at a rate comparable to that in grasslands, drying the vegetation at times to almost desert-like conditions. Relative humidity ranges from as high as 100 percent at night to less than 30 percent at midday. Sunlight bakes the vegetation, occasionally raising the temperature of the ambient air to more than 90°F, a full 10° higher than at ground level. Frequent rainstorms pound the branches and leaves, breaking away the weak ones. The rain, after filtering through the tree crowns, descends to the forest floor. It arrives as a delayed shower and rivulets that stream down trunks and elevated roots.



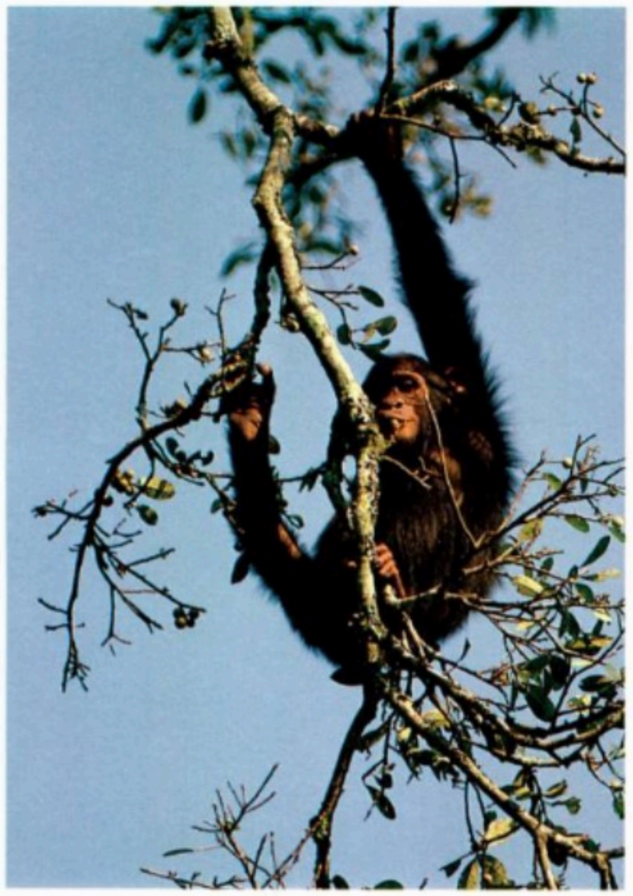
The drab coat of the three-toed sloth (top) is a "living bug carpet"—home to beetles, ticks, fleas, and a steady companion, a moth (above) that lays eggs in the sloth's dung. After hatching, the next generation of moths will fly, seek out sloths, and begin the cycle anew.

The exact structure of tropical rain forests varies from continent to continent, but one feature common to most is an abundance of vines. Most conspicuous are the lianas, which are thick, woody climbers. They sprout on the forest floor and then send out long shoots that grasp vegetation as the vines grow up into the crowns. Often they cross to other crowns, binding the trees together. Lianas have great tensile strength. They are composed of both hard and soft tissues, making them flexible and difficult to break or sever.

A real-life Tarzan could not have swung from tree to tree with lianas, which are attached to the ground. (And unlike biologists, he would not have been likely to endure the stinging wasps, biting ants, and spines and saw-toothed edges of the canopy vegetation. Tarzan would have stayed on the ground.)

You can categorize tropical forest plants by the way they respond to light. While lianas take root in the ground and grow upward, strangler figs do the exact opposite: They sprout in the canopy from seeds dropped by birds and bats, then send roots to the ground.

The stem climber *Monstera tenuis* of Central America, a member of the arum family so favored as houseplants, responds to light in yet another, radically different way. Immediately after sprouting from a seed on the forest floor, the *Monstera* grows toward the dark. This orientation, the exact reverse of that used by almost all other kinds of plants, leads its shoots to the deeper shadows around the base of a tree. Once on the tree trunk the *Monstera* apparently switches orientation and grows upward, toward the light.



ALTHOUGH THE TREE CROWNS and vines alone are enough to create an abounding and unique habitat, the canopy is vastly enriched by yet another dimension. Epiphytes, plants that use the trees as support but do not draw nutrients or water from their tissues, grow in luxuriant masses along the trunks and branches. They are extremely diverse worldwide, comprising 29,000 species of vascular plants in 83 families, more than 10 percent of all higher plants. In addition to orchids, which have the most species, there is a profusion of ferns, bromeliads, gesneriads, figs, arums, and members of the pepper family. There are also many nonvascular epiphytes, such as mosses and lichens.

At the Monteverde Cloud Forest Reserve of Costa Rica, Nalini Nadkarni and her fellow canopy researchers from the Marie Selby Botanical Gardens in Sarasota, Florida, have found one of the most complex assemblages of organisms on earth. There are worlds within worlds: Here and there small trees sprout from the epiphyte root masses, so that trees actually grow on the branches of other trees. Lichens and other epiphylls grow on the leaves of the smaller trees, small insects browse among the epiphylls, and protozoans and bacteria live within the insects.

The epiphytes add immensely to the productivity of the forest, filtering atmospheric nutrients and capturing solar energy that

Lured by lush vegetation, large mammals find forage in the canopy. A chimpanzee snacks on figs in Uganda's Kibale Forest Reserve. In Colombia, a spectacled bear looks for a meal of bromeliads. Largely because its forest habitat is being destroyed, the bear has been declared an endangered species.

would otherwise bounce and scatter away from the naked tree limbs. For the ecosystem as a whole, they act as supplemental foliage in the rain forest trees.

The most elaborate form of symbiosis in epiphytes, one that epitomizes the complexity of the rain forest canopy, is the ant garden. I have encountered many gardens in Brazil and Suriname at the edge of rain forests, where a bit of the canopy dips close to the ground. Spherical in shape and somewhat smaller than a soccer ball, they were made of soil and masses of vegetable fibers chewed and shaped by the ants. They bristled with small, succulent epiphytic plants that sprouted from their surfaces in all directions.

When I touched one—in fact, when I just stood with my face one or two feet away—large *Camponotus* ants swarmed out onto the surface and sprayed clouds of formic acid in my direction. The defenders seemed frantic to get to me, and I was thankful they could not fly like wasps or bees. In a lifetime of studying ants, I have never seen a species so suicidally aggressive and intimidating.

Protected and fertilized by the ants, the garden epiphytes flourish. In return, they provide their residents with food and shelter. The plants belong to at least 16 genera of philodendrons, bromeliads, figs, and cactuses. They are specialized for this strange existence, limited almost entirely to the gardens. Similarly, the most abundant ant species in the gardens appear to depend on their epiphyte partners.

How do the gardens get started? There seems to be no other way to explain it than to say that the ants plant gardens and harvest crops. They are initially attracted to fleshy appendages on seeds, called elaiosomes, that serve as food. The seeds may also smell like the ants' own larvae. After the ants have cleaned off these nutritious fragments, they drop the still intact seeds into the recesses of their nest, allowing the epiphytes to sprout and grow out through the nest walls. As the plants mature, the ants harvest food from them in the form of fruit, nectar, and elaiosomes.

The canopy serenade begins at dusk for Cathy Langtimm, sitting 70 feet up in a Costa Rican forest. Her shotgun microphone picks up the cries of tiny tree-dwelling mice, often mistaken for bird or insect sounds.

"The call is surprisingly loud, like a two-note whistle," says Langtimm, of the University of Florida. "The mice probably use sound to mark territory or locate mates. The canopy is a tangle of branches that makes it hard to attract mates by leaving pheromone trails." The calls are short—only a second or so—to evade predators.

TROPICAL RAIN FORESTS began to take form roughly 140 million years ago, near the beginning of the Cretaceous period in the age of dinosaurs. Early in that time, when most of the world's climate was tropical to subtropical, flowering plants originated and later spread as dominant elements around the world. Many of the species became partners with insects, which derived food from them while serving as pollinators and transporters of seeds. These insects, including a medley of wasps, beetles, bees, flies, butterflies, and moths, also rose to dominance. Some insect groups increased vastly in numbers and diversity simply by preying on flowering plants—feeding on them without pollinating them or giving other services in return. Still others consumed decaying vegetation or else simply used the plants for shelter.

Biologists who struggle with the task of collecting and classifying the immense cornucopia of biological diversity ponder the important ecological question it raises: Why are there so many species? Most experts on biological diversity agree that more than half the kinds of plants and animals in the world live in rain forests, yet this ecosystem covers less than 6 percent of the land surface. Of these species, more than half either live in the canopy or, in the case of the trees and vines, create it with their upper foliage.

The mystery of why so much of life is invested in rain forests is still far from solved, but clues abound. One is the greater climatic stability of the tropical zones. The temperate zones experience wide seasonal swings in temperature each year. The tropics as a whole, and rain forest areas in particular, enjoy nearly constant temperatures and have never been glaciated. Plants and animals in colder parts of the world are for the most part adapted to survive in a variable environment, and as a result they range widely. A plant species found in New York, for example, is also likely to be found as far away as Tennessee and Michigan. A tropical species, in contrast, is more likely to have evolved to fit a narrow niche in a constant environment. Plant species in South America and elsewhere are often limited to a single valley or ridgetop. So when you add up all the tropical species, there are many more of them.

Still more diversity is piled on by physical disturbances that create gaps in the forest. When the canopy is broken open, sunlight falls more abundantly on the ground, and a new burst of vegetation springs up. The species of trees and smaller plants in this assemblage are mostly different from those in the surrounding mature forest. So are many of the insects and animals that live on these gap specialists.

Gaps are continually created at random spots throughout the forest. As a storm passes, sporadic winds are likely to break a few large tree limbs that have grown weak and vulnerable from heavy growths of epiphytes. The rain fills up the axil sheaths of the epiphytes and saturates the humus and clotted dust around their roots. Occasionally a lightning bolt strikes and kills a tree.

Elsewhere a large tree sways in a gust of wind above the rain-soaked soil. Its shallow roots cannot hold, and the entire tree keels over. Its trunk and crown shear through smaller trees to open a hundred-foot path. As the sky clears and sunlight floods the newly opened gaps, the surface temperature rises and humidity falls. The soil and leaf litter dry out and grow warmer, creating a new environment for the plant seeds resting there. In the months to follow, pioneer trees take root. They are very different from the young shade-tolerant saplings and understory plants of the deep forest. Fast growing and short-lived, they form a single canopy far below that of the major forest. Their tissue is relatively soft and vulnerable to attack by herbivores.

One of the dominant gap-dwelling groups of Central and South America, the broad-leaved trees of the genus *Cecropia,* swarm with fierce ants that live in hollowed internodes of the trunk. The ants, a species of *Azteca,* protect the trees from all predators except three-toed sloths and a few other animals specialized to feed on *Cecropia.* The slightest disturbance brings them out by the

A deft grasp—aided by five digits and an opposable large toe on each foot—serves a small opossum well as it forages in a Brazilian canopy for fruit, insects, lizards, and eggs. The vision of this nocturnal creature is enhanced by huge eyes with widely dilating pupils.

hundreds or thousands, biting with their mandibles and emitting noxious defensive secretions. Because of their much smaller size, they are less formidable than the treetop garden ants, but only slightly so. On several occasions in Costa Rica I have tried to dissect good-size *Cecropia* trees to study the inhabitants, and each time found it a harrowing experience.

In short order the little defenders were under my clothing, in my hair, running over my eyeglasses. I had to stop frequently to clean myself off, and I finally gave up. But that, of course, is the point. I was Gulliver tied down by the Lilliputians in a successful defense of their land. Although I was 80 million times heavier than each *Azteca* ant, the tribe prevailed.

When the pioneer vegetation thickens enough to shade the ground, the cycle begins to draw to a close. Conditions of light and temperature improve for mature-forest species, and their seedlings take root and grow. Within a hundred years the gap specialists are gone, and the multiple-layer high forest has returned.

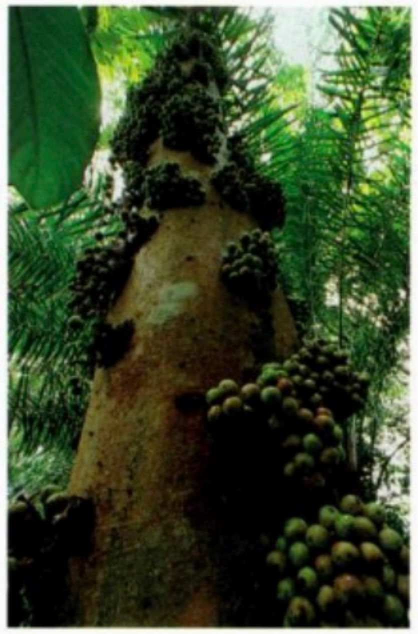
The pioneer species are the sprinters; the slower growing species of the mature forest are the long-distance runners. Together they create a mosaic of vegetation types throughout the forest that is forever changing, a dazzling kaleidoscope of biological diversity. When you walk for a mile or two through mature rain forest, you cut through many of the successional phases from gap to mature stands. Life is continually enriched by the passage of storms and the fall of forest giants.

LIFE IS THUS PILED UPON LIFE in the tropical rain forests. Long periods of uninterrupted evolution have pushed diversity to extremes along several dimensions: epiphyte gardens, intense specialization, delicate symbioses, and a constant turnover of plants and animals that fill the forest gaps. But this great edifice is all a house of cards. Most of the millions of species are so highly specialized that they can be quickly driven to extinction by the disturbance of their forest homes.

Unfortunately examples of such vulnerable species are easy to find. Spix's macaw *(Cyanopsitta spixii)*, a beautiful parrot of northeastern Brazil, is on the brink of extinction due to human interference. The forests in which it can live have been largely destroyed during the past century. In addition, the Africanized honeybee, the "killer bee" accidentally introduced into Brazil in the 1950s, has occupied many of the nest sites the macaw needs to reproduce. Finally, local fancy-bird dealers, able to get $18,000 or more for each bird, have reduced the remnant population until only one individual was known to remain in the wild in late 1990.

The fragility of the rain forests extends not just to single species but also to entire local ecosystems. In the early 1980s Alwyn Gentry and Cal Dodson surveyed the plants of Centinela, an isolated mountain ridge on the Pacific side of the Andes in Ecuador. They encountered almost a hundred plant species found nowhere else in the world. A few years later, before the Centinela flora and fauna could be studied further, farmers from surrounding valleys completely cleared the ridge. The unique plant species and almost certainly a host of animal species associated with them were gone.

The tropical rain forests are being reduced in this manner almost everywhere in the world at an accelerating rate. The original cover,



A smorgasbord of fruits plucked from the canopy in Borneo (left) owes its abundance to bats, monkeys, and birds that pollinate flowers and scatter seeds. A fig tree in Singapore (far left) aids its own cause by bearing fruit on its trunk, an irresistible treat to bats.

Tied to a tree in Borneo, Tim Laman aims to loop fishing line over another branch, to haul up climbing rope for his study of strangler figs. Despite the priority given safety, dangers remain for rain forest scientists, drawn to this high frontier by forms of life yet to be discovered.

before human populations had much impact, was about six million square miles. Now it is only three million square miles, less than 6 percent of the world's land surface, roughly the same as the area of the contiguous United States. In 1979, according to surveys conducted by British scientist Norman Myers and the Food and Agriculture Organization of the United Nations, the rain forest and similar, much less extensive monsoon forest were being destroyed at the rate of 29,000 square miles a year. By 1990 the figure had almost doubled, to 55,000 square miles a year, an area larger than the state of Florida.

As the area of a habitat such as a rain forest is decreased, the number of species of plants and animals it can support also declines. The relation between these two qualities of the natural environment, area and diversity, is consistent. A reduction of the habitat to one-tenth its original area means an eventual loss of about half its species. In other words, if a forest of 10,000 square miles and a hundred resident bird species is cut back to 1,000 square miles, it will eventually lose about 50 of the bird species.

This amount of rain forest reduction has already occurred in several of the biologically richest parts of the world, including the Philippines, parts of West Africa, and the Atlantic coast of Brazil. The current rate of deforestation worldwide translates to an eventual annual loss of species of at least half a percent a year. Even that figure is probably a considerable underestimate, because it does not take into account the near-instantaneous destruction of entire communities of endemic species such as that on Ecuador's Centinela. If the rain forests of the world hold ten million or more species, a figure many tropical biologists consider likely, the rate of extinction worldwide may well have already reached 50,000 species a year.

CAN HUMANITY AFFORD to lose so much of its natural heritage? The tragedy, as biologists see it, is that large blocks of diversity are being lost before they can be studied scientifically. The great majority of the vanishing species have never even received a scientific name.

Biologists and conservationists watch in dismay as the forests disappear, just as the extraordinarily rich two continents of life, the ground and canopy, are being effectively explored and compared for the first time. It is as though the stars began to vanish at the moment astronomers focused their telescopes.

A large part of the world's greatest biological treasure-house is being leveled for farming, ranching, and logging. The loss is compounded by the fact that if managed properly, the forests can yield a higher rate of income in perpetuity. Enough harvesting

A forlorn island of trees stands in Brazil amid an area cleared for ranching, which along with slash-and-burn farming accounts for 75 percent of all rain forest destruction worldwide.

Aided only by a strap called a peconha between his feet, Jay Malcolm shinnies up to explore a Brazilian forest "fragment" beside a clear-cut. Above him, a trap baited with bananas and peanut butter collects rodents and marsupials for a census. Researchers study fragments to determine how animal species react to such reduced habitats.

A hundred feet high, daredevil entomologist Jack Longino pops up above the canopy in Costa Rica. He and others wonder how long such vistas will remain unbroken. At present rates of destruction, earth's rain forests could be gone by the middle of the next century, a chilling prospect.

Says a veteran botanist: "Rain forest is the very core of the biology of this planet."

techniques already exist to make this dream a reality. When timber is removed from a succession of narrow strips following the contours of the land, native trees grow back rapidly.

Other materials can be drawn from the forest with even less disturbance. A wide range of natural products were either directly extracted from or at least were discovered in rain forests and transplanted to plantations elsewhere. Their names include both the familiar and unfamiliar: rubber, copal, dammar, chicle, balata, quinine, vanilla, cocoa, coffee, Brazil nuts, avocado, rattan, and a large percentage of our most favored species of houseplants.

The fruits of only about a dozen species of temperate zone plants dominate the commercial market. At least 3,000 may be available in the tropical forests, and of these, 200 are in actual use. Some, like cherimoya, papaya, and mango, have only recently joined bananas in the northern markets.

A fundamental difference exists between the two major forest types of the world, a difference that should concern economists. Whereas the commercial value of the temperate forests comes almost entirely from timber, the potential value of tropical forests lies mostly in the large array of other products available from the diversity of their species.

An important property of the tropical rain forest products we now use is that they originate in the lower levels, from understory shrubs and smaller trees and the trunks of the larger trees. The high canopy, so little understood biologically, is almost entirely unexplored commercially. No one knows what new foods, pharmaceuticals, fibers, vegetable oils, and other materials await discovery a hundred feet above the ground.

From a beetle without a name atop an orchid in a distant threatened forest may come a cure for cancer.

But such practical concerns are not what I ordinarily think about in more somber moments as I walk the trails of Barro Colorado Island and other remnants of the tropical forests. What comes to mind is what I like to call the ultimate irony of organic evolution: that life, in the moment of achieving self-understanding through the mind of man, has doomed its most beautiful creations. □