

## *In the Forest of the Waterbear*



"Mysterious and little-known organisms live within reach of where you sit. Splendor awaits in minute proportions."

E. O. Wilson



**T**he rain forest beckons to botanists like Mecca to the faithful. For years I dreamed of a journey to the cradle of plant civilization, the verdant Holy Grail. When the time came for my pilgrimage, my head was filled with wild anticipation of outlandish beings and greenery beyond imagination. The Amazon called and I followed, by plane to the waiting jeep, to the dugout down the muddy river, and at last on foot, into the dripping forest.

The interior of the rain forest is overwhelming in its complexity. There is not a bare surface anywhere. Branches are hung with curtains of mosses and sprays of orchids dangle among them. Tree trunks are filmed over with algae, studded by giant ferns, and wound about with vines. Ants travel in convoys across the ground and up the trees, and metallic beetles glint in sun-flecks on the forest floor. The forest itself is richly textured; stems embossed with every manner of protuberance, leaves ornamented by spines and pleats, scales and fringes. Long shafts of sunlight cut through the dark canopy and catch the flash of iridescent butterfly wings before diffusing in the vegetation below.

While the jungle was overwhelmingly exotic, I was haunted by a sense of having seen it all before. There was something strangely familiar about the quality of the light; leafy, wet, and saturated with green. The pervasive shadows and movements at the periphery of vision brought forth a familiar sense of possibility, and the desire to part the undergrowth and go wandering. It reminded me of walking through a moss.

This is entirely possible with a good stereomicroscope, which lets you go wandering at will through a living moss turf, like bushwhacking through the jungle. Tiny needle in hand, like a machete to make a path, or a walking stick to part the palm fronds, I've spent hours lost in looking, threading my way between the stems, bending low beneath a branch and turning over leaves to see what's underneath. The stereomicroscope provides a way into the forest of a moss clump, in three dimensions. I can zoom in for a closer look, or step back to see the panorama.

I'm struck by the parallels between the moss microcosm and the rain forest. The similarities are more than visual. While the height of the moss mat is approximately three thousand times smaller than that of the rain forest, they nonetheless exhibit the same kind of structure, the same kind of function. Like those in the rain forest, the animals of the moss forest are interconnected in complex food webs: herbivores, carnivores, and predators. The ecosystem rules of energy flow and nutrient cycling, competition, and mutualism still apply here. The patterns clearly transcend the vast difference in scale.

Accustomed to the benign nature of northern forests, I had to continually remind myself not to push through the jungle vegetation without looking first. Grabbing a branch might mean a sting from a conga ant that would lay you low for the next 24 hours. Stepping over a log without looking might yield an encounter with a fer de lance snake that could lay you low forever. Our Quechua guides taught us the three things one must take into the forest for safety: the eyes, the ears, and the machete. Most of the plants were surprisingly well armed. Toothed leaves, spiny stems, and prickly bark were the norm and my hands had enough scratches and punctures to make me attentive every time I walked through the forest. Dwarfed by the green, vulnerable, I felt something in common with the tiny creatures in a moss mat. I could imagine how a soft-bodied larva feels as it twists and turns through the dense stems of a moss mat, where the leaves are sharp pointed and edged with teeth.

My Ecuadorian colleagues brought us to a canopy observation platform in the ecological reserve. We climbed one at a time up a winding set of narrow stairs built around a gigantic *Ceiba* tree that rose up through the canopy and punched a hole through to the sky. The

canopy world is usually accessible only to the birds and bats, and now a few lucky scientists. With every spiraling turn around the tree, we moved through the complex layers that make up the forest.

The rain forest canopy supports a lush flora of epiphytes, plants living on the trunks and branches in the full tropical sun, getting their water from the rain and their nutrients from the air. Ferns and orchids carpet the branches and lianas twine around the trunks and bind them together in a tangle of vines. Ahead of me, just beyond arm's reach, is a garden of bromeliads, with waxy red leaves looking like flowers. The leaves overlap one another to create pockets that collect the rain, which comes every afternoon, predictably at 2:00. There are species of mosquitoes, and even frogs, that complete their entire life cycle in these bromeliad tanks, high above the forest floor. Far from the soil, mosses are the foundation for most of these epiphytes, forming a deep cushion all along the tree branches.

Mosses are not only epiphytic on other plants; they support epiphytes of their own. The interior of a moss clump can be heavily colonized by algae, making it look like a moss-draped rain forest in miniature. Golden disks of single-celled algae rest among the moss leaves. Threads of tiny liverworts coil around the stems like vines on a tree trunk and competing mosses may engulf a stem like a strangler fig. Clinging to the rhizoids of the moss are colorful spores and pollen grains, evoking the pattern of pastel orchids. The moss forest even has its equivalent of bromeliad tanks. The water-filled pocket in a moss leaf can support unique species of rotifers, invertebrates that know no other home but the tiny pool among the moss leaves.

A hallmark of the tropical rain forest is the intense vertical stratification from canopy top to the surface of the soil. The flora and fauna are adapted to the gradient of sunlight, intense at the surface and diminishing as it passes through layers of the forest to the deep shade of the forest floor. Fruit-eating bats cruise the top of the canopy, while bird-eating tarantulas hide in dim light among the buttress roots. The moss forest is stratified in a similar fashion. Some insects frequent the dry open top of the clump, while others like springtails burrow deep in the damp rhizoids at the bottom.

While one is walking in the rain forest, there is a steady pitter-patter, not of raindrops, but of bits of debris falling from the canopy. Old leaves, bugs, and spent petals are constantly drifting downward, enriching the soil and recycling nutrients from the producers at the forest top to the decomposers at the bottom. We were repeatedly startled when half-eaten fruit would come plummeting down from above, the remnants of a parrot's meal. Fruits or nuts falling from the high canopy can really pack a wallop on a bare head. Our guide displayed his egg-shaped bruise. If you could walk at the bottom of a moss colony, there would be the same steady rain of particles through the layers of leaves. The moss turf traps windblown soil, and leaf fragments, dead bugs, and spores, which collect at the base of the moss, gradually building up soil where none had been before. Decaying organic matter hosts filaments of fungi, which are greedily fed upon by springtails. It is this accumulation of decaying debris that provides an anchor for rooted plants, akin to orchids in the rain forest or ferns taking hold on a mossy rock.

A Berlese funnel is the tool typically used to study the nearly invisible fauna of microcommunities such as moss. Soil, rotting wood, or a clump of moss is put into a large aluminum funnel, fitted with a screen. A barrage of high-intensity lamps is placed over the top of the funnel for several days. Slowly, the heat begins to dry out the moss or other material. Fleeing the light and seeking out the remaining moisture, all the invertebrates move downward toward the tip of the funnel where they fall to their deaths, collected in a jar of formaldehyde.

The collection from a Berlese funnel might typically produce the following results. One gram of moss from the forest floor, a piece about the size of a muffin, would harbor 150,000 protozoa, 132,000 tardigrades, 3,000 springtails, 800 rotifers, 500 nematodes, 400 mites, and 200 fly larvae. These numbers tell us something about the astounding quantity of life in a handful of moss.

But the numbers themselves miss the point. Such lists remind me of the inconsequential facts tossed off by a tour guide, the number of steps to the top of the Washington monument or the number of granite blocks used to construct it, when what I really want to know about is

the view from the top and the jokes told by the stonemasons. Berlese funnels yield a good inventory of the biota, I suppose, but I'd rather go walking through a moss clump and see the thousands of creatures living out their lives than count their bodies in a jar.

Invertebrates are attracted to forests of moss for the same reasons that rain forests shelter such diversity of wildlife. They offer a favorable microclimate, shelter, food, nutrients, and a complex internal structure, which creates a great diversity of habitats. And like the rain forest, a moss forest is a hotspot for evolution. Mosses were the first plants to colonize the land, and paved the way for the creatures that followed. Many entomologists believe that the early stages of insect evolution took place in the mats of moss. The moist protection offered by mosses created a transitional environment between primitive aquatic life and more advanced terrestrial organisms. Today, many advanced insects still rely on moss mats for nurture of their eggs and larvae. Craneflies hover around mossy cliffs, waiting to deposit their eggs in the wet leaves. The cranefly mothers are quite selective in choosing a nursery for their offspring. They avoid mosses with sharp leaves and densely packed stems which would make life difficult for the tunneling larvae.

Each morning in the jungle, we'd awake to the sound of parrots, squawking through the canopy, vivid as a kindergarten paintbox. Long tail feathers streaming behind, the red of a scarlet macaw is startling against the green leaves. The forest of mosses has its own brilliant spots of color moving through the branches. Here the red belongs to Oribatid mites. Round and shiny, the mites remind me of eight-legged bowling balls scurrying over the foliage. When my probing disturbs them, they simply veer off in another direction, and I follow them along as they forage for spores, algae, and protozoa. Some of the mites are predaceous on other invertebrates, and some eat the moss foliage.

Amazon nights come quickly when the sun drops below the equator, without the interlude of twilight. At the fall of darkness, we'd return to the bamboo platform, which was our camp. The shelter was raised on stilts and we climbed to the platform up an inclined log with steps cut into it. Before we blew out the candle for the night, the log steps were pulled up to discourage unwanted visitors. Falling asleep was a challenge, despite the exhausting days of hiking in the tropical heat. The night

was alive with sounds: frogs bellowing, toads trilling, insects buzzing, and one night, the yowling of a panther.

Predators lurk in the moss forest, too. Pseudoscorpions conceal themselves among the dead leaves and dart out on rippling rows of legs to sting their prey. Carabid beetles, hard shelled and shining, patrol the moss turf with their enormous pincers and take small invertebrates wherever they find them. Predaceous larvae lie like snakes in the branches.

The intensity of predation in the rain forest has led to many adaptations for camouflage and mimicry. There are moths that resemble dead leaves, snakes that mimic branches, and caterpillars disguised as bird droppings. So, too, in the moss forest, there are creatures disguised as bryophytes. In New Guinea, moss weevils carry about tiny gardens of moss on their backs, growing in special cavities on their shells. The larvae of some craneflies are a mossy green color, marked with dark lines to hide among the leaves. They move sluggishly through the moss mat, further concealing their presence by lethargy. This same approach to predator avoidance is used by the tree sloth in the jungle, coated with algae and moving so slowly that it becomes nearly invisible in the canopy.

The dense foliage works to the advantage of predator and prey that do not wish to be seen. But this same concealing profusion can be a liability when the intention is sexual display. Life the jungle depends on the imperative for reproduction, to somehow find the right mate in a habitat already saturated with life. Birds resolve this dilemma by adopting gaudy plumage and loud calls, which penetrate the forest, advertising their availability. Likewise, every plant seems to be locked in competition to be noticed, to seduce potential pollinators to carry pollen to the next blossom. The fate of many plant species lies in the hands of complex interactions with pollinators, butterflies, bees, bats, and hummingbirds. Hummingbirds abound in the canopy, their iridescence dazzling in the sunlight. They move like dragonflies, zipping so quickly from flower to flower that you can hardly get a look at them. My best chance for close observation came when a jewel-like hummingbird hovered near the red baseball cap of a fellow hiker. He could hear the hum and feel the breeze from the beating wings and we

all silently begged him not to move, as the bird delicately probed the strange new Red Sox blossom that had appeared in its territory.

Mosses experience the same pressure for cross-fertilization, but lack flowers or any kind of showy display to attract insects as co-conspirators in fertilization. Mosses rely on the movement of water to carry sperm, and it is an inefficient process since the sperm can rarely travel more than a few centimeters. It appears, however, that the invertebrate community that inhabits mosses has the potential to carry sperm a bit farther afield. As they crawl through the moss, mites, springtails, and other arthropods passing by a male can become smeared with mucilage containing moss sperm. The sperm may then be carried on the bodies of the invertebrates and rinsed off into water droplets elsewhere in the moss, where they can swim to the waiting females. Invertebrates are unwitting but vital partners in the continuity of the moss forest, like the hummingbird with pollen accidentally brushed on its forehead.

The bright colors of tropical flowers are repeated in their fruits. The most common color for fruits in the canopy is red, since that is most visible to birds and to monkeys, the most important dispersers of seeds. Dispersal in mosses is typically by wind, although one species, *Splachnum*, has evolved a brightly colored sporophyte and strong odors to attract dung flies, which then carry its spores. Birds, mammals, and especially ants often feed upon the protein-rich sporophytes. I've watched a sparrow systematically harvest a crop of sporophytes from haircap moss, neatly clipping off the capsules in its beak and trailing a cloud of spores. Ants are no doubt good dispersers of moss, as they carry the open capsules on their backs, sprinkling spores all along the route to their nest.

Development and population pressure in the rain forest have triggered a sharp decline in wildlife populations. Therefore, our guides were very excited to pick up the tracks of a mother tapir and her baby in the mud. We woke before dawn the next day to follow their trail along the river in hopes of seeing them. In the misty stillness of the early morning, we wove our way through the palms of the riverine forest, listening intently. The tapirs had vanished, but quiet walking in the woods never disappoints. We heard a troop of howler monkeys waking and watched

them move through the branches overhead, perfectly adapted for life in the treetops.

Moving quietly through the microscopic forest, peering between branches and following a glimpse of movement, I'm on the trail of a tardigrade. If I had to choose one animal whose life is most closely tied to the life of mosses, it would be the waterbear, or tardigrade. Like the panda bear, which is totally reliant on the bamboo forest, the waterbear's life is inextricable from the moss in which it lives. Nosing through the foliage, trundling along on eight stumpy legs, the waterbear bears a remarkable likeness to a tiny polar bear. Low slung, with a round head, its body translucent and pearly white, the waterbear clings by long black claws to the moss stems. Instead of a jaw full of teeth, a waterbear has sucking mouthparts. It feeds by piercing a moss cell with a stylet like a hypodermic needle, and sucking out the contents of the cell. Other types of tardigrades graze on algae and bacteria, the epiphytes of moss leaves. A few are even predaceous, using the stylet on other invertebrates, sucking out their cells.

As their name suggests, waterbears are reliant on the abundant moisture held in the interstitial spaces of a moss clump. They cross between plants on fragile bridges of water, spanning the capillary spaces in the moss. A typical place I go to look for them is in a moss with deeply concave leaves. The tiny pool of water held in a spoon-shaped leaf is the perfect resting place for a waterbear, as plump and gelatinous as a candy Gummi Bear. The moisture in a moss mat is as vital to the moss as it is to the waterbear. But, since mosses are nonvascular, their water content fluctuates with the amount of water in the environment. The moss leaves shrivel and contort as water evaporates, leaving them crisp and dry. The waterbears, too, simply shrink when desiccated to as little as one-eighth of their size, forming barrel-shaped miniatures of themselves called tuns. Metabolism is reduced to near zero and the tun can survive in this state for years. The tuns blow around in the dry winds like specks of dust, landing on new clumps of moss and dispersing farther than their short waterbear legs could ever carry them.

Neither the moss nor the waterbear is damaged in the process of desiccation. In this state of suspended animation, they are invulnerable

to extremes of temperature or other environmental stresses. The moment that fresh water becomes available, as dew or a welcome rain shower, the waterbear and the moss soak up the water and swell back to their normal size and shape. Within twenty minutes, the moss and the waterbear, in perfect synchrony, resume their normal activities.

Rotifers, or "wheel animalcules" as they were first called, share this same remarkable ability to withstand drying. When moist, rotifers inhabit the water-filled spaces of a moss, like guppies in a multitude of tiny aquaria. They can be easily seen feeding there as their rotating cilia draw in food particles on a current generated by the spinning "wheel" of their mouths.

Within the moss microcosm, evolution has produced a shared adaptation to the inevitable fluctuation in moisture. Just as the evolution of birds is tied to the evolution of the trees they live among, the lives of waterbears and rotifers has been shaped by adaptations of the mosses.

All three—mosses, waterbears, and rotifers—figured prominently in a nineteenth-century debate about revivification and the very nature of life. The behavior of these three blurs the distinction at the edge between life and death. All signs of life are extinguished when they are dry: no movement, no gas exchange, no metabolism. All enter a state known as anabiosis, or lack of life. And yet, as soon as water is returned, life suddenly is renewed. Their apparent death, followed by resuscitation, suggested that life might be stopped and then re-started. Waterbears were the subject of intense experimentation to test the limits of their endurance. In the dry state, they were subject to conditions that would kill any known organism: boiling, being held in a vacuum only 0.008 degrees above absolute zero. But, without fail, they tolerated these abuses and were revivified with a drop of water. The addition of water unlocks the chemistry of life by a mechanism that is still largely unknown, but utilized by mosses and waterbears everyday.

After 350 years of lively debate and experimentation, it is generally agreed that life does not cease in anabiotic organisms, but continues at a barely perceptible rate. Sophisticated technologies are required to document the infinitesimal rate of metabolism, which permits life to be suspended indefinitely. The process that allows these beings to hover

at the boundary between life and death is still a profound mystery that is continually played out in the mosses beneath our feet.

It took a flight across the equator, a perilous crossing of the Andes and three days down the river in a dugout canoe to bring me to the heart of the rain forest. But at home I don't have to go that far to find a shadowy forest full of exotic beings that I've never seen before. In a five-minute walk down the path of my garden I can have a handful of moss, and a five-minute walk back to the microscope brings me to the lush interior of the moss forest. There is no word but awe for the biological excess of that place, the profusion of life, vivid and complex beyond our grasp. At every turn of a leaf, there are mysteries. There are life forms here that occur nowhere else on the planet and intricate relationships evolved over eons. You might take care not to step on them.