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LIVING EARTH

LIVING EARTH

by

Peter Farb

Photographs by Roman Vishniac

DRAWINGS BY LOUISE KATZ

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LIVING EARTH

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Preface

WE LIVE on the rooftops of a hidden world. Beneath the soil surface lies a land of fascination, and also of mysteries, for much of man's wonder about life itself has been connected with the soil. It is populated by strange creatures who have found ways to survive in a world without sunlight, an empire whose boundaries are fixed by earthen walls.

In spite of man's long curiosity about life in the soil, there has never been a book for the untutored in science on this subject; in fact, no technical study even existed until two years ago. In writing about the wide-ranging complexities of the soil, I have chosen to accent one part of the story, that of the tiny lives within the teeming earth, their relationships and unusual adaptations.

The apparent lifelessness of a piece of earth is an illusion. Specks of protoplasm swarm through the soil granules, invisible to the naked eye. Larger animals and plants are linked to them by invisible threads of food supply and living conditions. Similarly, there are interlocking relationships between the larger creatures, and so up the pyramid until we come to its apex, the fabric of Life itself.

To give order to the bewildering abundance of this soil life, the bulk of the book has been organized according to the three great soil types—forests, grasslands, and deserts—and their unique communities of living things. In each section, representative plants and animals demonstrate the wonderful diversity of ways in which the soil inhabitants survive inclement conditions, reproduce their kind and make inviolate their own niches in the soil life.

My approach has been that of the science reporter. I have inter-

viewed the scientists currently carrying on research in many fields of soil biology. As an enthusiastic layman I have also found it fascinating and rewarding, over the past few years, to observe closely the soil inhabitants carrying out their lives on my mountainside in Westchester County, New York. But this book is essentially the story being developed by highly trained specialists from years of painstaking research in the laboratory and the field.

To have attempted a glimpse into the secret lives beneath us would have been an impossible assignment without the generous aid furnished by many scientists. Primarily, the entire project was kept within the bounds of accuracy by the enthusiastic and friendly cooperation of the research workers at the Connecticut Agricultural Experiment Station in New Haven. A. E. Dimond, Chief of the Department of Botany and Plant Pathology, and Neely Turner, Chief of the Department of Entomology, not only gave freely of their time during the various stages of writing this book, but also had many helpful suggestions after reading the manuscript. Their broad understanding of the fascination of soil plants and animals made researching this book an exciting endeavor.

The idea for a book on soil life was first discussed with Charles Kellogg, Assistant Administrator of the United States Soil Conservation Service, and Edward Graham, also of SCS. Much early guidance was received from E. A. Steinhaus, Director of the Laboratory of Insect Pathology at the University of California, Berkeley.

Specialists in many fields relative to soil life gave bountifully of their interview time, opening their personal libraries to me, searching out specific studies. In particular, I would like to thank:

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Selman A. Waksman, Institute of Microbiology, Rutgers University (soil microbes)

I have drawn freely on the labors of many scientists whom I did not meet personally. It would be a lengthy task for me to itemize the debt I owe those specialists whose reports in scientific journals I consulted.

To Roman Vishniac I want to express my deep appreciation for his superb photographs accompanying the text. The effort and enthusiasm he gave to the project went much beyond mere contractual obligations.

I am indebted, also, to Louise Katz for her drawings which illustrate some of the lives to be found in these pages.

The publishers of the following volumes have kindly given their permission to use quotations: *The World Was My Garden* by David Fairchild, Charles Scribner's Sons, New York; *Leaf and Tendril* by John Burroughs, Houghton Mifflin Co., Boston; *High Jungle* by William Beebe, Duell, Sloan & Pearce, New York; *Edge of the Jungle* by William Beebe, Duell, Sloan & Pearce, New York.

South Salem, N.Y.
January, 1959

PETER FARB

I.

THE LIVING SOIL

1. *The Placenta of Life*

"THE SOIL is the placenta of life," a scientist once wrote, and truly the earth does nourish nearly every living thing on this planet. But to the ancients, Mother Earth was an actual scientific fact. So obviously was the soil teeming with life that the Greeks regarded it as a place from which life could arise spontaneously, without benefit of sexual reproduction. The Greek Thales instructed his students that they could watch life be born from slime under the influence of heat. Other writers of about 2500 years ago attributed the birth of life to ooze or as arising from heated earth.

Spontaneous generation was asserted as a scientific fact by Aristotle, the first great naturalist whose writings remain. He observed that creatures seemed to grow in a wondrous fashion out of the earth and lifeless matter around him. The larvae of some insects appeared to be born from the morning dew settling upon the soil; mice arose, fully developed, from moist soil; crabs and frogs came from slime rained upon and heated by the sun; humus gave life to flies.

Spontaneous generation was not disproven until the middle of the last century. Although the soil itself does not give birth to life, it is the incubator for the living world. The abundance of life to be found in the soil is staggering. The organisms vary from the submicroscopic up to the relatively gigantic. The largest invertebrate animal, the earthworm, is a million times the size of the smallest one visible to the naked eye, the mite; and the mite may be a million times larger than the smallest soil animal, a protozoan, which is itself a giant alongside the bacteriophage virus. In numbers, the soil

life ranges from billions to the ounce to only a handful of some species per acre. They carpet the particles of soil and weave a way through them. They make burrows and tunnels and underground nests; they honeycomb the earth with a latticework of passageways. They may live at the surface of the soil, like the millipedes, or dig more than 100 feet down, like some desert termites. Wherever life can exist in the soil, nature has evolved a form to fill that niche.

One of the first modern naturalists to be intrigued by soil life was Dr. William Beebe of the New York Zoological Society, the curator of the world's tropics. While he was on a bird-collecting expedition to Belem, Brazil, over forty years ago, it occurred to Dr. Beebe that the soil he had tramped on every day, while his eyes were aimed at the treetops, might also hold something of interest. So, just before heading downstream to board his steamer, he dumped handfuls of jungle earth, mold, and decaying leaves into an old bag.

A few days later, on the high seas en route back to New York, he began examining with a magnifying glass this thin veneer from the jungle floor. What he thought would be a shipboard diversion became a mighty labor. For the jungle soil was indeed alive, with ants, termites, beetles, scorpions and false scorpions, worms of every sort, springtails—all visible to the naked eye. With his magnifying lens, he discovered more organisms, each one hugging its grain of soil. Day after day he pored through the litter, drawn into its secret world:

Contracting the field of vision to this world where leaves were fields and fungi loomed as forests, competition, the tragedies, the mystery lessen not at all. Minute seeds mimicked small beetles in shape and in exquisite tracery of patterns; small beetles curled up and to the eye became minute seeds of beautiful design. Bits of bark simulated insects, a patch of fungus seemed a worm, and in their turn insects and worms became transmitted optically into immobile vegetation. . . . When we had worked with the lens for many minutes, all relative comparisons with the surrounding world were lost. Instead of looking down from on high, a being apart, with titanic brush of bristles ready to capture the fiercest of these jungle creatures, I, like Alice in Wonderland, felt myself

growing smaller, becoming an onlooker, perhaps hiding behind a tiny leaf or twig.

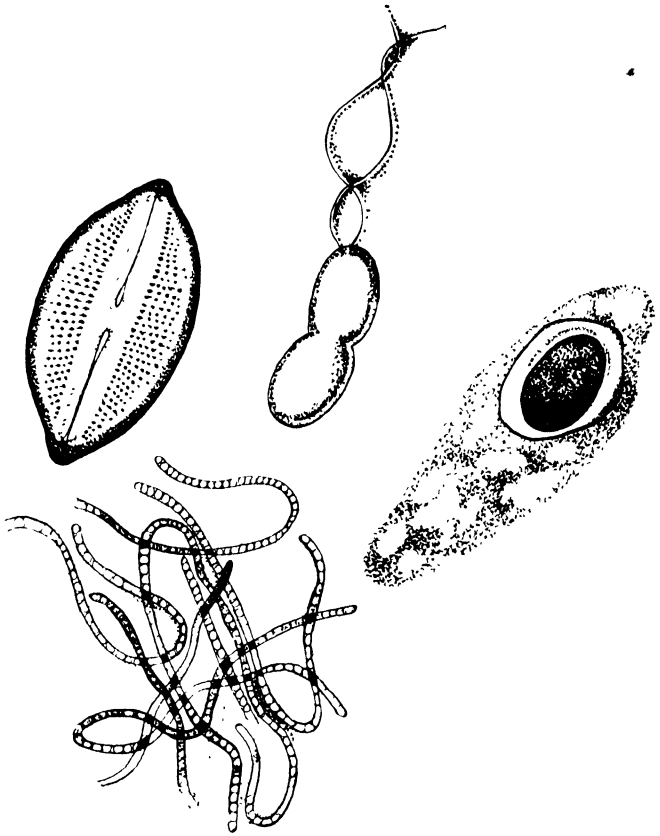
—from *Zoologica,* 1916

When his vessel reached New York City, Dr. Beebe had not yet completed his examination of the jungle soil. From this section of the tropics, four square feet in area, he had collected over 500 specimens, and calculated that at least twice that number remained. In fact, Dr. Beebe concluded, at least a thousand organisms visible to the naked eye were sheltered in this bit of jungle earth.

Nowadays one may wonder that Dr. Beebe found so few specimens, for many scientists have since made accurate counts of the soil population. The ants alone add up to tremendous numbers: in some western states, as many as twenty thriving ant cities are found to the acre. The construction of these cities requires that two tons of earth be moved by the ants. About 95 per cent of all insect species (and there are roughly a million of them) invade the soil at some stage of their life cycles; that is why a sample count of insect eggs, larvae, and adults on a single acre may total about half a billion. In addition, nearly a billion mites swarm through this same acre.

Dr. Beebe was not searching for soil microbes in his sample, but if he had counted them, he would have found unbelievable numbers. Even in a teaspoonful of soil from the temperate regions, there may be five billion bacteria, twenty million actinomycetes, a million protozoa, and 200,000 algae and fungi. These crowds of microorganisms carry on such fierce activity on each acre that they expend an amount of energy equal to 10,000 human beings living and working there.

Within the earth live strange and delicate forms, some almost aerial in their fineness. Then, too, there are algae and shrimp and familiar sea-dwellers which have somehow made homes for themselves in the soil. Many of these forms are of ancient lineage, their ancestors flourishing while man was only a promise in some tiny mammal quivering between the rocks. The slime molds, the worms,



STRANGE SOIL MICROBES (*clockwise, beginning upper left*): diatom, bacterium, bacillus, blue-green algae

the fantasies of underground vegetation—where does man fit into that scheme?

In the soil are the preyers and the preyed-upon, the tiny links in far-reaching food chains. The stage is set for competition, yet there is much less of it than might be supposed. Regulating the multiplicity of lives is the soil itself—conservative, buffering the populations against startling changes, a complex material that resists any

one form of life's becoming dominant for very long. Among the microorganisms, the very act of living keeps their numbers within bounds. For they are faced with the seeming contradiction of all life on the planet: they grow only in favorable environments, but their very act of growing removes the favorable conditions from the environment. Most microorganisms, for example, require oxygen—and when it is available, they multiply. But their increased numbers soon temporarily exhaust the supply in the soil, and their population shrinks.

A few cells, however, survive the downfall of their kingdom on a grain of sand, ready to begin again a new burst of activity when favorable conditions reappear. A single bacterial cell, producing a new generation every twenty minutes, in only two days could theoretically give rise to twenty-four trillion trillion of bacteria, an amount equal to 4000 times the weight of the earth itself. But runaway growth can never take place in the vast, and often hidden, complexities of the soil.

The soil beings are not evenly distributed as in a solution. Bacteria, for example, live in clumps or colonies. Most of the fungi are concentrated around decaying plant and animal debris. The roots of plants, in particular, swarm with microbes, and their numbers drop off sharply the further from the root that the count is made. Insects, too, often congregate in favorable places. The wild bees construct their individual burrows only a fraction of an inch apart; there may be 100,000 nests in that crammed piece of earth, yet not another nest within miles.

Nor are the numbers of soil-dwellers a constant thing. There are definite periods of activity and growth, usually in the spring and fall, alternating with periods of dormancy during the heat of summer and the cold of winter. Underground must be a scene of considerable turmoil, for the microbes are constantly changing in numbers. A bit of garden soil was examined every two hours around the clock, for two days, and counts made. Although the temperature and moisture were kept constant, the populations of microbes on a

teaspoonful of soil jumped from 2.4 billion to 3.4 billion in only a couple of hours.

The soil animals spend much of their time in restless movement, searching out favorable living conditions. Most of this movement is in the form of vertical migration—up and down in response to dryness, heat, food, and the other necessities for a successful soil life. Those form which cannot withstand radiation from the sun burrow downward during the day, to reappear in the upper horizons at night. The ants' devotion to work has been emphasized since the days of King Solomon, yet one aspect of their labors has often gone unnoticed: a whole corps of nurse-ants do little all day but move the brood from place to place, fussing to find warmth and moisture. Even the reptiles, which also have their representatives in the soil community, migrate within the soil: a legless lizard from Spain has been reported to fashion deep underground tunnels to escape the heat.

There is no soil that has proven inhospitable to life. It is crowded to its limits. A bit of fungus, before it is fully dead, may be attacked by ravenous bacteria. A highway gash leaves the bare ribs of the earth stripped of life; yet, shortly, fungi send out strands, binding together the particles, holding them in place while seeds of colonizing plants gain a foothold. It is the same story, with infinite variations, of all the triumphs and tragedies that have occurred since the seas first receded and left a forlorn patch of dry ground.

The Dark World

This solid earth is not solid at all; in fact, many soils are more than half empty, filled only with air, water, and a multitude of living things between the particles. The incalculable numbers of the soil population do not live *in* the soil but rather *between* the soil grains.

The grains make up a skeleton and they vary greatly in size. Clay soil, the finest, has particles that are smaller than 1/2000ths of an

inch in diameter, beyond the reach of many optical microscopes. Particles of sand, the largest, range up to one-twelfth of an inch. Silt is midway between sand and clay; any particles larger than sand are simply gravel. Each of these soil particles has a tremendous area, and collectively they provide a vast surface for living. Only an ounce of soil, sampled at Britain's Rothamsted Experiment Station, was found to have surfaces adding up to 250,000 square feet—about six acres.

The spaces between the soil grains offer a variety of habitats. The smaller pores and channels are filled with water, the larger ones mostly with air. Clay soils have narrow, threadlike channels that twist and taper downward; in sand, as might be imagined from seeing it on the beach, there are air pockets in the tiny spaces between the grains. Draped upon the skeleton of the soil are the sinews and flesh of a teeming life: each particle, even the finest, has a tight-fitting film of oxides, water, bits of organic matter. This skin is what gives life to the soil underfoot.

The soil is a most hospitable environment for life, and in many kinds, the conditions approximate those of an incubator. For one thing, moisture is abundant, and even a bone-dry soil, baked by the desert sun, still contains comparatively large amounts of water, held by tremendous pressure on the surface of the grains. The small animals of the soil differ markedly in their water requirements: the earthworm usually requires some liquid water at all times, but the larvae of many insects can make do with water-saturated air. Adult insects withstand dry air for short periods, but will often do everything possible to avoid it—like some ground beetles which swarm out of the earth only after sundown and when the air is very humid.

The underground world, too, knows mists, monsoons, and cloudbursts. A sudden rain is the undoing of many: some animals are suffocated where they lie, others burrow deeper to escape the onrushing waters. The earthworm can swim quite well, but it is bewildered and rushes toward the surface where it becomes paralyzed by the rays of the sun. The shrew sounds a shrill cry and crowds the

furthest reaches of its tunnel. The larva of the crane-fly becomes soaked and uncomfortable, but can resist the flooding. Mole-crickets, good swimmers, are only slightly inconvenienced.

As the rain fills the spaces between the soil particles, oxygen is cut off. Suddenly the whole microbial world undergoes a transformation. Most bacteria demand oxygen, and these forms become inert. But in their places other kinds flourish; these are called anaerobes, similar except that they can multiply in the complete absence of oxygen. The protozoa awaken from their protective cysts and decimate the bacterial hordes, swimming through the new underground lakes and picking off the dying game. But a few of the billions somehow manage to survive the storm; here a lone bacterium sheltered in an air pocket, there a solitary insect clutching its bubble of air, ready to repopulate its bit of earth when the floodwaters recede. The soil life is harsh on the individual, but mindful of the species.

The water-filled tubes and pores between the grains, and the moisture films on the particles, provide homes for soil creatures who make up the "water fauna." The smallness of the cavities in which they spend their entire lives eliminates all larger forms, and biologists have recently come to learn that these tenants are but dwarfed species of those more commonly found living in ponds. Extremely small specimens of some rotifers, protozoa, and nematodes have been collected from between the particles of soil; they correspond very closely with specimens taken in pools of water. One protozoan which normally reaches a size as great as 1/500th of an inch in ponds, measures but a third as much in the soil-water film. Biologists are uncertain whether these are merely undersized individuals which managed to penetrate the soil spaces, or whether they represent hereditary smaller strains.

In adapting their water needs to life in the soil, the animals have had to overcome many obstacles. None have done it more intricately than the woodlice (also called pillbugs). Their ancestors, and even their present-day relations like the crabs and shrimp, lived in the sea. How the woodlice managed to break with their ancient home

is not known, but it was obviously an event requiring millions of years. Possibly, the first arthropods to make the migration from sea to land were similar to the woodlice; but out of recollection of things past, or as if not yet committed wholly to life on land, woodlice still wear gills.

Woodlice are common principally in moist forest soils, and they much resemble dark, armor-plated pills with seven pairs of legs. A woodlouse can often be found by poking around in the leaf litter for a few moments; if examined carefully, it is seen to be very ill-equipped to solve the problems of water conservation. For one thing, this is a small animal; smallness means a large surface area in proportion to volume and thus more chance for water to be lost by evaporation. Insects have a similar problem, but many of them have skins containing a waxy coating which resists evaporation. Not only does the woodlouse lack this impermeable coat, but the water loss from its gills is very great.

Nature has provided the woodlice with very few physical modifications for a successful life in the soil. But they do have intricate behavior patterns which virtually insure that if there is any moisture around, the woodlice will locate it. The most notable thing about the behavior of woodlice is that they usually bunch together in moist areas; the advantages are tremendous, for when one body surface is in contact with another, there is less surface exposed to cause water loss. But how do woodlice unerringly manage to find, and remain in, these damp spots? This troubled biologists until they took the animals into the laboratory and performed controlled experiments. The scientists found that a high humidity caused the woodlice to move more slowly and also to change their direction more frequently. Thus, at very high humidity, the woodlice moved in lazy circles, the effect being to keep them in approximately the same spot.

But it is not that simple; few biological problems are. Their responses to light, although very complicated, are also important in survival. When woodlice are in a moist area, an automatic mecha-

nism within them makes the animals avoid light. However, should their damp spot dry up, then their response to light reverses and they become attracted to it, wandering about in the open and seeking another moist area. When they do find moisture, they avoid the light again, decrease their speed, and move in slow circles. A combination of all these mechanisms, built into the woodlice at birth and working with great precision, has placed them among the most successful soil-dwellers.

Microbes demonstrate extreme sensitivity to moisture conditions in the soil. So prodigious are their rates of reproduction when conditions are favorable that their equilibrium is constantly in flux. There is a different response to moisture among the bacteria that live on the outside of a soil crumb and those that live inside. With delicate instruments scientists have measured the variations in populations; they take place within minutes after the wetting of the crumb and continue even while it is drying out. The awakening is rapid, as, in a logarithmic scale, the bacteria multiply and reach astonishing proportions. Then their bursts of creation sputter out and the grand show is repeated by other forms. Whole species are annihilated, new lords ascend to the throne of that speck of earth.

Although the tenants of the soil are limited by moisture conditions, they find underground temperatures considerably more even than those above ground. Soil temperature studies made at Tucson, Arizona showed that the temperature remained constant throughout the day at a depth of twenty inches, while in the air above, the thermometer hovered between 52 and 108 degrees. An equable temperature is one of the reasons why soil microorganisms do not differ so much as might be expected in tropic, temperate, and even Arctic soils. At a depth of perhaps two feet below the soil surface, there is a more or less constant temperature around the globe.

It was only recently that scientists learned about the microorganisms of Arctic soils; in fact, it was not until 1934, when the Russians isolated seven groups of bacteria which were also common to temperate regions of the globe. More recent studies made at the

Arctic Research Laboratory in Point Barrow, Alaska, show that some soils there support relatively large numbers of bacteria, as many as ninety million to a teaspoonful. But the Eskimos have obviously known this all along; the summer before they plan to construct their skinboats, they bury the seal pelts in the soil, allowing them to rot to the point where the hair can be easily removed. Were it not for bacteria being present in the soil, the rotting could not be explained.

Great ingenuity has been shown by the soil inhabitants in altering the temperature conditions. One Australian termite builds its mound in the shape of a wedge, a dozen feet high and as many long. This long, thin mound always points directly north-south, like a compass needle. The orientation of the nest protects the termites from overheating, since each side of the mound receives sunlight for only half a day, and the noonday sun strikes only its thin edge.

The large black ants of the woods, *Formica,* common throughout much of the world, are expert at making living in the soil as comfortable as possible. Nests made by different colonies of the same species often vary greatly in design, depending upon the local living conditions. Many even build a summer residence, a solarium practically on the surface, but their home nest is usually deep in the soil. Here they lie all winter, several thousands of them clustered together in a tight ball. In fact, the ball is made up of sleep-walking ants: the mass is constantly churning as those on the outside move towards the center; that way, all get an equal chance at the interior warmth. But always remaining at the warm center of the churning mass is the queen, most necessary for survival of the underground city.

With the rodents, a rock lying on the surface of the soil becomes a solar heater that conducts and stores warmth. It is the hub of an underground world. About a foot or two from the rock, there may be an average of eight animal burrows and runways per foot. Nearer to the rock, the tunnels come closer together, until under the stone they practically merge. A diagram of their underground passage-

ways would reveal a crooked wheel with the tunnels radiating like warped spokes from the hub-cap rock.

The soil tenants have little difficulty in obtaining air, since it seeps through the pores and channels. Although carbon dioxide is produced in great amounts by the heartbeat of soil life, it does not accumulate there. The renewal rate of air is very rapid: in some soils, a complete turnover of all the air in the top six inches takes place about every hour. Air easily enters and leaves by the tiny passageways between the grains because the air molecules are extremely minute, perhaps only a thousandth the size of a typical pore in the soil.

The soil is a friendly place for life to be carried on in all its variety. There are abundant raw materials to provide energy, an equable climate, sufficient water supplies, no air pollution. In fact, the physical environment of the soil is hospitable, save in a single respect: it is a land where sunlight never penetrates, of darkness that knows no relief.

Here is a world in which many animals live without sight, as the common mole whose eyelids are permanently sealed, or the tarantula who may carry vestigial seeing organs of little use. Many of the soil-dwellers never leave the pit of darkness, others divide their lives with time in the light. Some, like the reproductive castes of termites and subterranean ants, have only an hour in the sun to disperse, mate, and found future colonies. As the earth suddenly opens where it was solid before, the last particles of soil removed by the workers, up come the virgin queens and males for their single moment above ground. Hundreds mill around at the exit hole, pushed on by those behind, lacking even lids to blink out the harsh light, burdened with untried wings.

Watching are the birds, toads, salamanders, other ants, centipedes—all come for a banquet of slaughter. The cloud of young virgins never gets off the ground; it is decimated before flight as other creatures of the forest gorge themselves. The toll taken is tremendous, and of those who get aloft to find a mate, perhaps only

one out of a thousand ever becomes the founding mother of a successful colony. It is ended as suddenly as it began; the earth is closed over again and those behind remain in their unremitting darkness.

In the depths of the soil live algae which are the exact counterparts in every way, but one, of the sunlight-loving algae—those plants which may commonly be seen as green scum on a pond or giant seaweeds of the ocean. They contain not a bit of chlorophyll. There is good evidence that many of the present-day microbes may have originated from forms of life similar to the colorless algae. For they seem to be moving in two directions: one, toward the familiar green algae and the higher plants; the other, toward the protozoa and minute animals. The dividing line between animals and plants is often a slim and artificial one.

The tiny organisms found in the soil demonstrate a most exquisite organization and complexity. Many are microscopic, but by no means simple. Protozoan means "first animal" and although it is the simplest kind on the planet today, it must have evolved from considerably simpler animals. Protozoa are one-celled, but they represent the highest degree of specialization in the unicellular line.

Even the first faint spark of life on the planet must have had behind it a long history of chemical evolution from the "primordial soup." Although life today does not originate spontaneously from non-living matter in the soil, it probably began that way. Glimpses of what original life may have been like can be seen through the electron microscope. Its tremendous resolving power reveals that the line between living and non-living forms is not so sharp as once supposed.

Viruses, for example, have characteristics of both worlds. They behave much like chemical substances, yet they can also reproduce once they arrive inside the cell of a host. In the world of the soil, the viruses are only one of the borderline forms. Plants that act like animals and animals that resemble plants, matter that is living and at the same time not living—all are inhabitants of the strange environment of the soil.

2. *The Story of Soil*

THE SOIL lies upon the planet much as the rind upon an orange. But the rind of the soil is not uniform everywhere: it is twenty feet and more deep in places like the Florida Everglades, less than an inch thick in sections of Canada where the glaciers have scraped the rocks bare. It is usually thickest at the Equator, and thins out toward the poles. Its color may be red, as in western Oklahoma, or black, as in Kansas. It may be sand or shale or clay, or fit any one of hundreds of other soil classifications. But always, it is the sole link between the lifeless earth and the teeming world on its surface.

The mountains appear to loom large and the depths of the sea to be unfathomed. Yet, for a ball the size of the earth, these surface irregularities are considerably less, comparatively, than on the rind of the orange. Even these slight configurations on the earthen ball are continually being worn down: the highest peaks lose tiny grains that start on an endless journey. "All soil," once wrote the Harvard geologist Nathaniel Southgate Shaler, "is rock material on its ways to the deep."

Landslides may launch the grain of soil, the grinding of rocks and glaciers propel it, winds catch and sweep it for miles. The soil that now lies upon the continents is merely at its resting stage, momentarily pausing and giving sustenance before taking up its long journey once again. A mountainside is a busy place, soil particles coming and going, grains dislodging each other, rubbing together like sandpaper. With time, there is no substance on earth too hard to be broken down into what may ultimately become soil.

John Burroughs, the Hudson River Valley naturalist, in his native Catskills watched the mountains of rock being created into soil:

> The mountain melts down into a harvest field; volcanic scoria changes into a garden mold; where towered a cliff now basks a green slope; where the strata yawned now bubbles a fountain; where the earth trembled, verdure now undulates. Your lawns and your meadows are built upon the ruins of the foreworld. The leanness of granite and gneiss has become the fat of the land.
>
> —from *Leaf and Tendril,* 1908

The rocks must endure all the ordeals of nature. The sun heats them to tremendous temperatures during the summer day, expanding the minerals lodged there; at night, the coolness contracts them. Repeatedly carried on over decades and centuries and millennia, the strain of expansion and contraction splits off pieces of rock; even the bulkiest must soon crumble.

Although the outside of a rock may be hot to the touch, a few inches inside toward the core it is still cold. That is because rocks are poor conductors of heat. Thus the outside layers expand and contract more than the core, eventually flaking off. Geologists call this "onion weathering," and it is very apparent in the deserts, where the relentless sun expands the rock skin to the limit, and the sudden temperature drop at night contracts it so quickly as to snap off the upper layers. At night in the desert mountains may be heard what sound like rifle shots. They are nature's artillery, shooting off rock that will someday become soil.

Larger fragments of rock, broken off by physical weathering, are further fractured. When they reach creeks and rivers they are rolled along by the waters, ground into ever finer particles. A bend in a river is nearly always sand or gravel, because a stream slows down there and drops its load of fine soil particles. During floodtime, when the stream leaves its course, it spreads the deposited grains thinner and further inland. On the deltas and flood plains of most rivers are built up masses of particles drawn from a drainage area that reaches out thousands of miles into the very heart of continents.

Each year the Mississippi River dumps 525 million tons of soil and rock fragments into the Gulf of Mexico. This means that about every 7500 years, a foot of soil and rock is removed over the entire drainage basin of the Mississippi, yet it is constantly renewed as more parent material turns into soil.

The soils deposited by river systems are known as "alluvial;" much of the state of Mississippi, for example, has been formed in this way. Alluvial soils are among the richest on the planet, and a large percentage of the world's population is fed from those formed by the Mississippi, Yangtze, Ganges, Amazon, Nile. The high fertility of these soils is due to the fact that the particles were drawn from diverse areas, with a whole range of rocks and minerals to provide copious amounts of every essential for plant growth.

Not only must the rocks submit to physical forces, but there are chemical ones as well. The rainwater that falls upon the rocks and flows over them is by no means pure. As it falls, it picks up some carbon dioxide from the air which dissolves and forms carbonic acid. It is not rain alone that spatters upon the rocks, but acids powerful enough to etch them away and even form limestone caves.

Finally, the forces of life itself create soil. Rocks are broken apart by the expansion of roots in crevices and are also dissolved by acids secreted from the roots. The roots continue to perpetuate the life of their piece of earth by bringing up water from the lower horizons of the soil, water containing dissolved minerals which eventually lodge in the leaves. When the leaves fall and decay, the minerals from the depths are then deposited on the surface of the soil. The giant oak in a meadow, which appears to be the very symbol of rest, is working actively underground to renew its own soil world.

The vegetation of this planet is not merely living off the stored-up fertility of the soil; it is constantly adding to the soil. Scientists have filled a tub with a weighed amount of earth and planted a tree seedling in it. After five years they have found that the tree is perhaps a couple of hundred pounds heavier than when planted, but the soil has lost only a mere pound or two. Where, then, did the tree gain

its bulk? From the sun, air, and water used during its growth. So when the tree dies, it returns to the earth not only the elements it obtained directly from the soil, but also the new supplies it manufactured. Vegetation adds to soil fertility, and there is no way to husband a piece of land so well as to let something grow on it and return its residue to the soil.

Thus, the soil is formed from the wearing away of the rocks, and because there are many kinds of rocks, with many possible combinations, countless sorts of soils will arise. Soils formed by limestones, for example, differ from every other kind because limestone rocks were created almost wholly through the action of living things under the oceans, later to be left by receding seas. Limestones consist mostly of corals, shells, and lime filtered out of the sea water by minute animals. Chalk, such as we see in the white cliffs of Dover, where it lies a few thousand feet thick, is the remains of little sea animals called Foraminifera. Coquina rock, used in the construction of St. Augustine and many old buildings on the Florida coast, is a warm-water limestone composed mostly of shell fragments. The peat of the Florida Everglades is underlaid by thick limestone, manufactured by sea animals; whereas peat is often too acid, except for specialized plant growth, the limestone layer has neutralized it and made the Everglades one of the richest agricultural areas in the world.

On many mountainsides, the past and future of soil can be seen on rock outcroppings at the summit. One end, embedded in the mountain, may be covered with a thin layer of soil; the other end of the rock is bare and crumbling. At the base is scarcely an inch of soil, deep enough to hold some annual weeds and a venturesome tree seedling; then comes a zone of crumbling mosses, as the soil mantle grows thinner. The mosses melt into a spreading film of crusty green plants—the lichens—then scattered lichen colonies, finally bare rock eaten away by weathering.

The advancing wave of the lichens is silently at work, dissolving the skin of the rock with acids. Its hairs are wedged between the

rock particles, growing and swelling, giving off harsh secretions, dislodging minute bits. Dust from the air settles upon the lichens which, when they die, become a nursery bed of organic and mineral matter, suitable for the mosses.

These scaly growths on rocks are composed of many lichens, but each member of the colony is not a single individual. Every lichen is a combination of a microscopic fungus and a microscopic alga; it is their partnership that results in a form large enough to be seen with the naked eye. This is a strange partnership—for the algal half can (and sometimes does) lead a separate existence, and the fungi are but slightly modified from those found growing in the soil on decaying leaves and wood.

In nature, the partnership of many kinds of lichens seems to come into being in this way: the fungus shoots out reproductive spores which are carried by wind and water until finally they settle down and germinate. The fungus cannot carry out photosynthesis—the process of manufacturing food from the green chemical chlorophyll, water, and sunlight—since it lacks chlorophyll. So it immediately sends out searching fingers for food and finds it in the form of a partner—a green or blue-green alga which, by carrying on photosynthesis, can make the food the fungus needs.

If the fungus finds the alga, it embraces it with strands, sends out special structures to cement the relationship, and thereafter the two live as one individual. But most never find the right companion, and they wither. In the limitless space of rock surface, it appears to be a chance encounter between two specks of dust. Yet, the harsh realities of this reproductive pattern are eased somewhat by the fact that *Trebouxia,* the most common algal partner of this kind of fungus, is widespread on rocky surfaces.

In this partnership, the fungus makes all of the decisions: it determines where the plant will grow, which direction it will spread, the size it should be. It is the fungus that does the heavy work of breaking down the rocks and pumping in the minerals. It is the receptacle that catches the rain and stores the moisture. The algal

partner has but a single task, and that is an essential one: it takes the raw materials gathered by the fungus' labor and transforms them into food. Only the alga can use the energy of the sun to build up a complex array of compounds. Through its partnership the fungus has gained by being able to colonize bare rock, something no other fungus can do. The alga, also, has extended its realm by now surviving in dry environments and being protected by the fungus against harsh living conditions.

Life Comes into the Soil

A mass of splintered rock particles, worn to tiny fragments, some of them microscopic, and deposited in the lowlands, is still not soil. And it will not become soil until life has been added to it. There is no soil without life; they are inseparable. The living things make the difference between a mere mass of mineral particles and a mineral *soil.*

Soils can be made, ultimately, only by the addition to the mineral particles of living and once-living matter, called organic matter. It is stuff that has seen the flame of life—the litter of dead leaves and twigs, husks of sucked-out insects, rotting plant roots, even the pinpoint bodies of microbes. The content of organic matter varies: in some peaty soils of Florida and Michigan, it is nearly wholly organic matter; on the other hand, some desert soils of the Southwest contain but a trace of 1 per cent of organic matter. A complex association of life is required in the skeleton of rock fragments and, as a general rule, the greater the complexity of living things that have inhabited the soil, the more productive it is. Soil must have a history, and be able to boast of a pomp of living creatures, each of which has left its mark.

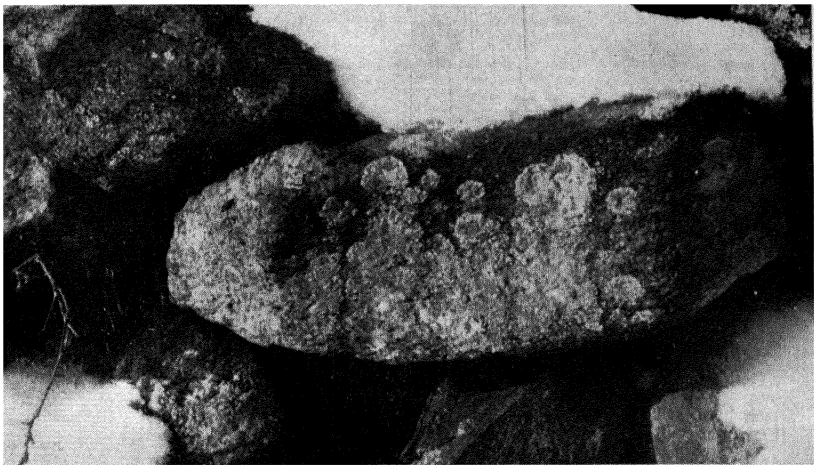
For perhaps three-fourths of geologic time there was no soil. It is a young substance. The earth before then must have been a dismal place, with no glory of the seasons—a world of rocks and seas, lacking a green mantle as protection against the pounding rains and

fierce sun. Occasionally the earth was rocked by quakes and volcanoes and tidal waves; when these were finished splintering mountains and dislodging giant boulders, the long lifeless silence again prevailed.

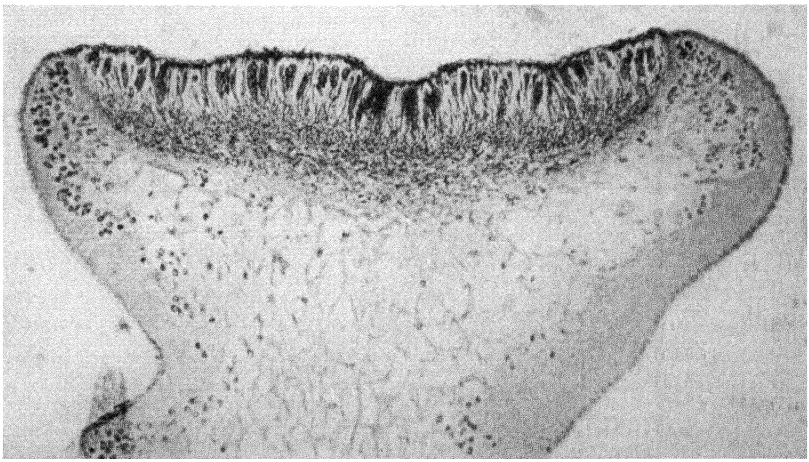
The first life on the planet probably originated in the sea. And as the forces of nature acted upon the corrugated land, wearing down the mountains, the skeleton of the soil was formed. Possibly spores of some of the lower plants, holding fast to rocks left by the tides, ventured into the skeleton and began the chemical work of converting the mineral particles into true soil. Millions of years later, after the mosses and simpler plants had pioneered the way, perhaps seeds fell on this clump and grew into tiny, spindly plants, no doubt utilizing every bit of nutrient lodged there, but also adding some from the air and water during their growth. In their death, the residues added more organic matter for the next generation of plants. Age after age, more seeds fell and took root, more particles washed down and joined those already assembled, more soil grains continued their untiring routes to the seas. The cycle of continual growth and continual decay has been unceasing in the soil.

The soils and rocks today are temporary forms of the basic stuff of the planet, the same material out of which it was originally made. The coal beds of Pennsylvania, the sands on a Florida beach, a Georgia muck—these are but different forms of the ageless raw materials of the earth. During the long history of the planet, there have been few additions or subtractions of materials. Bits of dust have been gained from the atmosphere, and also occasional meteors; the only losses have been hydrogen and helium. Otherwise, the earth is a closed corporation, its matter locked up but producing endless variations in form.

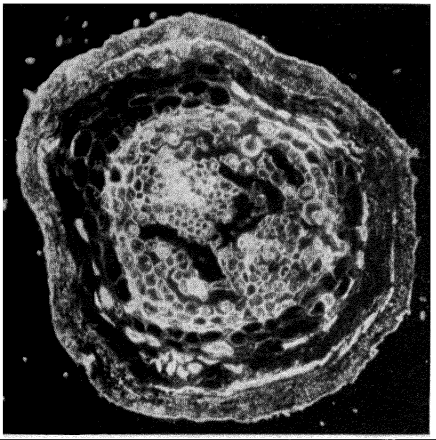
How did the first life get into the soil? Weathering supplied two of the essentials for plant growth, potassium and phosphorus. But the third, nitrogen, did not exist in the parent rock material, although it abounds in the atmosphere. There has been considerable debate among scientists as to how the soil obtained its first store of



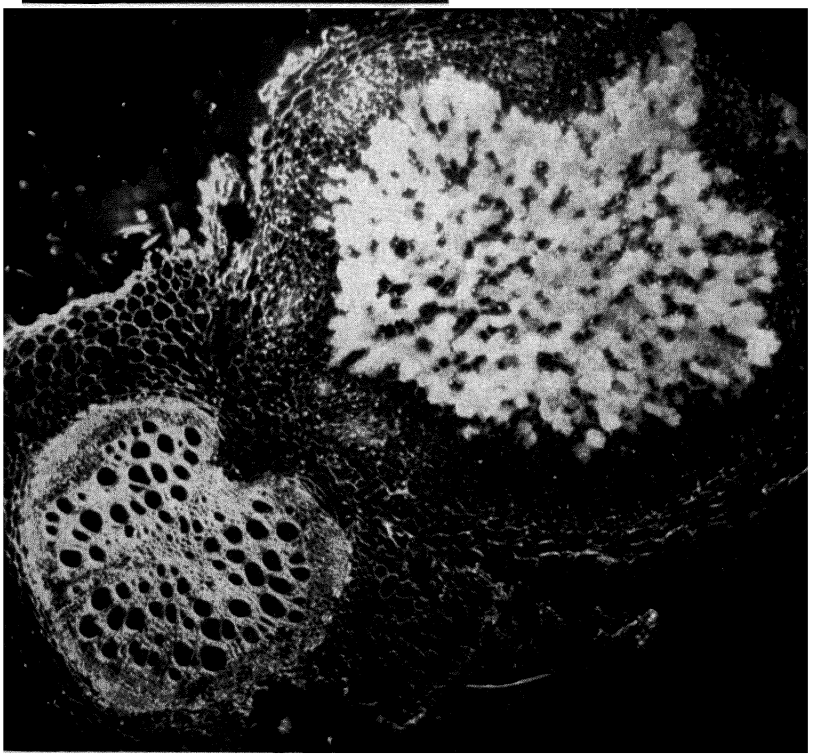
TWO FORCES OF SOIL FORMATION are here at work. Snow and ice have wedged the rocks apart and are grinding them into finer particles. Colonies of lichens, growing on the bare surfaces of the rocks even throughout winter, break down the rock surfaces with acids.



CROSS SECTION OF A LICHEN illustrates the partnership between the cup-shaped fungus and the cells of algae imbedded at the surface. (*Enlarged 110 x.*)



PINE TREE ROOT, shown in cross section, is encased by a mantle of fungus. The roots of most woody plants, by entering into this kind of a partnership with soil fungi, increase the amounts of nutrients that they absorb.



CROSS SECTION OF LEGUME ROOT AND NODULE. Into the nodule are tightly packed the nitrogen-fixing bacteria which convert nitrogen from the atmosphere, putting as much as 200 pounds of it every year into an acre of soil.

nitrogen. Many maintained that it came through lightning, for at the tremendous temperatures generated by a bolt of lightning, atmospheric nitrogen combines with hydrogen to form ammonia which is carried earthward in rainfall.

However, in the latter part of the last century evidence indicated that nitrogen compounds could be created in small amounts in the soil by microbes, and the problem of isolating the specific organisms occupied chemists across Europe. Many tried to show that the nitrogen-converters were various bacteria, but their experiments were never conclusive. Success was finally achieved around 1890 by one of the most brilliant and persevering workers in soil biology, Sergius Winogradsky.

Winogradsky's method of showing that some microbes can take nitrogen from the atmosphere and convert it into nitrogen compounds was startlingly direct. Since he was searching for an organism that could manufacture its own nitrogen compounds, this organism should be capable of growing in the *absence* of these very compounds. So he prepared arrays of culture dishes, containing every nutrient for growth except nitrogen. He added pinches of soil to the dishes and soon nitrogen was fixed. The only microbes to survive this starvation diet were three kinds of bacteria. Were all three bacteria responsible for the nitrogen fixation, or was it only one of them? It was impossible to tell, for the three bacteria were securely locked together.

A disheartening series of experiments followed before Winogradsky was finally able to separate the three bacteria. But now none of them—if grown alone—could fix nitrogen. When Winogradsky combined them once more, nitrogen fixation followed again.

Winogradsky had a final technique: he deprived the three bacteria of all air, except nitrogen. Two of the bacteria died, but the third, *Clostridium,* thrived. The reason was that Clostridium is an anaerobe, a bacterium that functions only in the absence of oxygen. But how could it separate nitrogen from the air when the air itself is over one-fifth part oxygen? Here was explained the two inter-

locking bacteria: they insulate Clostridium against the atmosphere, themselves absorbing the oxygen and leaving only nitrogen.

Winogradsky went on to prove much about the nitrogen bacteria in the soil, and so thorough was his work that after nearly seventy years little new information has been added. It is now known that actually very few free-living bacteria are able to convert atmospheric nitrogen, but that it is a very common trait among the blue-green algae (about half of the forty species tested so far are able to do it). A few yeasts have been isolated that fix nitrogen also, and claims have been made for various fungi.

Today the free-living bacteria fix but small amounts of nitrogen found in the soil; most of the store of nitrogen compounds comes from other bacteria which live on the roots of certain plants and are called legume bacteria. But the free-living nitrogen bacteria, or forms with a similar ability, were perhaps among the first inhabitors of the earth when the seas receded, for they would have had to build up vast amounts of nitrogen in the soil before other forms of life could gain a foothold. It will no doubt always remain an unsolved problem, for no record of this event has been left to us.

The Different Sorts of Earth

One of the earliest books about the soil, *Terra,* was published nearly 300 years ago, and in it the author wrote that scientists "reckon up no fewer than 179,001,060 different sorts of earths." That soils differ from place to place was recognized early, possibly as soon as man began cultivating crops. In fact, a classification of soils, based largely on color and structure, was developed by a Chinese engineer named Yu about 4000 years ago.

There are many thousands of different sorts of earth, each with its own individuality and characteristics. But so new is the science of soils that it was not until about eighty-five years ago that intensive study began. In Russia, a whole group of soil scientists emerged, and one of the first things they noted was that soil possessed layers, or

horizons, which began at the surface and continued down to bedrock. More than that, each kind of soil was soon seen to have its own peculiar arrangement of horizons. Here was a step forward, much like the knowledge of anatomy which opened new vistas in medicine. For now the scientist could examine the structure of a sample of soil and know much of its past life.

Like individuals, every soil has a unique personality which can be deciphered by the trained scientist. Most soils have at least three horizons—the uppermost A, an intermediate B, and the underlying C—usually subdivided into many more. The A horizon is often moist and spongy, and feels like a palmful of breadcrumbs in the hand. Occasionally it is almost completely organic matter, for it is the layer on which the leaves and dead grass fall, and is the zone of greatest penetration by plant roots. It is where the soil life is most active.

The B layer is heavier and more gritty to the touch; in some cases it may be quite densely packed and hard, and usually contains small pebbles and stones. The A and B layers together are the true soil, and it is only in them that life is carried on. The C horizon, the parent material out of which that soil was made, knows very little life, except for an occasional exploratory taproot.

The soil profile is a final synthesis of the entire landscape; it is the great compromise between parent material, slope, climate, and previous plant life. All of these factors, interacting in the same degree, produce a similar soil anywhere in the world. Northern New England is famed for its magnificent spruce-fir forests; this same plant community exists in other widely separated regions, such as the Rocky Mountains, the California Sierras, even parts of Michigan. All of these soils have a similar humus and degree of acidity.

Even adjacent soils, once launched in different directions, continue to follow their separate paths. This can nowhere be more dramatically seen than in the Florida Everglades. The Everglades is not a jungle, but rather a river of grasses adapted to the conditions of almost endless flooding. On this river are many islands, called

hammocks, some of great extent, but often covering only a quarter of an acre. They rise but a few inches above the surrounding muck, yet this is enough to support a dissimilar vegetation of palms, palmettos, and pine trees. The hammock soil and that of a neighboring muck have different profiles, a different structure of the soil particles. The amounts of oxygen present, the intensity of oxidation carried on, the very soil life—all are contrasting.

Throughout the world, there are generally three kinds of soil belts, each the result of many factors operating upon the parent rock material. They are the forests, grasslands, and deserts, and each has its own unique community of living things.

The United States contains all three soil groups within its borders. Any transcontinental route must pass through all of them. From the Atlantic seaboard to slightly west of the Mississippi River stretch the forest soils: in northern New England and in a belt across the Deep South, the soils were formed under evergreen forests; the remainder were formed under deciduous or winterbare forests. Ohio now has few trees, but historical evidence reveals that before the forests were cut a squirrel could have crossed the state without having to touch ground. These soils, and others in a band from New York to Indiana which have been severely cut over, are in transition. For some years now, biologists have watched them being slowly invaded by plants and animals of the grassland community.

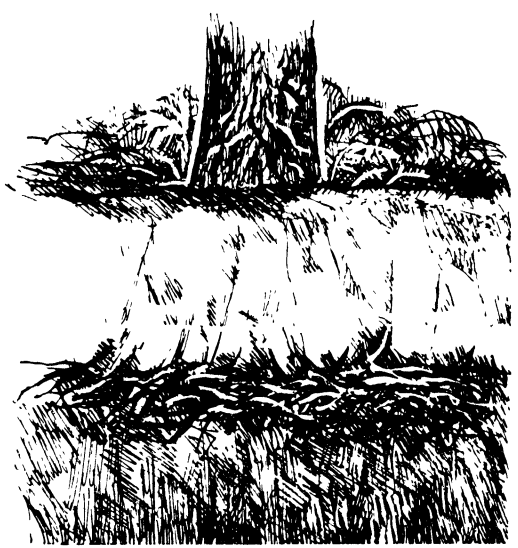
West of the Mississippi, the forests inconspicuously blend into grasslands. The trained naturalist notes the first indications in the gentle opening of the forest canopy, then the breaking up of the forest into pockets of growth. Soon these islands of trees become more widely spaced until only a few seedlings venture into the sea of grass. There they live precarious existences, established by a few consecutive moist seasons, husbanding their sparks of life when the drought returns.

The rich grassland soils, which extend practically to the Rocky Mountains, are divided into three belts: the fertile tall-grass zone, the mixed-grass prairie and, westernmost, the short grasses of the

high plains. At roughly the 100th meridian, a tilted north-south line near the Oklahoma-Colorado border, the grasslands merge into the deserts. This line is not a stable one; it swings eastward and westward for hundreds of miles, depending upon rainfall. Finally, much of the western third of the United States consists of arid deserts, with the exceptions of the forests of the Pacific coast and the mountains, and the tundra soils of the peaks of the Rockies.

When the Russian peasants, who seem early to have shown a curiosity about what was underfoot, examined forest soil, they noted a thick layer just beneath the surface which was greyish in color and appeared to be ashes left by forest fires. This kind of a layer is characteristic of evergreen forest soils almost everywhere on the globe. In fact, forest soils are known as *Podzols*, the Russian word for "ashes." (In deciduous forests the ashy layer is sharply reduced.)

This horizon has a more complicated history than a forest fire. Much living matter in a forest undergoes an annual change: the



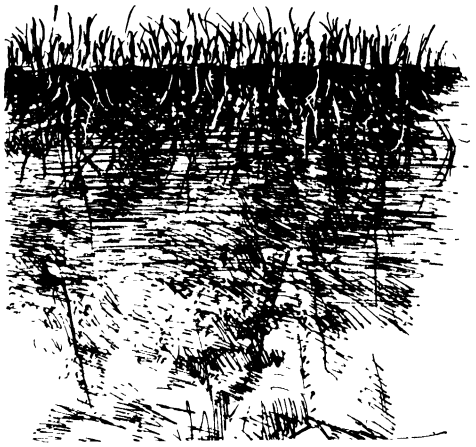
PODZOL, typical forest soil profile

steady rain of leaves, needles, nuts, cones, twigs, and branches to the surface of the soil. There they combine with the residues of ferns and mosses to form a soft layer which is bound together by the roots of shrubs and strands of fungi. Since forests are usually found in humid areas, this layer is besieged by moisture. A chemical reaction takes place, producing acids. The rains wash the acids downward, until the A horizon is little more than a topping of humus overlaying a barren zone of resistant quartz or silica (which gives the greyish color). All else has been washed out, to finally settle in the B horizon, which is usually brown or red because toxic aluminum and iron compounds are percolated down along with the plant nutrients.

This typical forest soil has a layer of raw humus on the surface, then a thick bleached layer, finally a brown layer rich in plant nutrients but also containing harmful compounds. Thus, the zones of life in a forest soil are at the surface—where the shrubs usually take root—and at the point at which the bleached and brown layers meet, where the tree roots are found. The layer of ashes between them is practically devoid of roots, or much other life.

In the interior of the continents, where the summers are hot and dry and the winters wet and cold, are the grassland soils. Many are completely treeless, since trees do not survive under such climatic conditions. The grasslands include the dark earths of the Russian Ukraine and the American Great Plains; the Russian word for the typical grassland soil, which has been adopted by soil scientists, is *Chernozem,* meaning "black earth."

The difference between an undisturbed Chernozem and a forest soil is that the Chernozem's humus is evenly distributed throughout the upper horizon, often to a depth of a few feet. The black earth is formed from the decayed roots of the grasses which penetrated the soil in all directions, tightly interlacing the particles. The Chernozems have been made by grasses for the perpetuation of grasses. That is the reason why agriculturists regard them as among the



CHERNOZEM, typical grassland soil profile

richest soils in the world: most crops, like corn and wheat and the other cereals, are themselves grasses.

Each fall, there is a severe drought in the grasslands, followed by a killing frost which turns all of the vegetation back to the soil (unlike the forests, where it remains in tree trunks.) The residues do not decompose during the winter, but vigorous biological activity starts in the spring and continues throughout the growing season; as the microbes break down the complex compounds, they release the simple nutrients needed by the growing plants. By fall, the residues have been completely broken down and thoroughly mixed into the soil by its tenants. So complete is the annual turnover in the grasslands that the only vestiges of plant life are underground, in the seeds and roots of perennials.

Few would consider the Arctic tundra and the deserts to be soil, but, except in extreme cases, they are. The influence of living things upon the formation of these soils is a leisurely activity, considerably less than the twelve-month cycle of the tropical rain-forest or the five-month activity period of the grasslands. In the tundra, the short growing season every year produces a very small amount of organic

matter in the form of vegetation which is quickly returned to the soil; but because of the shortness of the season of biological activity, there is very little decomposition by microorganisms. So, the organic matter of the tundra soil is often in the form of peat moss deposited on the surface of the mineral soil.

In the hot deserts, however, it is not cold that interrupts the season of growth, but rather lack of rain: since some desert areas may go for years without a measurable amount of water falling upon them, the production of plants is quite small. But the work of the microorganisms in returning the residues of this growth to the soil is thorough, completely breaking them down before the next period of growth begins. These small amounts of organic matter are inconspicuously distributed throughout the mineral particles, and the desert soil usually has no profile.

The color of the hot deserts is that of its soil, except in the brief periods when rain falls and renews the plant life. The plants often grow so separated from each other that they contribute little tint. To get the feeling of the sea an ocean voyage is necessary; similarly, to know the presence of the soil you must go to the desert. There is no monotony in desert soils. Its variations are many: the occasional drifting sand dune, mud baked by the sun, or strips of bare rock. More commonly, it is gravel from which the upper layers of sand have blown off. In some deserts there are thick accumulations of salt, such as those near Great Salt Lake in Utah or California's Death Valley. The salt deserts are perhaps the only completely sterile deserts that are known, for nothing green can survive there. Sometimes they are formed when underground water rises and is then evaporated by the hot sun, leaving behind the salts carried upward. In other cases, salt deserts arise from water draining into large basins which have no outlets, the salts left by evaporation accumulating year after year in sparkling drifts.

To see the deserts is like reading an early chapter in the story of soils and the rocks from which they come. For the desert is much as the young world might have looked. In the story of the continual creation of soil under us, the desert is the silent preface.

II.

THE FORESTS

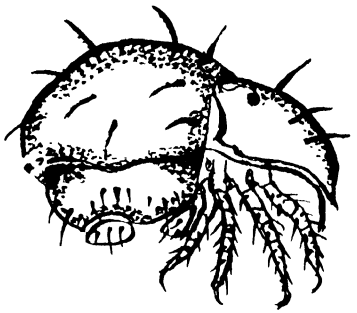
3. *The Forest Hive*

THE LITTER of the forest surface provides a special kind of habitat, rich in organic food, moist under the cover of dead leaves. There live an assortment of insects and related forms, typified by the springtails, mites, and millipedes. Mites and springtails are by far the most numerous organisms visible to the naked eye in the forest soil. In the top two inches there may be as many as 15,000 mites and 2000 springtails per square foot. Further down, in the layer that is six to eight inches below the surface, the mites drop off to about 1400, the springtails to 300.

So tiny are the mites that they resemble grains of soil with eight legs. In fact, the Greek Epicurus stated in his book on natural history that they were not composed of atoms at all, but that each mite was an atom in itself. Though so small as to be hardly visible to the naked eye, they are numerous enough that their bulk may make up 5 per cent of the weight of life in forest soils. They are world-wide forms, found wherever life exists, but are particularly abundant in forests, where they have filled every possible niche. Spruce leaves falling to the ground, for example, are attacked first by the fungi, which soften the hard tissues. This done, the mites are able to gain entrance. The young of at least three kinds of mites begin life only inside the walls of spruce needles; by the time they leave their cradles, nothing remains but the thin, exterior row of cells, the rest of the needle having been digested.

The mites that spend their entire lives in the soil, the Oribatids, have been little studied. They spread few diseases which scientists are aware of, do not interrupt man's activities, and inconspicuously

carry out their jobs. Such attributes do not encourage scientists to delve into their secret lives. So for the life history of a mite, we must go to one which has been studied because it does interfere with man. This is the harvest mite, or chigger, a parasite of warm-blooded animals in its larval stage, an inconspicuous soil-dweller during the rest of its life.



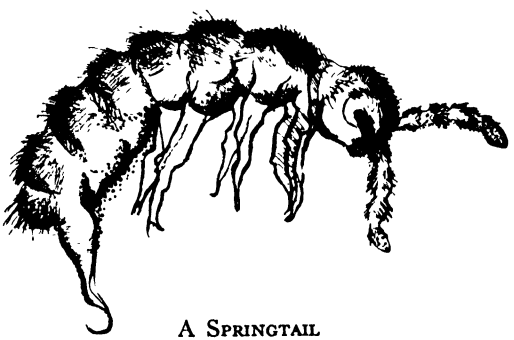
ORIBATID, a soil-dwelling mite

The larva hatches from pinpricks of eggs buried in the soil and clambers to the surface in the summer, when the temperature rises and the air is moist, for it cannot long withstand the dryness of the aerial world. Chiggers are attracted by the light, swarming on grass blades and leaves of bushes, climbing until they can climb no more. When one chigger brushes against another, a mechanism tells it to stop moving. Soon others brush against the first pair, and still more stop moving, until there may be a cluster of 100 of them on a leaf. There they lie quietly until the shadow of a bird or animal passes over them, or until, at night, the vibration of a nearby animal in the woods awakens them to action. Their legs wave wildly, so that even the slightest contact by a passing host enables them to hop aboard.

After having drunk its blood meal, the larva drops from its host to the soil. It may have been carried for miles on the breast of a bird, or it may still be in the vicinity of the spot where it emerged from its egg. But whether it will be able to carry out the rest of its

life cycle depends on the soil conditions where it abandons the host. If the soil is light and moist, the mite has little difficulty once again gaining entrance; otherwise, it perishes from heat and dryness—as most larvae undoubtedly do. If it lives, the rest of its larval and adult life is spent in the tiny crevices between soil particles, the world of darkness which it briefly abandoned. Its life in the soil is unknown, and undoubtedly aimless compared to the precision with which the unfed larva stalks its host. Possibly the adult chigger feeds upon other mites and insect eggs, but there is much uncertainty about that. It does take part in the great waves of migration in the soil, toward the surface in times of moisture, downward when dryness prevails.

Sharing the world of the mites are insects of tremendous antiquity, the springtails. They are perhaps the vestiges of what the insect world was like 300 million years ago. Springtails lack wings and undergo virtually no metamorphosis; they are little six-legged animals that resemble the larval stage of a more highly developed insect. They exist in most unlikely places; the snow fleas of the frozen Arctic and the heights of the Rockies are springtails. They are often found deep inside termite and ant nests, and are undoubtedly more primitive than their hosts. Sheltered by other insects, or hidden in soil crevices, springtails have long been off the main highway of insect evolution.



A SPRINGTAIL

The usual method of springtail locomotion is by rapid movement of the legs, but each one carries on the bottom of its abdomen a remarkable organ used for leaping. It is like a tiny spring, stretched forward and held in place by hooks. When the springtail jumps, the hooks are suddenly released and the spring snaps backward, launching the insect into the air, often for two feet—much as if we carried a pogo stick which projected us for 500 yards.

Some springtails emerge into the daylight for short periods when the air is moist; they possess sight and their skin is pigmented. But deeper down in the soil profile live other kinds that lack eyes and pigments; even their leaping organs are degenerate. They never leave the soil grains, but spend their entire lives in sluggish movement. They probably remove from the soil specks of plant life, such as pollen grains and fungus spores; and in the economy of the soil, they undoubtedly furnish food for other organisms. It is only the comfortable environment of the soil which has allowed these springtails, so ill-fitted for life today, to survive.

Similarly finding a haven in the soil against the tides of evolution are the millipedes, perhaps among the very earliest animals to leave the oceans and find a home on dry land. In the millions of years since, they have hardly altered their shapes and method of living. They are animals of the ancient forest floors, and if they are found today in a meadow, it may be that forests once covered that meadow.

Millipedes break down perhaps only a twentieth of the leaves falling to the forest soil, and the millipede is but one cog in the complex machinery of life working as agents of decomposition. They are extremely finicky eaters, and experiments have shown them to have preferences between leaves of different species of trees, leaves of nearby trees of the same species, and even different leaves from the same tree.

Although millipedes are comparatively large—often more than an inch long in temperate climates—and at times extremely numerous, they do not accomplish more in the cycle of matter because of their

limited periods of activity. They have survived in the soil since the Carboniferous period, but their existence is often a precarious one. They are inactive throughout much of the summer because of the dryness at that time; yet wetness is sometimes a hazard to them also. Many of the smaller species and the immature stages of larger species can be imprisoned on a film of water by mere surface tension, and a heavy rain may cut off their supplies of oxygen.

A few species, however, have developed adaptations. In some, the skin is coated with an oily film pumped out by special glands, which keeps their cuticle dry. Others are able to collect bubbles of air around their bodies and thereby withstand full immersion in water for a day, the air supply trapped at the surface of their skin. But most perish in wetness as rapidly as in dryness. In making the journey from the sea to land, the millipedes have not gained a sufficient foothold on the one and have lost their adaptation to the other.

Tunnelings in the Earth

Unmarked and trackless though the soil may appear, life exists throughout it in well-ordered niches. The millipedes and other inhabitants of the forest surface are as removed from the seething of the deeper layers as are the floating plankton of the ocean from the giant squids in the depths. In the soil, the realm of the burrowers descends many feet below the surface. There are the honeycombs of the moles, the borings of the shrews, the burrows of worms and lesser creatures. They exist in such profusion that a Cornell scientist found the tunnels of just one kind of burrower an average of every 2.2 feet in a New Hampshire forest. The burrowers cut their swaths through the forest soil, giving it the airy feel of foam rubber to a walker in the woods. The dominant mammals of the forest floor are the mice, and the little deer mouse—perhaps the handsomest, with soft brown fur, white belly, and large ears and eyes—inhabits all kinds of forests. It labors throughout the year, scorning the sub-zero

temperature of winter, in its search for nuts and seeds, sometimes storing as many as a quart of them in the earth.

Some authorities state that the most abundant burrower of the forests is the shrew, a broth of an animal whose secretive habits have brought it little notice. Yet, it is everywhere underfoot in the forest. On its rare excursions above ground, it whips across the field of vision like a blur. It is often confused with a mouse or even a mole, although it bears little resemblance to either. The shrew is distinguished from a mouse by its more streamlined appearance—long pointed snout and lack of large front teeth; it is considerably smaller than the mole and does not possess the mole's large, paddle-like front feet. All shrews are tiny, but the pygmy shrew of the eastern forests is the smallest mammal in the world, only about two inches from snout to tip of tail, and weighing less than an ounce.

A shrew is perfectly adapted to soil life. Its snout is composed of bones that much resemble a plow. Its velvety fur never musses, even when the animal travels backward, a decided advantage for passing through the confines of narrow tunnels. The small black eyes, hidden deep inside the fur, are practically useless, and at most are only capable of distinguishing night from day. It is surprising that the eyes have survived at all, for the shrew has little need for them in its black tunnels where it relies on hearing and touch stimuli from its extraordinarily sensitive whiskers.

Shrews are found around the globe, with the exception of Australia, and there are kinds that have made homes even in tundras and deserts. They represent the earliest mammal ancestors, the basic pattern from which all other mammals developed. Each of the mammals on the face of the earth possesses one or more specializations which sets it apart from the rest: the long neck of the giraffe, the cheek-pouch of the rodent, the hind-feet stance of the human. The shrew has none of these; it is the blueprint from which all other mammals developed. There is nothing radically modified about its head, tail, neck, or body; its four feet, with five digits on each, show little adaptation; even its teeth are in the basic mammalian pattern.

The shrew is a mass of energy that burns tissue with startling rapidity in its very process of living. It has the highest metabolic rate of any animal, even four times that of the nervous mouse. Its break-neck pace of living causes it to die young, usually in only a few months. Although a shrew can be coddled in captivity for a couple of years, in nature only about one in twenty born in the spring even survives the summer.

Because of its rapid expenditure of energy it must constantly eat, at least once every hour. It cannot hibernate, for if it tried to do so, it would quickly perish of starvation. One captive shrew was observed to eat over three times its body weight, day after day, turning a succession of snails, grasshoppers, worms, seeds, in fact anything available, into a few calories of heat. Its enormous appetite includes small living animals, such as insects and worms, but a shrew also takes on rodents, snakes, and birds.

The shrew is surely the fiercest animal on the globe, and ounce-for-ounce the measure of a tiger. Experimenters have placed a shrew in a cage with a large snake and within a short time found the little animal busily chomping on a reptile meal. Deprive them of food and they devour each other: Dr. C. Hart Merriam, the famous naturalist, once imprisoned three shrews in a glass jar; within a matter of minutes, two of them attacked the third and promptly ate him. When the naturalist looked again, only one shrew remained, contentedly licking its chops.

"It is a ravening Beast, feigning itself gentle and tame, but, being touched, it biteth deep and poisoneth deadly," wrote Edward Topsel, a seventeenth century clergyman, in one of the most delightful nature books of all time, *The Historie of Four-footed Beasts and Serpents . . . Countries of their Breed, their Love and Hatred to Mankind, and the Wonderful Work of God in their Creation, Preservation and Destruction.* Scientists regarded the claim that the shrew was poisonous as a quaint embellishment by the clergyman; no mammal possesses poison, they said. And they continued to

believe it until one of them was accidentally bitten by a shrew and suffered all the pangs of venom.

A closer inspection of the shrew was then made, and a tiny gland leading to a groove in one of its incisor teeth was soon discovered. The gland was removed, ground up, and put into solution. When mice were injected with droplets of the glandular secretion, they died at once; a large rabbit succumbed in only a few minutes. There is no doubt that if injected into a human, the secretion would have the same effect as a cobra's venom. But the shrew lacks fangs or any other mechanism for injecting the poison. It must first make a wound, into which the poison seeps with the saliva. The largest animal that the shrew is usually capable of poisoning is the mouse, unless of course it got its teeth into the fleshy part of a human finger. So far, the venom has been confirmed only in the American short-tailed shrew of the eastern states, but it probably exists in many other species.

The mole shares much of the range of the shrew, and there are five groups of them living in the United States as well as the more humid parts of Europe. Moles burrow through the earth, both to dig a home and to find the worms and insects which make up their diet. Their runways, especially when they pass under lawns or pastures, are conspicuous, for they are plainly indicated by mounds of earth. Each of the mounds indicates a place where the mole had to carve out a deeper channel, perhaps to avoid a rock, for they are made up of excavated earth pushed to the surface. Connecting the mounds are ridges where the moles burrowed so close to the surface that the entire soil crust was uplifted. The Townsend's mole of the Pacific coast forests is the master mound-builder of them all: in only seventy-seven days, one mole constructed 302 mounds on a quarter-acre field. Mound-building is much rarer with the eastern species, except for the star-nosed mole which uses this method to dispose of excess dirt.

The mole can be identified by his very large hands and strong claws, the palms twisted so that they face outward. The snout is

pointed, and often rather fleshy. The mole does not push out the earth with his snout, nor does he take scoops in his enormous hands. Rather, his movement in making tunnels is exactly that of a human swimmer using the breast stroke. His arms are first brought forward in front of his snout, with the palms facing outward. Then the powerful shoulder muscles snap the arms back, pushing the soil aside and propelling the mole's body for a few inches. It is by a series of such strokes that the mole manages to work his way through the soil.

Each ridge indicates a hunting tunnel burrowed for the purpose of finding food. Often the runway is used only once, but some are well-tended superhighways which are kept in a constant state of repair. Those in use can often be distinguished from runways which have already served their purpose: if the ridge follows a straight line, then it is probably permanent; but ridges that are flattened, or punctured by mouse holes, have been abandoned, for a mole is extremely conscientious about repairing his roads.

There is one place on my mountain where mole workings closely interweave a trail. And so each time I passed, I poked a hole into these ridges, and then the next day noted which had been plugged. No more than a quarter of the ridges turned out to be highways, but these were completely repaired by the time I took that trail the next day.

When were the repairs made? As a boy I had learned that the moles burrowed only at night. To find out, early one morning I flattened, in ten places, the ridges which my previous interference had shown to be in permanent use. I made rounds of inspection every few hours to see how repairs were getting on. Three of the breaks were mended almost immediately, before noon, and five more of them at varying hours until about 8 P.M. The ninth I found raised again when I inspected with a flashlight about 10 P.M. The tenth was never repaired, perhaps because I had accidentally chosen an unused runway, or my harassment had caused the mole to abandon that particular stretch of road.

I once again broke into the nine locations, this time in the late afternoon, to see whether the moles would again do most of their rebuilding during the daylight hours. Not at all: four of the breaks were repaired by midnight, with four more at varying hours until noon the next day. The ninth, though, was not put back into working order until the following night.

Moles work around the clock, repairing the breaks as they find them, and are not more active at one time of day than another. The mole also travels his runways at all seasons of the year. When the upper soil freezes, he merely excavates lower down. There is no need for the mole to enter a period of winter dormancy, for the cold has sent his insect and worm food migrating downward also. His digging is still rewarded by fresh game, now in a lower soil horizon.

The industrious diggings of the mole are not for him to enjoy alone. A host of other small mammals of the soil—shrews, meadow mice, voles, sometimes even pocket gophers where their ranges overlap—all travel his underground highways. The mole has been accused of injury to roots and tubers, but the blame must be heaped upon these intruders, as can be seen by examining the damaged roots. Moles have short teeth, completely unsuited to gnawing, and at best they could only mangle a tuber; rodents, on the other hand, always make a clean slice. Systematic trapping of the occupants of mole tunnels has revealed that on occasions the trespassers are more numerous than the moles themselves.

Of the many soil-burrowers, only the mole and the pocket gopher spend their entire lives in the soil, with rare excursions into the sunlight. Even some of the more famous diggers, the prairie dogs and ground squirrels and woodchucks, live but a part of the time in their dark homes, usually coming above ground to feed or reproduce. But they must return to the soil for long periods to avoid the harshness of the climate in the aerial world.

The mole is modified for its life in the soil and is an instrument

of perfection in its line, admirable in the same way as is the brute efficiency of a bulldozer. The body of a mole is elongated, the better to fit through narrow tunnels. The limbs are short and strong, not built for speed but rather for moving vast quantities of earth; in fact, the front arms are constructed much like shovels. The fur, like that of the shrew, offers no resistance to its passage through the tunnels. And the tail is very sensitive to touch, so that the mole travels equally as well backward as forward. All embellishments have been streamlined out of the mole's body: there are no external ears which might create friction; instead, a small circle of bone on the skull serves the purpose just as well. The nostrils are on the side of the head, not in front as with most other mammals, since less dirt enters that way.

Shakespeare, a good naturalist for his time, wrote: "Pray you tread softly, that the blind mole may not hear a footfall." In one sentence, he made two perceptive observations about moles. One is that the mole, if not completely blind, is nearly so. The mole's eyes possess all of the elements that exist in the eyes of other mammals, but the parts are so crowded together as to be virtually useless. And in some species, such as the common mole, *Scalopus,* of the eastern states, the eyelids are completely sealed. At the very best, in its rare expeditions above ground, the mole can do no more with its eyes than see the difference between night and day.

And correct, too, is Shakespeare's caution to tread lightly, for hearing and touch are the mole's two most acute senses. The world of the mole is circumscribed by the cylindrical sides of an earthen tunnel, but in this world it knows everything that takes place. It can easily distinguish an approaching footfall—and one way to get rid of moles, a countryman maintains, is to insert iron spikes in their tunnels and strike them sharply with a hammer. The vibrations so upset the mole that he will often depart to quieter surroundings.

The fleshy snout of the common mole is covered with extremely sensitive hairs. The star-nosed mole, *Condylura,* very much resembles a common mole in the act of eating an octopus—for

mounted on his snout are twenty-two tentacles, writhing and twisting to feel out his dark world. The star-nosed, by the way, is the mole one is most apt to meet from New York state northward. He is a gregarious animal—so much so that one area of lawn may be completely erupted with Condylura mounds and ridges, while a similar area nearby is unplowed by them. This mole is commonly found along waterways, and his diggings often lead directly into lakes and ponds. In the winter, he may be seen swimming under the ice and nosing into the bottom muck for aquatic worms.

"The Intestines of the Earth"

Earthworms are a primary food of moles: in fact, it has recently been shown that moles even bite off the front ends of worms, enough to prevent regrowth, and store them as food for the winter. In just one mole tunnel, more than 1000 worm corpses were found, hung on the walls like trophies.

G. V. Jacks, Director of Britain's Commonwealth Bureau of Soil Science, once lived near a tennis court where each spring, after the rains and snow had completely washed away the court markings, the lines could still be traced, for mole ridges followed them unerringly. After much detective work, this was shown to be the explanation: the court was built on acid soil; earthworms will not live in very acid conditions, but the chalk used in marking the lines had neutralized the soil underneath. Thus, in the whole expanse of tennis court, the worms were restricted to the earth under the chalk lines. The moles had discovered this, and in their search for worms cut straight swaths under the court.

Throughout the deciduous forests of the temperate zone, as well as in many grasslands, the plowing of the soil is performed by earthworms. There are about 1800 species of them around the globe, ranging from tiny one-inchers up to the ten-footers of Australia that weigh a couple of pounds and have a girth of about three inches. They are surprisingly common in many soils, occasionally at the

rate of a million or so to the acre, but are very rare in evergreen forests because they cannot endure the highly acid soil conditions. They have been recorded as deep as ten feet, and they interlace the soil crumbs in such numbers that their total weight in an acre may very well equal the weight of grazing animals at the surface. Aristotle regarded them as "the intestines of the earth."

Earthworms belong to the class of organisms known as *Annelida,* meaning "rings" in Latin, which very well describes them. Many common worms have from 100 to 200 rings or segments, most of which are miniature bodies in themselves, endlessly repeating the internal organs. But it is not true that an earthworm can be cut in half and that each half then grows into a new worm. Segments that have been lost, as when a bird is able to bite off only a part of a retreating worm, can be regenerated, but this ability is somewhat limited. The first dozen or so segments can be removed and a new head will be grown, but it will not be so large as the one that was amputated. The hind segments can be regenerated more easily: remove as much as the rear four-fifths of the worm and a new tail-piece will grow.

Nor is it true that worms reproduce simply by splitting in half. Their breeding habits are in fact quite complex. First of all, each worm is male and female at the same time, producing both eggs and sperm. Hermaphrodites are widespread throughout the natural world, but the earthworm does not use its dual sexual organs for self-fertilization. It still has to find a mate, although any passing worm of the same species will do, since every worm is both male and female. When they mate, each partner impregnates the other one, and both partners end up producing eggs. Two worms result in two broods, a much more efficient system than that found in the higher animals.

The worms mate by placing their clitelli—the clitellum is a collar of enlarged rings about a quarter of the way back from the head—in contact, then secreting a fluid which binds them together. The male organs of each worm give off the sperm, after which they separate.

Now each worm must work the fluid secreted by the clitellum forward over its body, like a girdle, picking up the eggs and sperm on the way. As the clitellum finally slips over the worm's head, it closes automatically, tightly encasing the fertilized eggs. This is the cocoon where the eggs develop into young worms.

Earthworms "are much addicted to venery," stated an eighteenth century parson, and so they are, for cocoons are produced continually during the periods of earthworm activity, often on an average of once a week. The size and color depend on the species. Some cocoons are only a capsule one twenty-fifth of an inch long, although others are as large as one fourth of an inch. Cocoons can be easily identified in the soil since their color is markedly different from the surrounding earth. What appears to be a purple grain of rice is really a cocoon that is about to hatch in a few hours. As the young worms emerge, they are completely white, but become the familiar reddish-brown as soon as they take their first meal of soil.

The earthworm's cocoons have been designed to survive unfavorable conditions. Although the cocoons will often hatch in a couple of weeks if conditions are suitable, they can withstand extreme drying out and even freezing. Some capsules remain in the frozen soil throughout the winter and hatch when the thaw comes. Dormant capsules have been kept in the laboratory for as long as two years without any lessening of the ability to hatch.

Each of the worm's rings carries four pairs of tiny bristles, which can be turned in any direction by powerful muscles to aid in burrowing. Additional muscles allow it to stretch out and contract its length, and also to swell or become thin. A worm can move backward and forward, and at the first vibration of danger can become a blur retreating into the burrow. They wriggle their way through clay soils and even some hardpans; they have been known to move small stones fifty times their weight. Their usual method of progressing through the soil is to wedge their front ends (the more pointed) into tiny crevices between soil particles, then expand their bodies, shoving the crumbs apart. They attain very rapid speeds by this

method in soft soil; but if they find themselves in a compacted soil where this method no longer works, they merely eat their way through it.

Most earthworm burrows are U-shaped, although simple straight tubes are often made. During the summer drought and the winter frost, the burrow is considerably lengthened, descending several feet to better climate. At dusk the worm begins to feed, stretching its front end from one arm of the U to find food in the form of leaves, then jerking them into the burrow. It is reluctant to abandon the safety of the burrow, but will do so when the atmosphere is sufficiently moist.

The earthworm is little more than a humus factory, a streamlined digestive tube into which go particles of minerals and organic matter. What emerges are castings, a mechanical and chemical blend of minerals and once-living matter, the larger soil particles strained out, rich in nutrients and having a more neutral reaction than the surrounding soil. It is topsoil—and recent research in England has shown that worms yearly pass more than forty tons of castings through their bodies on each acre. In some places, such as the Nile Valley, the weight of castings reaches 200 tons per acre.

Most of the worm's body is taken up by its digestive system. Just behind the mouth slit is a protrudable trunk which is pushed out for feeding. Digestion takes place outside the body, for the vegetation is first moistened with an enzyme which softens the plant tissues. (The part of a leaf inside the burrow, on which the worm has been feeding, is darkly discolored by the enzyme, while that outside is still fairly fresh.) Behind the trunk is the oesophagus, and it possesses half a dozen remarkable glands found in no other animals; these glands secrete calcium and their possible use is to neutralize the acids of the plant tissues. Further back is the gizzard, little more than a grinding machine, with powerful transverse muscles to crush the tissues. The food is run through perhaps 100 more segments for refining. Because of the enormous intake of food and water, nearly

every segment contains two kidney-like organs. Through this humus mill passes an amount of food equal to the worm's weight every day.

Gilbert White, the eighteenth century British naturalist, was among the first to make a study of worms; he declared: "Earthworms, though in appearance a small and despicable link in the chain of nature, yet, if lost, would make a lamentable chasm. For to say nothing of half the birds and some of the quadrupeds which are almost entirely supported by them, worms seem to be great promoters of vegetation." An analysis of earthworm castings has shown that, when compared to the surrounding soil, they contain about 45 per cent more phosphorus and nitrogen, 50 per cent more potassium. In addition, their countless tunnels aerate the soil, turning it over, bringing up additional minerals from below and thus increasing the depth of the soil profile. Plant roots have been seen to follow the easy paths blazed by the worms.

It was Charles Darwin who made earthworms a modern-day interest. In fact, the study of them occupied most of his life, beginning in his student days. One of his first scientific papers was on their burrowing activities, and his definitive volume on the subject—*The Formation of Vegetable Mould Through the Action of Worms*—was published the year before his death.

In 1842 Darwin spread cinders on the ground; when he examined the location thirty years later he found that the cinders still formed a distinct layer, but now they were seven inches below the surface. He attributed this burying to the immense amounts of earth brought up from below and deposited as earthworm castings on top of the cinders. In meadows where he made frequent inspections, Darwin noted that the worms brought up an average of about one-fifth of an inch of earth a year. When his gardener ceased to sweep off a flagstone path, it soon was covered by castings. At Stonehenge, the temples of the early Druidical religion in Britain, he found some of the immense boulders buried under nearly ten inches of mold. Concluded Darwin:

It is a marvelous reflection that the whole of the superficial mould over any such expanse has passed, and will pass again, every few years through the bodies of worms. The plough is one of the most ancient and most valuable of man's inventions; but long before he existed the land was in fact regularly plowed, and still continues to be plowed, by earthworms. It may be doubted whether there are many other animals which have played so important a part in the history of the world as have these lowly organized creatures.

There is no doubt that through the ages of earthworm existence, much of the soil on the globe has passed through their bodies at least once, and possibly hundreds of times. But Darwin may have overstated their case. The cinders that he buried were inspected recently by researchers at Britain's Rothamsted Station, who found little further activity by the worms in burying them. And tremendous as the earth-moving operations of worms may be on natural soils, they are negligible when compared to the operations of modern agriculture. A single farmer in a day can accomplish more turning and aerating of the soil than a very large earthworm population could accomplish in centuries.

Claims have been made that earthworms make soils more productive, and these claims have been denied with equal enthusiasm. So, about ten years ago, two researchers at the United States Department of Agriculture set up an elaborate experiment. They filled twenty large barrels with extremely impoverished soil, and planted them with grass. Half of the barrels were seeded with living earthworms, and the other half only with dead worms (the reason for using dead worms was that the researchers wanted both barrels to contain exactly the same amount of organic matter.) Finally, they gave all of the barrels equal doses of organic fertilizer.

The difference in yield between the two sets of barrels was startling. Those barrels containing *living* worms produced nearly four times as much grass. The dispute as to whether worms actually increase productivity or naturally live in the more productive soils was finally settled. For the soils used in the experiment were totally

unproductive to begin with, and in the barrels where living worms were not introduced, they remained unproductive.

Then why not merely add more worms to worn-out soils to increase productivity? Unfortunately, it does not work, as numerous tests have shown. Experiments have failed to reveal any *permanent* higher yield because of adding earthworms to the soil; there is a slight increase for the first year or so because the worms soon die, leaving their valuable organic matter in the soil. The reason for these failures is that earthworms, like all soil life, are living at the maximum populations that the particular soil can support. It is very possible to increase the worm population on an acre from 50,000 to 500,000, but to do so would require a lengthy and expensive remaking of that soil to support this heavy worm population. And once the soil had been recreated, it would have such a high organic-matter content and be of such good tilth that the worms could add little further fertility.

The earthworm was not endowed with very much in the way of a brain, merely a few knobs of nerve tissue. But they serve it very well for the rather limited decisions it has to make. Darwin was extremely interested in the question of earthworm intelligence, and he performed whole series of experiments. He observed that earthworms plug up their burrows with leaves and each leaf might be pulled into the burrow in any one of three ways: by the pointed end, by the stalk, or by the middle. Since each kind of leaf is shaped differently, some being wider at the stalk and some thinner, Darwin concluded that the worms were presented with a choice.

He investigated worm burrows and found 227 withered leaves of all sorts which had been pulled into the burrows. About 80 per cent were drawn in by the tip, 11 per cent by the middle and only 9 per cent by the stalk. Obviously, the element of chance was not in control here, for if it were, the worms would have used all three possibilities about equally. Darwin decided that to make a fair test he must use the leaves of plants totally outside of the experience of these worms, of a shape which they had not come up against previously.

So he spread leaves of an exotic rhododendron upon the soil and waited for the worms to pull them into the burrows. Ninety-one leaves were used by the worms, and sixty-six of them were drawn in by the stalk, a complete reversal of their usual method with the English species of leaves. Twenty-five went in by the tip, and not a single one was drawn in by the middle.

Perhaps the worms had tried to pull the leaves into the burrows in their usual way, by the tip, but were unable to do so. Then they may have experimented with the various choices and found that rhododendron leaves slip in most easily by the stalk first. Darwin concluded that the leaves entered the burrows by this method of trial-and-error. It is surprising to observe animals so low on the evolutionary ladder demonstrating even this glimmer of intelligence, for trial-and-error does require thought, evaluations, and then conclusions. Worms obviously profit by their experiences.

In recent years, more elaborate tests than Darwin's have been devised. A maze was constructed in the form of a T, one arm containing sandpaper and an electric shock, the other a reward of moist earth. After repeated trials, the worms learned to choose correctly, and whole classrooms of trained worms have been put through their paces as many as seven consecutive times. But an unusual thing was noticed: when these tests were performed during the night hours, the worms made a higher score of correct runs to the earthen arm of the T than they did during daylight hours. Since worms are nocturnal animals, very possibly their nerve tissues work at greater efficiency during those hours.

Seventeen Years in Darkness

If it were possible to x-ray a patch of soil to a depth of a few feet, it would look very much like a busy intersection in a city. For the soil is a great concourse of throngs which jostle through the particles. Sometimes the traffic is vertical, as when the caterpillars of the Sphinx and other moths dig their way down to the soil traffic; they

turn a lifeless brown, pass into shrivelled sleep, to awaken again in the colorful form of a winged adult. Other insect species may cast their shiny eggs into the soil incubator, and the hatched young will wriggle off into the moving swarm.

But no insect relies more thoroughly upon the soil incubator than the periodical cicada. Its life-span of seventeen years is passed almost completely burrowing in the soil—until, in some summers, it seems as if the soil has suddenly opened up, shooting into the air thousands upon thousands of them which transform into adults. For several weeks, they are the most prominent life of the treetops, and seem to rival the leaves in numbers. They mate and carry out the business of egg-laying, scarring the twigs with slits where eggs are deposited. Only the males make music, if that is what it can be called; it is more like the whine of a buzz saw or the taut quivering of a violin.

During the late summer, the young hatch from the eggs. Those that the breezes do not carry off climb to the furthest twigs of trees and then tumble, from leaf to leaf and branch to branch, into the awaiting soil. They feel an immediate need to enter the moist earth, rushing through the grass and brush, seeking a crevice to receive them.

Little is known of their lives in the soil. There are two races in the United States, the northern one which lives underground for seventeen years, and a southern race which emerges again into the sunlight after only thirteen years. When the cicada enters the soil it is a tiny creature, soft-bodied and light-colored and only about a twelfth of an inch long. It does not possess the chewing jaws of the locust (to which it is quite unrelated), but the sucking beak of the aphid. With that, its only food-gathering tool, it sustains itself by drinking in the sap of roots. Usually it confines its feeding to the upper two feet of soil, but some follow wherever the roots go, often as deep as ten feet into the ground. Throughout the long years of its interment in the soil, it molts about half a dozen times, each time exchanging its old skin for a closer approximation of the adult form.

For seventeen years the cicada wears a mud-bespattered coat,

laboring for its sustenance in the soil. But, suddenly, in its last spring as a tenant of the soil, it migrates toward the surface. It constructs a chamber about six inches down, and from there erects a chimney leading to the sunlight. But it does not break through the surface until the final emergence hour. It lies in its chamber, often for weeks, awaiting some unknown signal that the time has come to leave the soil.

Scientists are not certain what the signal is, but it is one felt by almost all the cicadas in the vicinity at the same time. The signal could not be the length of daylight, because the cicadas are still locked in darkness; nor does it appear to be temperature, since the times of emergence are usually the same from year to year, in spite of varying weather conditions. But toward dusk on the day chosen, the soil is punctured with holes as the adult cicadas crawl out. Their first act is to molt, splitting off their nymphal skin and emerging as insects of the aerial world. The earthen smock is exchanged for a coat of rich tan; the eyes flame with red and the veins of the wings are scarlet.

Seventeen years of laboring in the depths of the soil have brought the cicadas no reward. In a wild three weeks of song, the mating and gentle feeding upon the leaves are ended. But each night, the song in the treetops grows less strident. They are attacked by a fungus disease which spreads through the crowded treetops killing off whole populations, and they drop to the forest floor like autumn leaves. The cicadas have many other enemies: they are besieged by parasites and mutilated by predators; the birds wreak havoc among them. Finally, the last quivering notes of the males are ended, and the only signs of their visit to the aerial world are the imperceptible passages into the soil, from which will arise a new generation seventeen years hence.

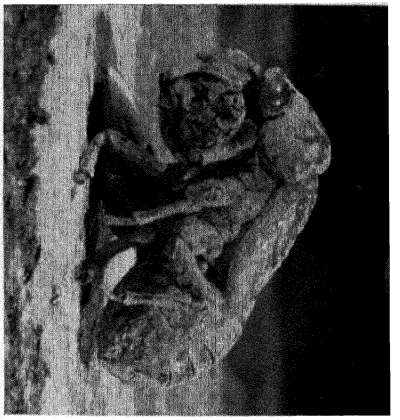
4. The World of the Root

THROUGHOUT the forest soil the roots are prying and twisting; they interlace the soil grains and embrace boulders, sometimes cracking them open. The ground never quivers, yet massive weights are being moved underground. Roots of ponderosa pine growing in the Rocky Mountains have been found forty feet down, following the fractures in the granite. A root that is but four inches in diameter and three feet long can raise a weight of fifty tons.

More than half of a tree's bulk is underground in its root system. That is because there must be at least as great a surface of roots to absorb water from the soil as there is leaf surface to lose water to the air. The giant redwoods of California, largest living things on earth, are supported only by surface roots. A redwood's system consists of an anchoring brush of sturdy roots which go down only six feet or so into the earth. Radiating outward from these are the long absorbing roots, usually trailing only a few inches below the soil surface. Elms and birches and spruce have similar sorts of surface roots. But some trees, like the oaks and hickories, send down deep taproots which plumb the earth for a support. A wayward hurricane which came through my mountainside a few years ago failed to topple a single oak; their trunks snapped first.

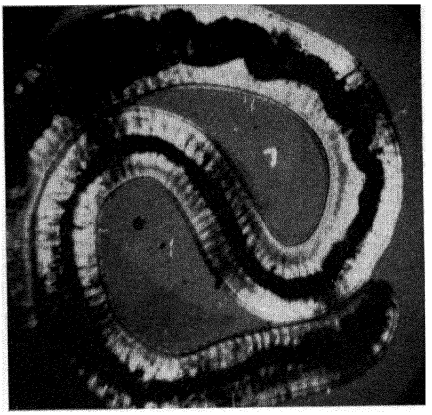
A healthy root system can scarcely be destroyed. Chop down the forest giant and its roots sprout dozens of new saplings before the season ends. My mountainside is in one of the most prolific sprout-forests in the country. Practically every tree sprouted from a stump left after cutting or fire or hurricanes; rarely did a tree ever grow

THE WOODLOUSE resembles an armadillo as it rolls into a ball for defense. Although abundant in forest soils, woodlice have not developed physical adaptations. To survive, they possess intricate behavior patterns which insure their finding the required moisture.



EMPTY SKIN OF THE PERIODICAL CICADA on a fence post marks the end of its seventeen years in the soil. The adult has already climbed out of this earth-covered coat, mated, and produced young which return to the soil for another seventeen years.

MILLIPEDES are animals of tremendous antiquity which have survived to the present day in moist forest soils. They are important agents in returning to the soil the nutrients lodged in dead leaves.



THE HUMUS FACTORY OF THE EARTHWORM is revealed in an x-ray photograph. A stream of soil passing through the worm's system becomes ever thinner as food particles are removed. The earthworms in a single acre may pass upward of forty tons of earth through their bodies every year, thus improving the fertility of the soil.

PRIMARY ROOT OF A NEWLY GERMINATED SEEDLING is attacked by the ravenous grub of a beetle. Some beetle grubs, such as wireworms, are known to follow a chemical highway which leads them to the root.

from acorn or seed here, since it could not battle against the vigor of roots already established in the earth.

In the oak-chestnut zone, which covers southern New England and extends southward down the backbone of the Appalachians, the ability of a tree to sprout is retained almost indefinitely, perhaps as long as the aged roots survive. That is why many trees, tall stalks without very much age on them, are greybeards beneath the soil. They may grow on the same root-stock as those giants which greeted the pioneers. Wiped from the American forests by a virulent disease are the chestnut trees, yet their roots hang on to life, still sending up doomed sprouts. These were the master sprouters of all: one chestnut stump is recorded as having put out 375 shoots, and a good average might be sixty. Black oaks cannot equal this: one, which I took down, presented me with only sixteen tasks a year later.

The massive underground works of the root cannot be seen in a transplanted and carefully tended tree in a garden. Roots, sturdy individualists that they are, grow best when faced with adversity, when the soil is poor and the water hard to come by. Then they grow and develop, sending out scouts in every direction, often leaving the preferred soil horizon in their search.

It would be an impossible task to dig up a giant tree to measure its root system, but experiments have been performed in the laboratory with the grasses: a rye plant, grown for only four months, developed an underground system of 7000 *miles* of roots and root-hairs. A single bluegrass, seeded in a pot three inches across and six inches deep, grew a mammoth root system that filled 3 per cent of the soil volume. With even the little grasses putting out such tremendous systems, the activity under the forest floor on a moist spring day must be tremendous.

Roots go back in the history of the soil about a third of a billion years. There were many plants before then, but the belief of botanists who study fossil plants is that they were not rooted to the ground. Plants have greatly modified their aerial parts, the stems and leaves, in the past 350 million years, but fossil records show

little change in root structure. Perhaps in the conservative environment of the soil there has been little need for adaptation.

With a magnifying glass, four separate areas can be identified in a root-tip. At the very tip is the whitish root-cap, which fits like a thimble and takes the brunt of pushing through the soil. It is constantly losing cells from abrasion against the soil particles, but those that rub off are renewed by more cap cells. This tiny, graceful tip does the massive work of the root, boring through the soil, as if a battering ram were to be made of cotton-wool.

Directly behind the cap is the zone of elongation, seldom more than three tenths of an inch long. It is where rapid cell division takes place and is the *only* part of the root that increases in length. In back of this zone is a mass of felty root-hairs which is the *only* place where the roots feed. The hairs live but a few weeks and new ones are constantly developing as the zone of elongation advances through the soil; thus fresh hairs are always in contact with untapped soil particles. Finally come the serpentine lengths of the corky brown roots which are the familiar ones seen while transplanting. They are older roots, at one time covered with hairs and feeding the sapling, now brown, no longer taking in water but merely serving as pipeline connections to the trunk. The brown covering is cork, the same as on the bark of the tree. It looks different because thick layers of bark cannot accumulate in the soil, since the underground tissues are constantly besieged by the teeming soil microbes.

How do these delicate tips manage to weave a tapestry through solid earth and the obstacle of stones? The force exerted by the zone of elongation is perhaps a pound or two of pressure—not much if exerted against a flat object, but affording tremendous push to the needle-point tip of the root. The tip is a delicate, probing finger which can respond to varying conditions: when it meets a hard object, it veers off; or if the earth is soft, it penetrates. In penetrating, the motion is the twist and turn of the corkscrew. The cork-

screw motion and the expansion of cells are what result in the living maze of roots in a forest.

A blacktop road is often punctured by seedlings which have forced their way through three inches of asphalt. The force that allows them to grow through asphalt is what scientists call *imbibition*. Take a substance that can absorb water, confine it in a narrow space, water it, and it will swell with power enough to split rocks. Even a ship's cargo of beans, if water reaches it, can expand and burst the hold.

The power of imbibition is a common one in nature, and so is the reproduction of living cells. Combine them, as in a growing plant, and there is a force which can move mountains or easily grow through a blacktop road. A classic experiment in botany was once made with a growing squash plant to test the expansive power of cells. The squash, while still on the vine, was tightly boxed in and weights were added to the framework to keep it enclosed. At first, the young squash moved sixty pounds of weights; a month later two and one half tons were not enough to contain its power of growth.

An acorn, germinating in the litter of the forest soil, sends out two blanched shoots—one, destined to become the trunk of a massive oak, points upward; the other, the taproot, grows into the soil. If the acorn is now turned over so that the positions of the root and shoot are reversed, in a day or two they will have made a full about-face and once more the future trunk grows skyward. If the acorn is turned day after day, the tiny embryo will exhaust its strength in winding about itself like a ball of yarn.

Responses such as these are known as *tropisms* and they intrigued Charles Darwin, who overlooked little in the natural world. In fact, Darwin wrote a lengthy book about his experiments with plant tropisms called *The Power of Movement in Plants*. From the first germinating root, he found the plant to be caught in a number of tropisms. The most immediate, that of the sprouting acorn, was the attraction of gravity upon the primary root. When he cemented a strip of cardboard and another of very thin paper to the sides of the

root-tip, the root bore away from the hard-surfaced cardboard toward the tissue paper. Darwin concluded that in the soil the root-tip bends away from obstacles and follows "with unerring skill" a line of least resistance. But after an obstacle deflects the course of the primary root, Darwin found it able to right itself and point downward again.

He also learned that there are different tropisms acting upon the primary, secondary, and tertiary roots. The first root grows downward, the secondary ones follow a diagonal course, and the thin tertiaries are not sensitive to gravity at all, but branch out in a horizontal direction. Thus, all three kinds of roots have equally divided the nutrient hoard in the soil, each mapping out its own zone of growth to cover the maximum amount of soil.

The root-hairs are the only place where nutrients and water enter the tree. (Watering a tree near the trunk only gives the corky roots a bath and not a drink; the root-hairs are usually further out, under the tips of the branches.) Only an inch of some roots may contain as many as 50,000 hairs. Each of the hairs wraps itself around the particle of soil and sucks off the thin film of moisture. As it sucks one grain nearly dry, the water from the neighboring grain moves in to replenish it—and the water on each of the other grains moves up a notch to refill the blank spaces of moisture. The process is called capillary attraction, and it works much like a piece of blotting paper in ink. The water taken in by each root-hair is infinitesimal, but, cumulatively, the microscopic films of water on the soil grains may add up to more than fifty gallons a day for a large tree.

The root-hair is a remarkable tissue. Through it must pass every molecule entering the plant from the soil. But how is the water able to pass through the cell wall into the root's pipeline? The cell wall is a membrane. If two solutions are separated by a membrane, water will move from the solution of less concentration into the solution of higher concentration. Since the solution inside the root cell is highly concentrated, the water moves into it from the soil.

The root-hair is not taking in nutrients *and* water; it is imbibing

nutrients *in* water. For the process of plant nutrition is that the nutrients must first pass into soluble form and be taken up by the soil water; then both are absorbed together by the tree root. Roots feed only in the presence of oxygen, and that is why overwatering of a shrub or tree can kill it, since the water then fills the air spaces in the soil.

We do not yet know what governs the selection of various elements from the soil by the root membrane. For example, potassium and sodium are chemically very much alike, but the membrane is quite expert at telling them apart, or so it seems. The cells may accumulate large amounts of potassium, up to thirty times its normal concentration in the soil, and only small amounts of sodium. Some plants are able to tolerate unusual amounts of particular elements. There is the common horsetail, often found bordering a pond, which is the last descendant of the coal-forming Calamites of the Carboniferous Age. Many horsetails can extract comparatively large amounts of gold if it is present in the soil. Members of the dandelion family are often miners of copper. One of the rare earths much used in industry, selenium, is taken out of the soil in commercial amounts by the locoweed; the locoweed is anathema to western cattlemen because the selenium it harbors is poisonous. Prospectors and geologists are becoming more aware of these accumulators since whole spectrums of minerals are sometimes found under various plants.

Once the solution of plant food has entered the root cells, how does it reach the leaves, often 250 feet above the roots? What allows a drop of water, pulled in by the root-hair, to ascend the hundreds of feet is, simply, evaporation from the leaves. As each of the hundreds of thousands of leaves on a forest giant breathes, it evaporates water into the air in a fine mist. Extending from the veins in every leaf down to the furthest root-hair is an elaborate plumbing system; the loss of water from a leaf causes a deficit, and this need is communicated through all of the pipelines to the root-hairs. Because the molecules of water tend to group together, the loss of a molecule at

the top of the tree pulls up another from below to replenish it, and so on all down the line.

The sloughing off of root-cells in the soil is continuous—from the root-cap as it grows, the hairs after they have served their usefulness, the corky material of older roots. Around the roots many soil microbes find a renewable resource of food, a special habitat where microbial activity is intense. The soil surrounding the roots is a little world of its own, called the *rhizosphere*. Not only is food being served raw, but there are also hormones and acids secreted by the roots and microbes which aid their mutual development.

The numbers of microbes in the rhizosphere are usually much higher than in the surrounding soil. Comparison counts made of soil samples taken near roots and away from roots of young plants reveal about 33 per cent more fungi and more than twice as many bacteria in the rhizosphere. And the numbers of microbes in the rhizosphere increase greatly as the root ages, possibly due to the greater amount of root secretions. Counts made of rhizosphere microbes have shown an unsuspected variation: their numbers were often highest in the spring and fall, with less active periods during the summer and winter. But usually this activity is independent of seasonal temperature or rainfall. It is now believed that the plant, in responding to the seasons, somehow alters the chemistry of its root, which in turn affects the rhizosphere population.

Many, and perhaps all, roots excrete chemical substances. The roots of some desert plants send out toxic substances to prevent germination of other plants. Varieties of flax are able to secrete acids which poison certain root fungi. The potato's secretions have been its downfall in some areas: they stimulate nematodes to awaken from their cysts and follow the chemical trail to attack the potato tuber. A countryman will state that many crops cannot be grown near a black walnut, and even in a forest the number of other species is limited near this tree. A chemical compound has recently been isolated from the roots of black walnut which has proven toxic to many plants. Only in the last few years has much research been

done in studying root secretions, and the subject may prove to be a most important one. This is indicated by a recent survey of native trees in California which revealed that at least half of the species produced substances toxic to other plants.

A Strange Partnership

The strands from the base of a common forest toadstool usually can be traced through the soil directly to the roots of a nearby tree. There, they often form a partnership with the roots, replacing the hairs on most forest trees, and many other plants as well, by what are known as *mycorrhizae* (literally, "fungus-roots").

The tree roots form many short, knobbed branches which are mantled with fungus. The mantle, seen closely, is smooth and shiny, ranging in color from pale white through red and brown to deep black. One kind of fungus may form mycorrhizae on several different kinds of trees, and one species of tree may have several fungus partners on the roots. But, generally, certain fungi are usually found on the roots of specific trees.

The association between roots and fungi has been known, or suspected, since classical times. Theophrastus, an enthusiastic woods-walker of over 2000 years ago, seems to have traced some toadstools back to oak trees. Mycorrhizae have been found in some of the early fossils; the pre-conifers, ancestors of pines and spruces, are believed to have had a similar sort of fungus-root. They have been seen in all soils from the Arctic to the tropics, and even on desert cacti. A study of 134 families of plants in Japan some years ago revealed that 82 per cent of them were mycorrhizal. In fact, one authority believes that there is no woody plant on the face of the earth which does not grow a fungus-root in some part of its range.

Fungus-roots are much more common on trees growing in soils where nutrients are low; therefore, mycorrhizae might develop on a species in one location while in more favorable locations they will

not. The fungus appears to be a true friend of the tree, always ready in time of need, inconspicuous in time of plenty.

The first scientific study of fungus-roots resulted from man's expensive appetite for truffles, the underground mushroom delicacy. About seventy-five years ago, the German government anticipated a thriving business enterprise if it could discover how to grow truffles artificially, rather than smell them out laboriously by means of pigs. Dr. A. B. Frank, a leading botanist of the day, was approached and asked to work on the problem. His first step was to examine the truffles as they grew naturally; he immediately noted that they were found only under certain species of trees.

Frank quickly abandoned his assignment to take up the trail of a new botanical discovery. (To this day, truffles are still hunted the way they were when Frank dropped his investigation, although in France the search has been improved somewhat by the use of trained dogs.) Frank had been amazed to observe that the feeding roots of trees under which truffles grew did not have hairs at all, as the textbooks stated. Instead, they wore short, stubby rootlets—which under the microscope emerged as a tiny root strait-jacketed inside a layer of fungus.

Frank launched himself on a survey of tree roots, and he dug up the earth around the trees in Berlin parks, woodlands, and streets. He found that oaks and beeches were mycorrhizal, and so were related species like the chestnut, alder, and hornbeam. Looking over the spruces and pines, he found fungus-roots there, also. It appeared that the mighty giants of the forests rested upon a foundation as fragile as the strands of a fungus. Frank promptly labelled the mycorrhizal fungi "the foster-mother of trees."

About the same time that Frank was carrying on his research in Germany, other botanists were intrigued by a little flower found in many woods around the world. Once seen, Indian pipe is never forgotten, a jewel set upon the litter of the forest floor. It is shaped exactly like a long-stemmed pipe, with a single pink flower on a

waxy white stalk. A hundred stalks on the needled floor of a pine woods light the way through the darkness like candles.

The intriguing fact about this plant is that it contains not a speck of chlorophyll. Although a relative of a large family of plants which include mountain laurel, blueberries, and heather, this eccentric has cast off its whole tradition of greenery. How does Indian pipe survive, even flowering and producing seed, with no chlorophyll to make its living in the forest?

Botanists examined Indian pipe's root system, and found the secret there. It was a root unlike any before seen, much resembling the prickly ball of a sea urchin. The spines are tiny rootlets, thoroughly encased in fungus. When scientists cut cross sections through these roots and studied them under the microscope, they found that some fungus strands enter the Indian pipe's cells while others trail off into the soil. Thus, the fungus gathers the food and injects it into the roots of Indian pipe.

Indian pipe is one of the very few flowers of the forest floor, where the lack of sunlight automatically eliminates most other plants. But Indian pipe survives where nothing else will grow simply because it has become independent of sunlight. It carries on no photosynthesis; its fungus partner does all the food-gathering and feeds the Indian pipe intravenously. The fungus, too, has profited by this arrangement. In the search for a piece of forest floor to call its own, the fungus has been able to stake out a claim by aid of its higher partner.

Like Indian pipes, most orchids have little or no chlorophyll so they, too, must depend on fungi. Orchids arise from microscopic seeds, so tiny that only a single seed capsule of one tropical orchid was shown to contain 3,750,000 of them. This speck of dust, consisting of only a few unorganized cells, is sent into the world without a dowery of stored-up nutrients. The hazards awaiting it are many: not only does it undergo the dangers common to all seeds, being blown to an unfavorable environment or destroyed by insects and fungi, but without an adequate food supply it can survive for only

a short time. It must germinate quickly, and to do that it has to stumble upon the right kind of fungus. Most terrestrial orchids are the result of a harmonious, accidental union of two successful partners; the statistical probability of this ever occurring must stretch the law of numbers to the utmost.

The orchids, crowning achievements in the evolution of a whole division of plant life, are inconspicuous features of the landscape, except in some tropical localities. A day's hunt through the northern woods might turn up a ladyslipper or two. In fact, so rare are they that a new species may be discovered, and then no duplicates found for decades. Orchids have placed themselves at the top of the evolutionary ladder, and they appear ready to topple.

The Rattlesnake orchid, an attractive plant whose mottled leaves much resemble a snakeskin, has as its range most of the area east of the Great Plains. Its seed is as small as that of any orchid and contains no soluble sugars by which to effect germination; it grows only when the right kind of fungus has entered its cells. The fungus keeps expanding into the orchid until the seedling calls a halt, and whenever a fungus strand strays beyond this line, the orchid digests it. The two organisms are now welded together by a food pipeline, and the orchid increases rapidly in size, putting out many rootlets which are also invaded by the fungus. Only when all of these arrangements have been made does the plant send up a shoot to take its place in the darkness of the forest floor.

The fungus-root association appears to be such a limiting one that botanists early wondered about the benefits of it. But a study has shown that benefits are indeed many: a mycorrhizal pine seedling absorbed 86 per cent more nitrogen, 75 per cent more potassium and 234 per cent more phosphorus than non-mycorrhizal pines growing in the same soil. This greater extraction of nutrients from the soil might be in part because the fungus-roots have much larger absorbing surfaces than the root-hairs.

The exchange of growth-promoting substances, called *auxins*, between plants may also affect the mycorrhizal association. Many of

the mycorrhizal fungi produce indoleacetic acid, which stimulates the tree to produce additional short roots on which the fungus can grow. Tree roots, in turn, secrete substances which stimulate the growth of the fungus and, possibly, of the reproductive toadstools. Perhaps the great benefits in this partnership are not to be found so much in the exchange of food as of growth-promoters.

Since fungi are more affected by soil conditions than are trees, they may be very important factors in the distribution of tree species. When a pine tree grows on a particular site, it may not do so because the soil conditions there are hospitable for it. In fact, the tree is possibly growing where the soil conditions are best *for the fungus partner.* Pines and firs, which almost always have fungus-roots, usually grow only where the soil is highly acid, between pH 5 and 6. But it is believed that the trees themselves could survive a much wider range of soil conditions than that were it not for the demands made by their fungus partners.

The Ever-Present Fungi

The fungi are the most widespread microorganisms of the forest floor, and they bear the burden of decomposing the vast amounts of dead wood and leaves which fall to the surface every year. Indeed, much of the humus of the forest soil is made by fungi, and a goodly portion of the organic matter consists of their own decaying structures. Their growth through the soil is often so extensive that it actually holds the soil particles in place.

Until 1914, most scientists did not believe that fungi were actually permanent tenants of the soil or played any part in its workings. They had accounted for the presence of fungi in soils as an accidental blowing in of spores. However, Selman Waksman, of Rutgers University, thought that the soil was very much alive with fungi of all kinds, and he set out to prove it. In a painstaking series of experiments, he was able to demonstrate that the bits of fungus gathered in soil samples were actively growing there, and were not

merely germinating spores. Waksman later went on to show that there is a definite flora of soil fungi, and that the same kinds will often be found in similar soils around the world.

Now it is known that there are many specialized fungi which take an active part in the life of the soil, in an orderly sequence. A recently dead root might first be attacked by a sugar fungus, which leads the way for a whole host of other fungi, each of which takes as its sphere of influence one of the substances that made up the root. That there is a "pecking order" among the fungi can be seen on any compost heap. In the early stages of preparing a bed of compost, if spores of the common mushroom are inoculated, they will not take. But after the heap has been sufficiently aged, the spores germinate and a good crop results. The reason is that the common mushroom is a lignin-decomposer, the last of a long series of fungus specialists, and it must wait its turn.

Most fungi live on organic matter in the soil, and since it is found in greater quantities on the surface, the fungi are more abundant there. An ounce of rich forest soil may contain nearly two miles of fungus, nine-tenths of it in the surface soil and only occasional strands in the subsoil. The number of species also decreases sharply with depth: Sir John Russell in England found thirty species of fungi in the topmost inch of soil, nineteen species at a depth of six inches, only eleven species a foot down.

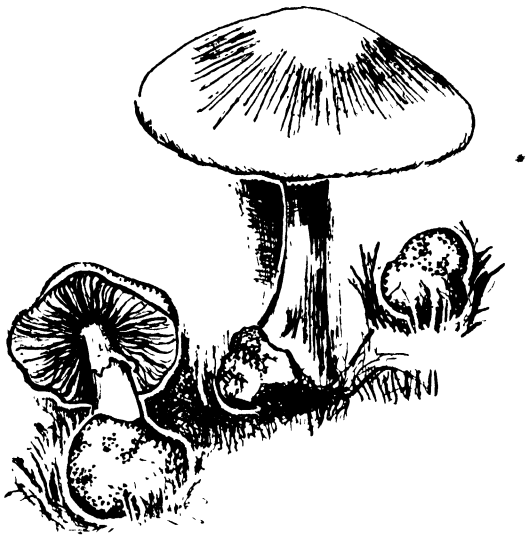
The most obvious part of the fungus to the woods-walker is its vegetative organ, the toadstool (toadstools and mushrooms are the same, but common usage has assigned "mushroom" to the edible varieties). However, most of the life of the fungus is spent underground as the bundle of strands called *mycelium*. In the darkness of the soil, fungi do not need leaves to carry on photosynthesis; thus they are plants of remarkable simplicity and efficiency. If a bit of fungus is scraped into a dish containing nutrient solution, its rapid growth can then be witnessed. From a tiny speck it soon sends out reaching fingers which branch off into more fingers. An advancing cell puts out a new branch about every half-hour, and this new

branch grows at the same speed and rebranches in the same length of time, and so on. Each strand of each branch may be growing at the rate of 1/100ths of an inch an hour. That is why, in only a day or two, the dish has been covered with fungus mycelium, miles and miles of it.

The mycelium is like a string of tiny cells, utterly simple in construction. Each cell has a wall, made of cellulose as in most other plants, which encloses protoplasm and a nucleus. An individual cell may range from 1/2500ths of an inch down to 1/100,000ths. Each cell of the fungus mycelium is a self-operating subsidiary of the larger corporation. It carries on its own chemistry in nutrition and getting rid of wastes. It manufactures dozens of kinds of acids and enzymes which predigest the food before it ever reaches the cell protoplasm. The mycelium squirts its chemicals onto the tough wood or leaves, chemically breaking them down into simpler substances which are taken up by the mycelium. They are immediately put to work to manufacture more mycelial cells to predigest more wood, and so endlessly.

The bacteria, primary microbes of decomposition in the grasslands, retain only slightly more than 1 per cent of the material that they digest. But some fungi are able to convert as much as 50 per cent of their food into living matter for their own cells. At the exterior of their cells, the food is manufactured into chitin, the same stuff that armors the hard bodies of insects and a few related forms, and no other living things on earth but the fungi.

Every toadstool on the woodland floor is nothing more than a temporary structure designed to produce vast amounts of reproductive spores as quickly as possible. In the majority of fungus species, mycelia from two different fungi must first unite before the toadstool can be formed. With the simplest of these, there are plus and minus strains which unite, but other fungi have wider ranges of mating types. Each of the mycelia may belong to one of four genetic types, called simply types I, II, III, and IV. But they can join in only two combinations: type I with type II, and type III with type IV. No



other combinations are possible, and the two mycelia coming in contact must belong to the correct strains. If they are compatible, they fuse and grow their own special mycelium.

This mycelium is a tight little ball which starts growing in the direction of the soil surface; it is the first sign that a toadstool is about to be produced. The parts of the toadstool have already been mapped out in this tiny mass: there is a blueprint for the stalk and the cap and the gills. Each strand in the mycelium knows its job and is ready to go into action. This is why one may tread a familiar path, noting that here is a toadstool which did not exist the night before, suddenly sprung up a distance of two or three inches. For the toadstool is like a balloon, merely needing inflation by food and water to surge through the last remaining soil layer.

The umbrella of the toadstool is designed for dispersing the spores by wind, and its underside is composed entirely of spore-shedding gills. The gills are mottled: the darker spots are the ripened spores, ready to be discharged, while in the lighter areas the spores have

not yet sufficiently matured. Watched under a low-power microscope, one of these dark areas changes from dark to light and back to dark again, as salvo after salvo of ripened spores is shot off.

Under the microscope, spores are beautiful and varied things—simple spheres and crescent moons, others starlike, some coiled like watch springs, many with spikes and whiskers. Spores are no larger than some bacteria. Even the tiniest of all seeds, those of the orchids, are many times the size of a fungus spore. The little orchid mote has an embryo and tissues, and is enclosed in a coat of elaborate manufacture. It germinates in a pattern, unfurling its parts in well-ordered symmetry.

Not so with the spore, a mere droplet of protoplasm, occasionally joined with an oil globule as food supply. It germinates rapidly, often within twenty-four hours after being shed. Little is known about the process, and it may be deceptively simple. For example, spores often germinate better when they are in the vicinity of a parent toadstool, and possibly there is chemical interplay involved. To germinate, the fungus spore merely extends part of its cell wall into a tube. From this tube will arise all the involved branches of the fungus mycelium.

If a mature toadstool is brought fresh from the woods into a darkened room, a flashlight beam held under it reveals the specks of spores raining down from the gills. A common toadstool from a nearby woods may shed half a million spores a minute, and continue shedding for a day or two. But there are some toadstools that can liberate eighty million spores *a minute,* five billion an hour, and continue their discharge day after day. A single decaying log may furnish a foundation for dozens of these toadstools, sending clouds of spores through the forest.

The Strange Slime Molds

Fungi were inconspicuous inhabitants of the soil-scape long before many of the higher forms of life adapted to an existence there; and

through the many intervening pages of time they seem to have lost little of their original strange ways of living. The slime molds in particular evoke an image of the fantasies of a younger planet. So unusual is the pattern of their existence that scientists are not even certain whether they are truly fungi. A borderline form at the crossroads between plants and animals, it is claimed in the province of the zoologists (who call it *Mycetozoa*) as well as the botanists (who label it *Myxomycetes*). This mold may well be "the slime of the earth" of the Book of Genesis, a primordial substance, perhaps evoking memories of the great ooze out of which were founded the kingdoms of living matter.

Slime molds are everywhere in the woods, half a thousand different kinds already identified. They look like white jellyfish—although they may attain colors like shining purple, bright yellow, or tan—and are quite small, no more than an inch or two at their widest point. They are tiny masses of blubber pulsating with the spark of life, just naked protoplasm, with no cells, no structure, no tissues, only living matter on the move.

The slime mold moves, not like a four-footed beast, but like a one-celled protozoan. It ventures out of the soil and migrates at the pace of a slug to exposed positions on rocks and logs. There, in only a few hours, the slimy mass transforms itself into a bouquet of fantastic flowers—wispy things on slender stalks, clusters of exotic blossoms, puffballs, colored cups, toadstools. The animal has become a plant, one of the most beautiful objects of the soil.

There is not another form of life on the planet that approaches the strange ways of the slime mold, a compact lesson in the wonders and mysteries of all life. Here is a fungus that gobbles its food whole instead of predigesting it with chemicals. It moves as a protozoan animal, but it roots its fruiting bo like flowers. With no identifiable brain or nerve cells, its locomotion is nevertheless precise as it willfully migrates from dry to damp areas. It lacks sex organs, but it unites sexually by the union of two cells. At times it has no covering,

yet the protoplasmic mass may hibernate for as long as three years, growing a hard, protective skin.

The naked-protoplasm stage is its animal stage: eating the way any other tiny animal eats, using the nutrient gained for the common good of the organism, leaving behind the wastes of its living. The slime mold remains inconspicuous in the moist soil until, somehow, in that collective pulp, there is communicated a need to reproduce its own kind. Lessened moisture, sudden light, disappearing food resources, any threat to its existence, triggers it into reproduction. It abandons the security of its dark home and emerges into the sunlight, becoming a respectable fungus which liberates clouds of spores.

To watch the mold in its transformation is, for a few hours, to contemplate the bare facts of life. For this jelly, which has directed itself toward the sun in a way biologists cannot fathom, proceeds to make of its chaos a thing of organized form and beauty, a unique and intricate structure which it shares with others of its species. It is like watching the creation of life between three and five in the afternoon.

A mass of spore-dispersing structures—technically known as *sporangia,* but somewhat similar to toadstools—has grown from the protoplasm and is mounted on a stalk. Inside the sporangia are springs, ready to discharge vast quantities of spores by catapulting them into the air. Like other fungus spores, these too are minute, and germinate quickly if conditions are favorable.

But when the walls of the spore open, out swims a microscopic animal again, equipped with lashing flagella for locomotion through the water film. This animal divides a few times by simple fusion (like a plant once more) and sooner or later meets with another flagellated speck. They unite nal-like, this time) and launch a new protoplasmic mass. They may also team up with a few more mated couples, but once the community is formed, the new animal grows only from these cells. It is still in the upper layers of the soil

surface, and will take its food where it can get it, gobbling fungus spores, bacteria, even the ununited cells of its brethren.

Then this animal oozes—that is the only word for it—into the soil, much as a spilt spoonful of milk might be absorbed by the soil. It breaks up into tiny rivers and streams that flow through the soil crevices, reuniting and separating again and again. It is engulfed once more into the soil, seeking a warm, moist area where it will continue its animal existence until the call to reproduce.

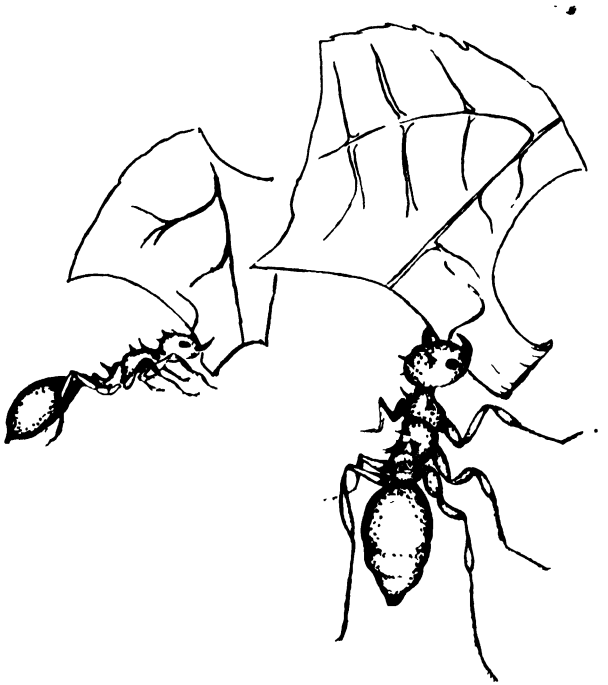
5. Soil Societies

THE FUNGI of the forest have entered into one of the most complex of soil relationships with various species of ants. These are the fungus-growing ants found only in the New World, ranging from Long Island, New York, throughout the southern states and into the tropical rain-forests—the only other beings on the globe, besides man and certain termites, to farm for their daily rations. They prepare their seed beds and sow the fungus; they weed and they fertilize; when crops are good they break new land for more gardens; they harvest the bounty which may be the sole food for a thriving city of 500,000 ants. Millions of years before man became a tiller of the soil they perfected their agriculture.

There are about 100 species of fungus ants which feed themselves and their brood on homegrown fungus. Most studied have been the leaf-cutting ants of the tropics, the tribe of Atta, which snip off leaves (sometimes defoliating an entire tree in a single night) and carry them back to the nest. They are familiar ants in Louisiana, Texas, and the Southwest and, although the various species differ in appearance, they are usually only about a third of an inch long, red or brown with spiky skeletons. They can be most easily identified by their behavior: they often tote their bits of leaf over their heads like parasols. Reverend Henry McCook, as enthusiastic an entomologist as minister, once described them as looking "like Sunday school children carrying banners."

Some nests are giant underground cities that embrace hundreds of square feet of tropical soil. The earth-moving operations they engage in would overwhelm our human contractors; in building a

typical nest, an Atta colony might move as much as four cubic yards of earth. One South American farmer attempted to exterminate a colony by blowing sulfur fumes down one of the nest entrances with a large bellows; the smoke emerged from another nest gate nearly



FUNGUS ANTS

200 feet away. Some gardens are rectangular greenhouses, almost three feet at the longest dimension, and a thriving Atta city may have hundreds of them. On the floor of each greenhouse grows a thick, velvety carpet of the fungus cultivated by that particular species of ant.

Their constant foraging operations wear down paths, often an inch or two wide, through the forests, and are indeed conspicuous features of the tropic landscape. The paths lead to the favored forag-

ing areas; after stripping the tree bare, they switch to another vicinity while the first is putting out more leaves. To speed up operations, often one team of ants is assigned to biting off whole leaves and letting them fall to the ground. There, waiting workers cut the leaf into manageable pieces that can be toted back to the nest. Each clipped bit of leaf may weigh more than eight times as much as the ant carrying it, yet, at a jog-trot they stumble over roots and pebbles until they find the worn trail. Then they rush back to the nest at a speed of sometimes a foot in a couple of seconds.

Among the earliest to observe that the ants gathered leaves was Henry W. Bates, one of the outstanding naturalists that England has produced. His name should be better known. In 1848, Bates, a promising young scientist named Alfred R. Wallace (who later was co-discoverer with Darwin of the theory of evolution), and Wallace's younger brother joined forces on an expedition to the Amazon River of Brazil. Their purpose was to gain evidence supporting Wallace's theories about evolution. In order to pay expenses, they planned to move everything that was not nailed down in Brazil back to England where the items could be sold to natural history collections.

They endured more hardships than any naturalists should be exposed to. Collections were gathered and lost. Illness struck repeatedly and Wallace's brother died of yellow fever. They were robbed of their money, managed to borrow more, and were robbed again. After four years of poor health, poverty, and isolation, Wallace went back to England, then made another trip to the Far East where he conceived the theory of natural selection. Bates remained for seven additional years, discovering a total of 8000 new species of plants and animals. He returned to England in poor health and puttered around for two years; but Charles Darwin encouraged him to write the story of his travels. The result was *The Naturalist on the River Amazons,* in which he recorded the gathering of the leaves by Attas:

Their progression looks like a multitude of animated leaves on the march. Generally, each marches off with the piece it has operated

upon, and as all take the same road to their colony, the path they follow becomes in a short time smooth and bare, looking like the impression of a cartwheel through the herbage. . . . It has not hitherto been shown satisfactorily to what use it applied the leaves. I discovered it only after much time spent in investigation. The leaves are used to thatch the domes which cover the entrances to their subterranean dwellings, thereby protecting from the deluging rains the young broods in the nests beneath.

It was not until a few years later that Thomas Belt, who explored in Nicaragua, learned that the leaves were not used for thatching nor for food either. Their sole purpose is to provide compost for the mushroom gardens.

When the unmated ant queen leaves her parent nest, she carries her dowry in a special pouch in her mouth: it is a scrap of fungus, the same kind as her colony cultivated, and the success of the entire ant city which she is to found depends on how well she nurtures it. Immediately after mating, she drops to the ground and digs a chamber in the soil, scraping away at the grains with her jaw and pushing them behind with her forelegs. Then she seals herself into a world of darkness for the rest of her life. From such feeble scrapings will someday emerge an Attine Manhattan or Bombay.

Now she must get the garden started, and a difficult task she has assumed, as any human mushroom-grower can testify. Temperature and humidity conditions must be just right; competition from other fungi must be eliminated. Somehow the little speck of garden survives, the queen fertilizing it with her own droppings and even many of her eggs. Not only is she tending the garden, but also rearing her first brood. The young are fed the eggs of their sisters, for the garden is not yet productive enough to support a household. The first brood consists of dwarfs, and they quickly wear themselves out caring for the fungus; their bodies, some still barely alive, are tossed onto the garden for additional fertilizer. Every Atta colony is based upon the sacrifice of the first-born.

The queen does not go foraging, and since the garden is not yet producing crops, how does she live? She is sustained by an unusual

property of her wings. Those flimsy wings, sprouted only for a single mating flight, have another use. They were powered by large muscles which she now reabsorbs as food into her body.

If the colony survives the hazards of the first year, it quickly increases to huge populations. At the end of the first year a second opening is added to the nest. By the second year there may be more than fifty; a three- or four-year-old colony may have over 1000 entrances. Unlike many other ant, bee, or wasp nests, Atta colonies receive new queen hospitably, so that an underground city continues to flourish until catastrophe strikes.

A thriving nest is a most impressive sight, and when William Beebe saw one in the British Guiana jungle he was reminded of a World War I battleground:

> In front of me was a glade, about thirty feet across, devoid of green growth, and filled with a great irregular expanse of earth and mud. There were the rain-washed gullies, the half-roofed entrances to the vast underground fortresses, clean-swept, perfect roads, as efficient as the arteries of Verdun, flapping dead leaves like the omnipresent, worn-out scare-crows of camouflage, and over in one corner, to complete the simile, were a dozen shell-holes, the homes of voracious ant-lions, which, for passing insects, were unexploded mines, set at hair trigger. It was an ant-made glade, with all new growths either choked by upflung, earthen hillocks, or leaves bitten off as soon as they appeared.
>
> —from *Edge of the Jungle,* 1921

The ants maintain an absolutely weedless garden despite the fact that every leaf they bring back is coated with weed fungi which might thrive in their hothouses. Why is there never an alien growth in these gardens? Dr. Neal Weber of Swarthmore College, the authority on fungus ants, has watched the tiny workers at their task: he enclosed some ants and a bit of their fungus in a dish containing nutrient solution for the fungus to grow, thus relieving the ants of the task of foraging for leaves. Within a few days after collecting his colony, the ants had cropped and reworked the fungus into a presentable garden; they pressed their mouthparts against the fungus

and licked it continuously. The garden soon responded to the care and flourished in an intertwining mass of felt across the dish. Not a single weed grew in this garden, and Dr. Weber suspects that there may be more to this trick than expert cultivation. Very possibly there are antibiotic or growth-promoting substances in the ant saliva. Evidence that this might be so is that the bodies of the larvae, which are also licked by the mature ants, develop flourishing "gardens"on their bodies.

Only under cultivation by the ants does the fungus produce little knobbed cauliflowers called *bromatia*. These are what the ants eat, not the mycelium itself. No ant-raised fungus has ever been known to produce a mushroom while under cultivation, although occasionally giant toadstools, as much as a foot and one-half across, have arisen from abandoned nests. No spores are produced, and the ants propagate their fungus by planting cuttings. Dr. Weber has observed ants pulling out tiny tufts and planting them in other parts of the dish; even a tiny fragment of leaf compost added to the dish had five tufts planted on it within only a few minutes.

Each species of ant generally grows its own brand of fungus. A few of these fungi have been identified as belonging to familiar groups, but most of them no longer exist in the wild state and can be found only in the hothouses of the particular ants that cultivate them. Most ant species show a decided preference for their home-grown variety, and will often starve before accepting a strange fungus. Yet Dr. Weber discovered a limited interchange of fungus food: when he fed a colony of New Jersey fungus ants with the bromatia from a colony of closely related Panamanian ants, the fungus was accepted and cultivated as its own.

The association between ants and fungi is an ancient one, and it has probably been carried on in the identical manner as today for about forty million years. There is, of course, no evidence as to how the partnership originated, but it is possible that fungus ants arose from seed-gathering ants. Seeds stored in underground nests occasionally become moldy, and some venturesome ants might have

begun feeding on the mold as well as the seed. But probably the explanation is simpler: since ants are extremely finicky about sanitation and maintain garbage heaps where refuse is dumped, these heaps would provide ideal conditions for fungi to develop.

The life of the fungus ants is one of untiring labor, beset by all the difficulties that face the human farmer, plus some additional ones. The largest workers, called the majors, perform the heavy labor of foraging. The smallest workers, the minims, never emerge into the light of day but spend their entire lives tending the garden and caring for the brood. The queen, the matriarch in her underground cell, sealed tight with not even room to turn around, eats fungus at one end of her body and pours piles of eggs from the other.

But through this mirthless life of labor, the fungus ants have escaped the most obvious fact of ant existence: ants, like people, are their own worst enemies. As the most successful forms of insect life, they are the rulers of the soil surface over much of the globe: wherever ants can exist on the planet, they do so in great numbers. Fratricidal wars of expansion are constantly being fought among them and the carnage of an ant war is terrible to behold. But the fungus ants have escaped this turmoil by withdrawing from the arena; they obtain their food in a manner which competes with no other ants.

The other dominant ant of the American tropics is the Eciton army ant, most feared creature of the jungle, the nomad who swoops from the forest and destroys every living thing that cannot take wing. What happens when Eciton mets Atta? Dr. William Beebe is one of the few scientists to have reported the meeting. On one of his walks in the Venezuelan Andes, he saw that overnight the army ants had made a bivouac within only fifty feet of an Atta citadel; at one point the trails of the two species even crossed. Beebe braced himself for carnage as the two goliaths must inevitably contest that piece of ground. He was wrong. An Atta worker bumped against an army-ant soldier without even flinching, and neither took notice of the other. Yet, what prey were the army ants carrying back to

their bivouacs? The pupae and eggs of other ant species, but not Attas! Wrote Beebe:

Not a bite was given, nor a leg or head broken. Whether through scent alone, or by what eyeless means, the crisis had been met and solved by the two great tribes. With food so utterly unlike, with no conflict of daily routine, they could live for a time in each other's hunting grounds. On the whole there was far less excitement and running around on the part of the Attas. They had their generation-old Roman road; they were indigenous natives, not nomads, and their fungus diet had made them the equal of the high-strung, nervous eaters of the flesh.

—from *High Jungle,* 1949

Ant Guests

The success of the ants in the soil may be gauged by the fact that they have so very many hangers-on, invited and uninvited. Although there are only about 15,000 species of ants in the world, they have about 5000 different kinds of camp followers. A careful examination of the nest of any species of ant will turn up at least one, and very probably many, for no nest is completely free of guests. There are a number of different kinds of spiders, for example, who perfectly mimic the ants by carrying their extra pair of legs high like antennae; they often escape detection and live quite comfortably in the nest. Cleverest, perhaps, is a tiny beetle which fashions itself a coat of soil particles and much resembles a crumb of soil on the move. But in the front of its coat, where its mouth is, it leaves a tiny cavity. Then it backs against the wall of the nest and waits, for soon a nurse-ant will come along and fussily search for a place to put a newly laid egg. The nurse immediately sees the crevice in the soil coat of the beetle and leaves the egg there. The beetle merely extends its jaws to snap up the egg, leaving the cavity again bare for the next one to be deposited.

The fungus ants, in particular, are overrun with guests. One of the mildly poisonous snakes of Trinidad lays its eggs in the mush-

room gardens. Probably the gardens are chosen because they are like incubators, due to the favorable climate that the ants create inside the nests. Moreover, the ants treat the eggs as if they were small stones, covering them with earth and thus keeping them moist. The newborn snakes, as soon as they hatch out, immediately leave the nest and do not bother the ants.

Cyphomyrmex, the most common fungus ant of the eastern United States, is rarely without mite guests. In fact, every colony that was collected at the Archbold Biological Station in Florida, and inspected by Dr. Weber, contained mites hitchhiking on the workers. The mites usually took positions that inconvenienced their porters least, one riding on each side of the ant's back for balance. Thus carried through the gardens, they were clearly seen to lean over and poach the fungus cauliflowers as they passed.

But the primary guest of the fungus ant, for whom it is always open house, is a tiny, golden roach. It is not at all like the loathsome roaches of the city, but a blind roly-poly found only in these nests where it has made itself very much at home. Even its small size seems nicely adjusted to the dimensions of the ant passageways. The roach is called *Attaphila* ("friend of the Attas") and after perhaps a million years of living in Atta nests, it has lost its powers of sight.

Attaphila does not eat the fungus, but rather tends the armored coats of the soldier caste. The roaches lick the soldiers continuously, gathering the secretions from the ants' skin and probably assisting in cleansing. They lead a rollicking life, with nothing to fear, for they are under the protection of the soldiers. Since Attaphilas are found only in Atta nests, and nowhere else, how do these blind roaches manage to migrate to newly formed colonies?

What Attaphila does is to stake its future on the success of the young queen in establishing a new colony. When the queens emerge from the parent nest on their wedding flight, female roaches climb aboard, too. They cling to the spikes on the queen's back as she climbs high into the air, dodging predaceous birds, finding a male, falling to the ground, eluding animals that would consume her, and

finally scraping her way to safety in the earth. Throughout the terrifying adventure of the wedding flight, the blind roach maintains its grip on the spike. Once safe in the soil, it dismounts, a friend of a new colony of Attas.

Life of the Termite

The only other insects besides ants to maintain fungus-gardens are a group of higher termites. In fact, it was just a few decades ago that David Fairchild, the most famous of the United States Department of Agriculture's plant explorers, discovered that the giant termite mounds of the Old World tropics contained fungus greenhouses. While in Java on one of his searches for new species of plants, he uncovered a termite mound—and became convinced that the fluffy mass in the interior was a fungus-garden. But it took him six months of diligent labor to prove it. Dr. Fairchild combed the countryside, examining termite nests everywhere, to see if different kinds of termites cultivated different crops. And so they did, for nearby were two other species which had their own particular brands of fungus. He wrote, later:

> There was something utterly fascinating about these gardens built within the termite strongholds. Their interior walls were covered throughout by pearly-white filaments of fungus, which lined the passageways as though with white velvet. I always believed that these fungus filaments were deliberately maintained at uniform length, perhaps sheared off by the jaws of the workers, just as humans keep the grass cut on their lawns. Here and there on the white velvet covering of the mushroom gardens, glistening white bodies, about half the size of a pin, rose on short stems.
>
> —from *The World Was My Garden,* 1939

Fungus-growing termites are found only in Africa, Asia, and Australia where their giant mounds make them the most conspicuous of termite species. But termites are a world-wide group, and they rival the ants for the dominance of the soil. Only about fifty different kinds occur in the United States, but they are widely

distributed in every state. They abound in the tropics: man may pay the rent in Africa, but termites hold the mortgage. They are even found in the deserts of Arabia, the Sahara, and the American Southwest.

The termite is a misnamed beast. Carolus Linnaeus, the Swedish botanist who invented the modern method of classifying living things into various categories, confused the termite with the death-watch beetle. This beetle, to the superstitious, was the symbol of death when its knocking inside wood was heard. So Linnaeus named the dusky little insects "termites"—meaning "the end of life." However, this is not nearly so incorrect as calling them "white ants," for they are not quite white, and not related to ants at all.

Termites are a very ancient form of insect life. They appeared toward the end of the Age of Reptiles, before man or bird was on the planet; their food must have been the giant cycads and other ancient vegetation. They seem to be closely related to the roaches, which are among the oldest insects in the world, with fossil records going back well over 250 million years. The current belief is that both roaches and termites descended from a common ancestor. In their great age, termites question one of the popular beliefs about evolution—that all living things on the planet are progressing toward more perfect organisms. The termites reached their full structural and social development, including their very complicated system of castes, in the Tertiary period, many million years ago. Since then, they have neither advanced nor fallen by the wayside, but now populate the earth in their age-old pattern.

The termite has come into the world with none of the endowments for survival bestowed on other insects. It has not the sting of a wasp, nor the armor of an ant. It cannot endure sunlight, nor can it fly, except for the few reproductives which take wing on a wedding flight. It is soft and small, easily preyed upon by hosts of enemies—from the African natives down to the most inconspicuous insects of the soil—and survives only in high humidity.

Yet, termites have built an empire on the face of the earth that

appears impregnable. They have created their own atmospheres: on a beastly summer day in South Africa, when the termite mound is too hot to touch, Dr. S. H. Skaife has found the temperature in the center of the nest only 86 degrees; and during the cold winter, the interior of the nest is considerably warmer than the outside. Their mounds are demonstrations of weather engineering. Some are tall spires, like Cleopatra's needle, more than thirty feet high; others are built like staggered skyscrapers, and if man erected structures of relative proportions, the Empire State Building would need be two miles high. They freely use terraces, arches, and turrets. So strongly made are the nests that they blunt a pickax, and when land is cleared, they often have to be dynamited out.

The mounds shed water, the tubes aid in condensation of moisture, some spires provide ventilation. This is how they create their atmosphere, and not by chemical magic, as David Livingstone believed. Dr. Livingstone, before being hounded by the intrepid Stanley, was an enthusiastic naturalist, and he was puzzled that the inside of a termite nest was moist while outside the African plain was dry. But he attributed the humidity to powers the termites do not possess: he thought that they were able to combine the oxygen from the air with hydrogen from their wood diet and thus make water.

The appetite of termites is voracious. A few years ago, they nearly destroyed a thousand-foot hedge of *living* yews at the Bethesda Naval Hospital in Maryland. One African explorer of the last century reported that they ate the clothes off his back while he lay exhausted after studying their nest. If it were not for termites, the rain of twigs and leaves upon the soil of the tropics would soon accumulate to such depths as to choke off the vegetation and lock up all the nutrients. The termites are the prime agents of decay in the warmer parts of the world, attacking the tough cellulose of wood and breaking it down, much as earthworms do in more temperate climates, keeping the machinery of life humming.

They plow and churn the soil in which they nest. The amount of soil moved may be judged by the fact that in tropical Africa there

are often thirty mounds to the acre, a few of them fifty feet in diameter and about ten feet high. In the construction of these mounds more than 5000 tons of soil are moved on each acre. The mixing and aerating obviously enrich the soil in the vicinity of the mounds.

The entire life of most termites is spent in darkness in the earth, except for the winged reproductives. Termites carry their night with them by erecting tubes of soil over them whenever they leave the nest. They have circumscribed the limits of their world of darkness, and rarely stray outside of it. But do not the termites soon become choked in their own refuse? Castoff skins, food remains, corpses—everything is eaten by the thrifty termites. Even their excrement is mixed with particles of soil to make cement, quick-hardening and waterproof, for the mound and covered trails.

Reticulitermes is the termite most commonly found in the United States, and it has been reported from every state. The cold northern weather inconveniences them only slightly, since in winter they nest below the frost-line. Unlike the tropical termites, the king and queen are free agents; they may move outside the royal cell to find favorable temperature and humidity. When Reticulitermes has to travel above ground to feed, it takes its moist atmosphere with it by means of roofed passageways. This is the way they bridge the concrete foundation of a house to get at the wooden beams.

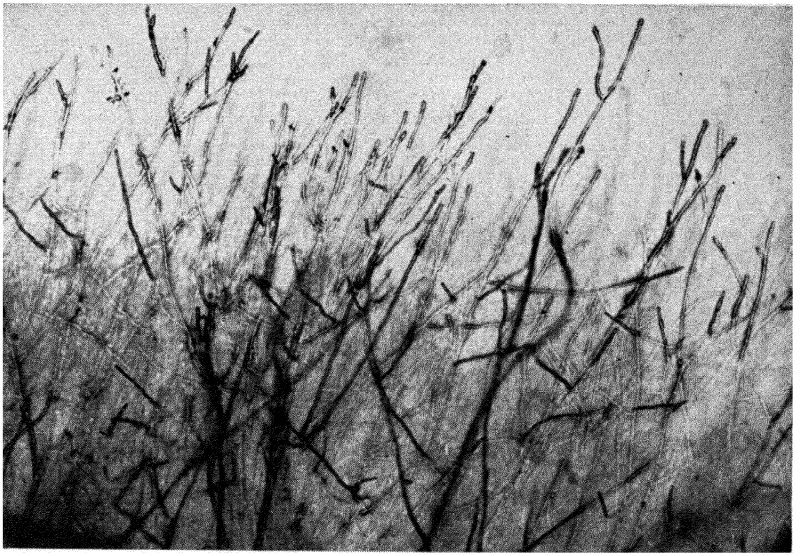
They build the covered passage in much the same way as a human building contractor might enlarge a room in a house—if he had to work only from the *inside* of the house and not alter its temperature or humidity. How would he go about it? Probably he would first knock a tiny hole in the wall, perhaps the size of a few bricks, and build on a tiny extension. Then he would knock another hole alongside and build yet another extension, connecting it to the first. He would continue to do this until the whole wall had been torn down and a narrow extension erected. Now he would have to build extensions onto the extensions, tearing down the walls between them, until the room was sufficiently enlarged.

This is exactly the method used by the termites. The holes they make are no bigger than their heads, and are quickly plugged by a grain of earth mixed with excrement. No sooner have they finished the extension, only a particle of soil in length, than they must knock it down and repeat the process. Their labors continue through the addition and subsequent destruction of millions of mortar particles, and the tube gradually lengthens. A colony may complete nearly a foot of tubing in a day. Arduous work indeed, but at no time is their bastion breached. Should ants, the termites' principal adversaries, discover the tiny openings and attempt to force admission, the soldiers defend it while their brothers and sisters erect a wall behind them. The soldiers are left outside the tube, a sacrifice offered for the good of the nest.

When we see a termite, only half of a most unusual partnership is visible. The other half is hidden inside the termite's gut and consists of many one-celled protozoa which are able to chemically digest cellulose so that it can be used by the termites for food. Since protozoa are unable to bite off fibers of wood, and termites can bite wood but are unable to digest cellulose, they function remarkably well as a team.

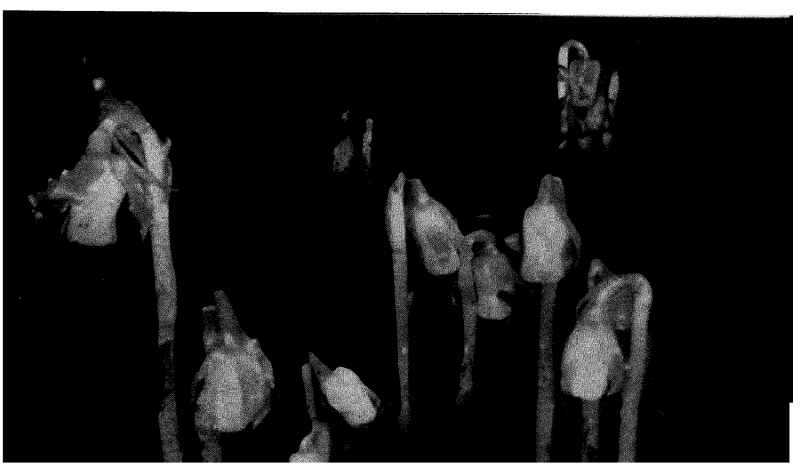
If a termite's intestines are examined under a low-power microscope, the field of view swarms with strange tenants. They seethe and jostle one another; they churn and push; so tightly packed are they that they make up perhaps a third of the termite's total weight. Here is a little world in itself, for even in the confines of a termite's gut the protozoa are attacked by parasites.

The stomach of the termites, like that of the ants, is a collective one. The entire colony is fed by mutual regurgitation of food from one termite to another until nothing is left of it. And with the food are passed the protozoa. Probably the protozoa harbored by termites today are the direct lineal descendants of those in termites millions of years ago; they may have been handed down from generation to generation. Into their dark worlds have come the bits of cellulose that made up the seed ferns, the Calamites, the pre-conifers.



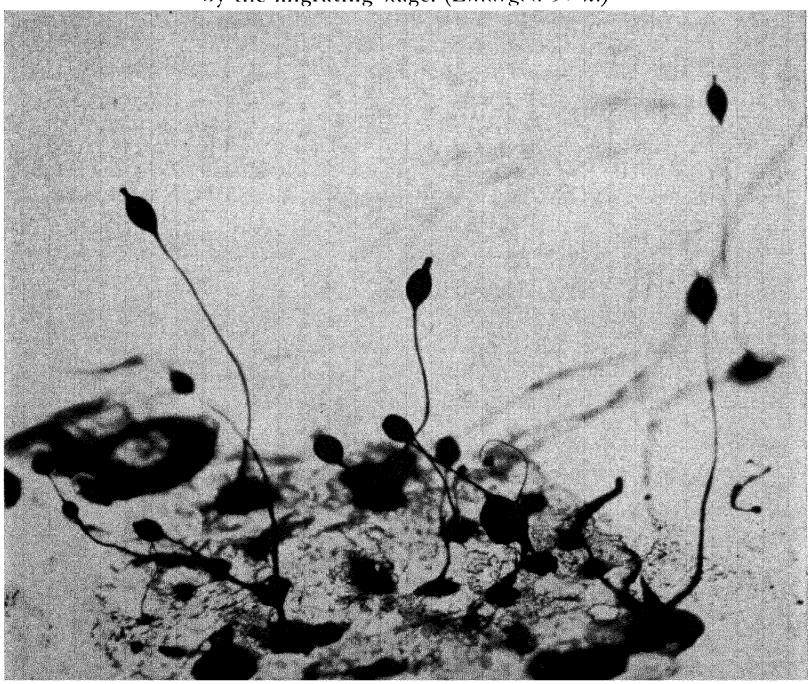
A FOREST OF FUNGUS STRANDS, branching and rebranching about every half hour as well as growing in length, can put out miles of threads a day. Sometimes the strands are so plentiful in the soil that they hold the soil particles in place. (*Enlarged 40 x.*)

INDIAN PIPES shine in the darkness of the forest like candles, one of the very few flowers to be independent of sunlight. This flower lacks the green chlorophyll by which other plants manufacture their own food; instead it is fed by the fungus partner attached to its root.



SLIME MOLDS during their animal-like stage much resemble tiny moles. Unfavorable conditions in the soil cause them to migrate to the surface, where in the space of only a few hours, they . . .

. . . ABANDON their animal existence and turn into plants. Here, like fungi, they grow reproductive, fruiting bodies. Note the wispy trails left by the migrating stage. (*Enlarged 35* x.)



TERMITES IN THE PROCESS OF MUTUAL FEEDING

About 300 species of protozoa from termites have been identified. Most of them are very highly developed and, except for a few protozoa found also in wood roaches, they exist exclusively in termites. Most termites do not harbor more than three species of protozoa, frequently only two, and usually but a single kind. But whatever their number, the protozoan fauna of each species of termite, no matter where it is found, is always the same. There is one protozoan which exists in the stomach of an African termite and a California termite, and nowhere else; this seems to indicate that perhaps the association between termite and protozoa goes back to an epoch before the continents were formed. Termites early found a way to survive in the crowded soil: their diet of wood may be unpalatable, but it brings out no freebooters to contest it.

That there is a rich protozoan fauna inside termites was first noticed about 100 years ago. But real knowledge about it did not come until 1926 when Dr. L. R. Cleveland of Harvard and Johns Hopkins developed methods for removing the protozoa from the termites so that each might be studied separately. He accomplished this in a number of ways, such as submitting the termites to oxygen under pressure, or heating them to high temperatures, which killed the protozoa but not the termites. He was thus able to demonstrate conclusively that the protozoa are vital for the life of the termite: the defaunated termites soon died, although they were furnished wood products for food.

Neither the insect nor the protozoan partner can exist without the other. As with the fungus ants, the virgin termite queen carries her protozoa with her when she sets out to found a new colony. After each molt, when the termites cast off a part of their gut as well as their skins, they are reinfected with protozoa by mutual feeding from the communal stomach. Newborn termites receive their patrimony of protozoa in this way also.

The Hierarchy of Termites

A fascinating problem in biology today concerns the castes of termites. Their caste system is much more complex than the simple queen-male-worker system of the ants or bees. In the first place, in a tropical termite city, there may be *three* reproductive castes, and each one has both kings and queens. The primary queen may grow to a length of four inches and become as thick as a frankfurter, many thousand times the size of a worker in the colony. She is little more than an egg-laying apparatus that can turn out 7500 eggs per day, day in and day out, year after year for decades. In the midst of her tiny workers, locked in the royal chamber with her king consort, she "sprawls like a whale surrounded by minnows," as Maurice Maeterlinck once described her.

The primary king and queen in the colony are the only ones out of the many thousands allowed to reproduce. Through the decades of their reign, they may become the parents of millions. When the queen grows old, and her egg-laying capacity begins to dwindle, she is quietly disposed of. Usually the method is by simple starvation, although one naturalist witnessed an aged queen being licked to death by her offspring. The *coup* in the termite state, whatever the method, is always a gentle one. After death, like everything else in this well-run household, her remains are eaten. Her place, or that of the king if he should pass out of the picture first, is taken by a member of the secondary reproductives, nymphs chosen to ascend

the throne. Some termite species even have a third reproductive caste, made up of soldiers who are allowed to lay eggs.

Unlike most insects, which have practically eliminated the males, masculine contributions are found throughout the whole hierarchy of the termite nest. The enormous-jawed soldier caste, like the workers, consists of both males and females. (Many American termites do not have a true worker caste; rather the young nymphs run the city.) An ant-worker or -soldier is sterile; not so with the termites, who are fertile but voluntarily castrated. They could produce young, but never do so until called upon by the needs of the colony.

Scientists have kept termite colonies in observation nests, and noted that castes are produced in a most unusual way. For example, in a newly founded colony, only one soldier is usually produced out of the first dozen or so young. But if that soldier is removed from the nest, another soldier quickly develops to take its place. If the new soldier is now removed, still another will develop. Scientists have repeated this removal experiment a dozen times in succession, and always the new soldier appeared.

However, if the scientists *add* a soldier to a new colony—before the eggs already laid have produced their single soldier—then the brood of eggs will *not* give rise to another soldier. The presence of an introduced soldier seems to inhibit the growth of another soldier. But the colony can be manipulated still more. If all the nymphs are now removed from it, leaving only the king and queen and the single soldier, one of the nymphs will always develop into a soldier. If all the nymphs *plus* the soldier are removed, no new soldier form will develop.

Since all termites in a colony are fertile, what prevents them from laying eggs? They never become egg-layers—so long as the primary king and queen are present. But if the king is removed, a new king develops; if the queen is removed, a new queen develops; remove all of the supplementary reproductives and new supplementary reproductives arise.

It was inevitable that a problem so perplexing should have attracted the minds of biologists for many years. One of the earliest theories was that the different castes were determined at the egg stage. But researchers at the University of California demonstrated conclusively that any nymph may develop into a soldier, a worker, or even a reproductive. Experiments have shown that no egg laid by the queen is any different from any other egg. The castes appear to develop as the colony needs them: remove one soldier and a new soldier is required to take its place.

The theory about termite castes now most widely accepted is that each caste secretes its own kind of hormone "inhibitor" which is passed around the colony by mutual feeding. For example, a soldier sends a hormone into the collective stomach of the colony which inhibits more soldiers from developing. But as the colony grows, the hormone inhibitor sent out by the single soldier becomes diluted, since it is now being passed around among many nymphs. Finally, the hormone is so diluted that it is no longer effective, and another soldier is allowed to develop from a nymph. Now there are two soldiers to secrete "soldier" hormone into the collective stomach, and the development of more soldiers is again inhibited.

Attempts to verify this theory in the laboratory have been spotty. The classic experiment is to make an extract of the bodies of the king and queen and then feed it to a colony lacking reproductive castes. For comparison purposes, another colony, also lacking reproductives, is *not* fed the extract. The colony given the extract was inhibited; it produced fewer supplementary reproductives than the colony fed none of the inhibitor. But the unanswered question is why the colony given the extract *produced any reproductives at all.* If the inhibition theory is correct, then the colony fed the extract should have been completely inhibited.

There may well be more to the hormone theory than mere inhibition. For example, an isolated egg from a termite colony often does not hatch unless it is licked by other termites. An isolated termite, allowed to keep its protozoan stomach fauna, even fed

choice bits of wood, soon dies. Very possibly, other essential substances are passed along with the inhibitors.

Caste-determination in termites seems to be a process similar to cell differentiation in the human body: undifferentiated cells eventually turn into bone cells, blood cells, and so forth. In fact, many experimenters have looked upon the termite nest as actually a superorganism in which each of the castes functions as a part of a larger, single organism.

Thus, the termite colony may be conveniently substituted for the human body in studies of cell differentiation. That is exactly what Dr. Martin Luscher of the University of Basel in Switzerland is doing. He has found a number of striking similarities: the cells in a human embryo do not begin differentiating until they reach a critical period where they are needed by the larger organism; in the same way, he has also found a critical period at which a termite nymph will develop into a needed adult caste. The "social hormone" of the termites might possibly have its equivalent in the human body: out of the reservoir of undifferentiated cells in the human body, muscle cells are produced only when needed and in the proper amount. Out of the reservoir of undifferentiated nymphs in the termite colony, a soldier is produced only when needed, and never more than the number required. The superorganism theory of the termite nest has many biological obstacles to meet before it can be thoroughly accepted, yet in the hot termite mounds may lie an answer to one of the most perplexing questions about life itself.

City of the Yellowjackets

As befits a doomed and wicked city, the Gomorrah of the yellowjackets—social wasps which rest underground—is a preempted cavern once burrowed-out by the mammals of the forest floor. The honeycombs of the shrews and mice are often only temporary thoroughfares for nesting or finding food, to be bulldozed out by the

next highway builder passing through. But short stretches of these thoroughfares do achieve a certain permanence by serving well the nest-building activities of the yellowjacket societies. These yellowjacket nests are crude affairs, completely unlike the masterpieces of engineering of the honeybees, or those of other hornets which nest above ground. The yellowjacket *Vespula* is not a builder, she is a remodeler.

The Vespula queen, bright in her black and gold, courses low over the landscape in early spring, investigating rodent tunnels, dismissing each in turn because of some hidden flaw. Finally she lights on one and inspects it more thoroughly; she flies off to search some more, but always she returns to compare the new finds with this one. None better seems available, so she makes her choice.

The queen first digs a chamber for herself. In and out of the hole she flies, directly to a woodpile or log, where she scrapes off splinters and fibers and kneads them into building mortar with her jaws. The yellowjacket queen begins her house with the ceiling first. It is a large canopy, propped by the construction of pillars and arches. She rolls pebbles and stones out of her way, or cements them to the sides of the nest; she excavates where necessary and seals off the tunnels formerly used by the shrew. When the land is cleared and excavated, she adds her next story, a ceiling *below* the first ceiling.

Throughout the history of the nest, the yellowjackets carry out a rebuilding operation that would appall a human contractor. As ceiling combs grow old, they are discarded, much as if an architect kept shutting off old rooms in a house and adding new wings. Additions to the Vespula nest are always made below, but if a rock should interfere, they will also expand to the sides. Little planning or structural beauty can be seen in the nests, but they are sturdy jobs. The array of ceilings are well-propped by flying buttresses and inverted arches.

On the first ceiling that she constructed, the queen builds several small cups—upside down, like everything else in this city—and lays

(or rather pastes, since they would otherwise fall out) her eggs. The eggs hatch in about eight days, and now she is not only founding a city but also feeding a brood. Adult yellowjackets sip nectar, but the larvae need red meat; she must not only carry back pulpwood but also game. Fortunately, unlike most wasps, the yellowjacket young are not very particular about the kinds of insects they are fed. Once the first brood has matured, the queen turns over to them the entire job of managing the city. She devotes her energies solely to egg-laying.

Now the city grows quickly, in a few months enlarging to perhaps twice the size of a man's head. In all, some queens may produce about 25,000 short-lived offspring, of which more than 5000 can be found in the nest at any one time, although the average numbers are usually considerably less. The original scrapings in the rodent nest have grown to a teeming city, with whole ceilings razed, rooms rearranged, new wings added. The city hums with industry, and into its coffers is brought pillage from the surrounding countryside. Throughout the forest, insects venture abroad to be swooped upon and mutilated by the daughters of Vespula. So prosperous does the city become that by the end of August it can afford to send out colonizers, lords and ladies beautifully clad in shining coats that have never been splattered with the mud of artisan labor. They are the future queens, and kings for the moment of impregnation only, ready to be launched into the world to found new dominions.

With their departure, the queen loses all energy. Her production lessens markedly, and she sluggishly moves to the cups to insert her egg-laying drill. Soon she finds a corner to lie in, gasping from the exertion. The days of her empire are now numbered. Occasionally, the workers fight among themselves, some breaking into the larval cells and devouring the young. A madness begins to eat away at the very foundations of the city.

More and more workers take to devouring the larvae; but still unsated, they abuse, then torture, the young. An orgy has begun

that will end only with the death of the city. No longer do the workers set out on expeditions of pillage, but like a mercenary army without discipline, they rush through the combs looting and destroying. The queen is assassinated, and every worker becomes a queen. It is democracy in its most horrible form. So well do the assassins do their jobs that but few remain, the fluttering of their wings reverberating through the empty halls.

The walls of the city have been breached, and in slinks the silent army of destroyers. Mites overrun the combs, and millipedes and woodlice chew down the pulp walls. The silverfish, the spider, the earwig enter, and even the rodent returns to reclaim his nest. The last of the yellowjackets are quickly killed off by the invaders, or die simply of hunger, too listless to seek the fall flowers for their sweet nectar. The walls of the city crumble, and it is no more. The only survivors are the few mated queens, sent off in the days of the city's prosperity, who seek out warm places to hibernate until the next spring. They remain innocent of the carnage until the following year, when they too will be victims of the assassins.

The destruction of the yellowjacket city marks the end of the living year in the forest soil. One by one, the dwellers of the forest prepare for the winter cold. The trees have already shut down their waterworks; only a few brown leaves still hang from oaks like wilted banners after a parade. The leaves are heaped in drab monotony on the forest floor, a task of decomposition awaiting the fungi in the spring. The earthworms have burrowed deep, and the mole now makes his borings at greater depth. Some organisms, like many insects, have cast their eggs into the soil, and the species is represented on the planet only in that stage. As the temperature grows colder, a quiet settles upon the soil, and nothing remains of the throbbing life of summer but the deer mouse on his endless rounds, searching for forgotten seeds.

But the lifelessness of the winter soil is an illusion. For were we to dig down under the snow and into the hard, frozen earth we should

come upon the hope of the next season: the roots, ready to put out new growth; a frozen mite awaiting the thaw; the spores of countless numbers of microbes. All will arise again from the soil in a magic promise of spring that has never been broken since life began.

III.

THE GRASSLANDS

6. *Dwellers in Darkness*

BEFORE THE COMING of the pioneers, the grasslands of the Great Plains were a stabilized community of life which ranged from the Indians down to the smallest viruses. Its entire economy was based upon grass. The soil itself was created under grasses which were fed upon by bison and other grazing animals. They, in turn, kept it so closely cropped that shrubs or weeds could not invade. Feeding on the droppings of the grazers, and returning the nutrients to the soil to help grow more grasses, were a host of little organisms. In this vast fabric of living things, the gophers, meadow mice, worms, and ants repaired the packing of the soil surface by the bisons' hoofs. The residues of this economy were every year broken down by the bacteria, which of all the microbes perform the major work load of the Chernozem, the grassland soil.

Pocket gophers are usually found in grass soils, and trees or even brush often act as barriers to their movements. They are widespread throughout the western states, on the plains of the Dakotas, and even on 9000 foot peaks; surveys in California have shown them to abound at sea level as well as above timberline in the High Sierras. "Gopher" is derived from a French word meaning "honeycomb"—and that is exactly what they do in the earth with their tunnels. Ernest Thompson Seton, who observed the life history of gophers in Manitoba, Canada, stated that in wilderness areas it was often impossible to walk without sinking a few inches, or sometimes feet, into their diggings.

The mounds of pocket gophers are occasionally confused with those of moles, but their earthen heaps are completely different. A

mound made by a mole is rounded and symmetrical; that is because it is built up like a volcano, successive upheavals of earth pushed towards the surface from beneath. Not so with the gopher, who brings up the soil in his arms and dumps it to one side of the mound. Thus, his hill is low, with the exit hole usually at one end.

Like moles, the pocket gophers are active throughout the year. Long after winter has hardened the surface soil, and snow lies in tremendous drifts, the gopher is still busily at work, pushing his tunnels through the snow. When the thaw comes these tunnels do not melt, because they are made partly of soil and matted grass. They trace the surface like ghostly wintertime workings.

The gopher spends practically all of his life underground, a timid creature fearful of the dangers of the world of light. Seton wrote that gophers leave their burrows open for a few hours on sunny days, and that they lie below the opening to drink in the warmth; but the ventilator is soon plugged up again, for the gopher is harassed by many enemies. They rarely move above ground to feed, preferring to burrow to reach plant roots. They often do this without even disturbing the surface soil, cleanly nipping off the roots and leaving no visible evidence of their depredations until the plant withers.

Joseph Grinnell for many years studied the burrowing rodents of California and he found that the most abundant and effective in turning the soil are the gophers. Grinnell, in collaboration with Tracy Storer, made one of the most thorough evaluations of an animal that exists in biology: they studied the importance of the gophers in Yosemite National Park and concluded that the amount of earth moved by them in the park each year was about 160 carloads of fifty tons capacity each, requiring the expenditure by the gophers of more than 5500 foot-tons of energy. Over the past couple of hundred thousand years, they estimated, the gophers gave this soil the equivalent of 3400 plowings to a depth of six inches.

In many grassland areas, the gophers are in competition with grazing animals for vegetation. Yet, their benefits in wild places

compensate: they counteract the heavy packing of animal hoofs on these soils. On overgrazed western ranges, one occasionally sees scrawny grass surrounding oases of green; the greener places are where the gophers have been at work in loosening and plowing the soil.

The Bacteria and the Devourers

All the vegetation of the grasslands each year passes back to the soil. There, the primary agents of decay are the bacteria. They can break down a tremendous range of materials and use them as foodstuffs, even some that man, using elaborate arrays of equipment and very high temperatures, has difficulty with in his laboratories. Chemists have fed bacteria complex materials, such as do not exist in the natural world, and found them expert in fracturing them and decomposing the fragments. Some soil bacteria even break down the strongest poisons, the very stuff used to kill them.

Bacteria have their representatives throughout the world, in living and non-living matter. There are the autotrophs which do not need organic matter, are incapable of breaking it down, and may even be checked in their development by it; they live on the basic elements of our planet, such as sulfur, nitrogen, and even iron. At the other end of the scale are those which decompose solely organic matter. Some of the latter exist only where oxygen is present, others where it is absent. There are bacteria that develop at 162 degrees but not at room temperature.

Bacteria vital to the existence of life are found on the roots of legumes (plants such as the clover on lawns, beans, peas, and so forth). These bacteria are the primary fixers of nitrogen from the atmosphere, producing as much as 200 pounds of it to the acre each year, more than 20 times the amount fixed by Winogradsky's free-living Clostridium. Their job is a necessary one; the most difficult element for living matter to obtain is nitrogen. Although the air over each acre of the globe contains more than 36,000 tons of it, nitrogen

does not usually combine into suitable compounds for plants to absorb through their roots.

As far back as the writings of Virgil, it was observed that the leguminous plants have unusual structures on their roots which much resemble warts or galls. Furthermore, the agricultural writers of Rome noted that growing legumes on worn-out lands often restored fertility. For nearly 2000 years, the causes of neither the galls nor the increased fertility were known. But in 1837, a French chemist named Boussingault performed an intricate series of experiments in which he showed that when clover was grown the soil gained in nitrogen; when he planted wheat there was no such gain. The experiments led to an amazing conclusion: legumes such as clover are somehow able to take nitrogen from the air. But the problems still appeared insurmountable, for no one could visualize how the plant might accomplish this feat.

During the next fifty years, a solution to the nitrogen-fixing problem was built block upon block by brilliant research in England, France, America, Germany, Russia, and Poland. Few advances in science owe so much to international exchange of information. Finally a Dutchman, in 1889, isolated the microorganism responsible for the process. As many researchers had suspected, it was not the plants themselves which fixed the nitrogen, but rather the unusual warts or nodules on the roots. Each nodule is filled with millions of bacteria, and each nodule contains only a particular strain of a particular bacterium. Also, each bacterium is attracted only to a certain kind of plant, and no other.

Neither plant nor bacteria alone can achieve nitrogen fixation, even when the bacteria are taken directly from the nodules. The growing plant serves the bacteria carbohydrates and energy in the form of sugar; the bacteria take the nitrogen from the air and make it available to the plant. Together, they form a remarkable team.

That the legume without its bacteria has no advantage over any other plant was proven early. A legume seed and its soil were both

sterilized to remove all bacteria; when the plant was grown it was able to use only the nitrogen that was already present in the soil, but it formed no nodules and there was no gain in nitrogen. However, if the nodule-forming bacteria were then inoculated into the soil, the nodules soon appeared and the soil gained in nitrogen.

The nodule bacteria move about in the soil considerable distances for such puny bodies, as much as an inch every day or two. The legume is not ready to be joined by the bacteria until it has germinated and put out its first leaf; but once it has done that, a substance is sent out from its roots which stimulates the bacteria to multiply and congregate in the vicinity of the root. When a good supply of the right kind of bacteria have gathered in the neighborhood of the root, the bacteria use chemicals of their own which cause the legume's root-hairs to curl up. The bacteria enter the hairs, migrate into favored regions of the root cells, and begin multiplying.

There is much chemical interplay in the formation of nodules. For example, if nitrates are already present in the soil, the bacteria may still enter the legume root, but they do not form nodules. And the bacteria are chemically able to stimulate the root cells to enlarge and form the nodule swelling. Also, it seems that the legume puts out chemical compounds to keep away all but the favored bacteria.

The bacteria have found a haven within the roots and are isolated from many of the hazards of soil life. Should some calamity overtake these bacteria, or a sudden change occur in the environment of the planet, then their numbers might be so seriously reduced as to collapse our superstructure of life, which is hinged to the nitrogen fixed by these microbes.

The bacteria have many enemies, of which none is more serious than the *phages* (meaning "devourers"). Each strain of bacterium is attacked by its own particular kind of phage. Phages are strange organisms, existing in fantastic numbers, which are only a little larger than simple molecules. They can be squinted at through the powerful electron microscopes, but even then scientists are unable

to tell much about them. They are viruses, about 1/2,500,000th of an inch in diameter. They have a spherical head, composed of nucleic acid (but no nucleus has yet been discovered), surrounded by a very thin membrane; many kinds of phages also have a tail made of proteins.

Much of the actual workings of phages may be inferred by adding some to a culture dish of growing bacteria. The most apparent change in the dish is that holes of nothingness suddenly open up in the opaque layer where the bacteria have been growing. Each of these bare spots is a seat of phage infestation where they are carrying out their unusual life cycle. The phage first attaches itself to a passing bacterium, many hundred times its size, by its tail. The tail acts much like a hypodermic needle, injecting into the bacterial cell the phage's nucleic acid. The phage leaves the empty husk of its tail and membrane outside of the bacterium and is engulfed; during this "stage of eclipse" it disappears from sight.

The bacterium has swallowed up the phage, but soon its interior swarms with perhaps hundreds of phages. Obviously, they have multiplied (we do not know how) and become visible once again when they don a membrane and tail. Suddenly the bacterium dissolves—a complete disintegration into nothingness—and the hundreds of phages are liberated to repeat the cycle. If no fresh bacteria are in the immediate vicinity, the phages can remain almost indefinitely within their coats.

At first look, this appears to be a simple predator-prey relationship. But the phages and bacteria have been closely studied in genetics research and their lives found to be a most complicated affair. For example, if the phages are allowed time to devour the entire dish of bacteria, eventually almost all of the bacterial opaqueness would be gone. Remaining, however, are tiny, isolated white specks around the dish. These are bacteria resistant to phage attack. Out of every few million bacteria selected at random, one is naturally resistant. In the normal course of a bacterium's multiplication, some bacteria eventually result that are phage-resistant. But so long

as phages are absent from the colony, these resistant bacteria are obscured by the general success of the colony. However, the phages, when introduced, act like strainers, removing all the susceptible bacteria and leaving only the resistant ones.

These white specks can be transferred to a fresh culture dish and a colony of bacteria resistant to that particular phage grown. If a new kind of phage is now introduced, the same process will be repeated and the surviving specks are now resistant to two kinds of phages. This process can be continued until there emerges a colony of bacteria resistant to a number of different sorts of phages.

During this time the phages have not been idle. They, too, have been adapting by means of new strains to prey on the resistant bacteria. But now we are up against a serious obstacle that is difficult to explain away. The bacteria form resistant strains faster than the phages are able to do so. Then why are not *all* soil bacteria resistant to phage attack? Why have not the phages been starved out of existence by the ability of the bacteria to become resistant?

The resistant bacteria have paid a price for their immunity. They are more demanding: as if in return for immunity from the phages, they have complicated their existence by requiring special foods or living conditions. If no phages are present to strain out the susceptible bacteria, these more demanding members of the colony will be eliminated by their need for special conditions. The susceptible bacteria again build up, inundate the resistant ones, and are ultimately attacked by phages which allow the resistant forms to emerge once more. And so the cycle continues, insuring the presence in the soil of both phages and bacteria: the resistant bacteria will then be attacked by a new strain of phage, from which super-resistant bacteria will prevail.

Nematodes Everywhere

Nematodes do not furnish hides, horns, tallow or wool. They are not fit for food, nor do they produce anything fit to eat; neither do they sing, or amuse us in any way; nor are they ornamental—in fact, when

they are displayed in museums the public votes them hideous. Lacking in all of these respects, they fail even in furnishing moral or praiseworthy example; they are not known to be industrious like the ant, or provident like the bee, indomitable like the spider, or frugal, or honest, or anything else that is admirable.

So wrote nematologist N. A. Cobb in a 1914 report to the United States Secretary of Agriculture. Facts about nematodes were little known then and it must have been difficult for him to justify basic research on a form of life so lacking in interest. Nematodes do not furnish hides nor anything else—but they are certainly among the most destructive pests on the face of the earth. Their yearly ravages cost American agriculture a conservative half a billion dollars, probably many times that amount; just one species in Britain yearly destroys about $6 million worth of potatoes. Their severe damage is not confined to farms alone; often unnoticed they work their destruction in all natural areas, particularly grasslands. City trees and kitchen gardens are often attacked, as are flowers in window-boxes.

Most nematodes are not more than one twenty-fifth of an inch long (less than the size of a period on this page), and many are considerably smaller than that. Although thousands of times larger than the bacteria in the soil, they are just on the threshold of visibility with the naked eye, even when separated from the soil particles. Seen under the microscope, they much resemble tiny eels, with long thin bodies that taper toward the tail. In fact, "nematode" means "thread-like." Tiny as they are, they are still complete and complex animals, possessing elaborate feeding organs as well as digestive, excretory, nervous, and reproductive systems. They are equipped with powerful muscles that enable them to make the violent thrashing motions of the eel.

Many thousands of kinds of nematodes are known, and they occur everywhere. They have been found in the boiling waters of hot springs as well as in polar seas (members of the Shackleton Expedition to Antarctica discovered nematodes in thawed ice). They abound deep in the ocean and in the most arid deserts; they are

found in all soils. As parasites of birds and fish they fly over continents and span the seas. There is a particular species that lives in man's vermiform appendix, and nowhere else (more common human nematode parasites produce trichinosis and hookworm).

"In short," wrote Cobb,

> if all the matter in the universe except the nematodes were swept away, our world would still be dimly recognizable, and if, as disembodied spirits, we could then investigate it, we should find its mountains, hills, vales, rivers, lakes and oceans represented by a film of nematodes. The location of towns would be decipherable, since for every massing of human beings there would be a corresponding massing of certain nematodes. Trees would still stand in ghostly rows representing our streets and highways.

Abundant as the nematodes are, they are limited by one environmental factor, the presence of water. For no matter where nematodes are found today, or how early in the history of animal life some migrated to the soil, they are still very much tenants of a water world. They must seek as their special habitat the thin films of moisture surrounding soil particles. They cluster around plant roots, and the top inch of a square yard of grassland soil may contain upward of twenty million of them.

Many nematodes prey on bacteria, fungi, protozoa, and other nematodes; there is no evidence that they feed on decaying organic matter. Early investigators doubted that these tiny creatures could cause extensive damage to plant roots also, even when they granted the tremendous numbers of nematodes in the soil. But the scientists did not reckon on the extreme efficiency of a nematode's mouthparts. The nematode is armed with a hollow spear that is as rugged and precise as any human weapon. With it, the nematode can penetrate the toughest root; the feat is roughly equivalent, on the human scale, to driving a fingernail through the bark of a tree. The nematode's spear is connected to a sucking bulb behind the oesophagus: in reality, it is an atomizer or force pump which is worked by powerful muscle fibers. Contracting the bulb results in suction, and

this draws the plant juices through the hollow spear and into the bulb; the next squeeze forces the fluid backward through the bulb into the nematode's intestines. It is an extremely efficient organ and with it the nematodes are able to drain plant roots of their sap, leaving them shrivelled wastes.

The most widely distributed nematode in this country is the root-knot, found from Maryland southward and in almost all northern greenhouses. For a creature so small, its existence is amazingly intricate. It hatches from an egg in the soil and migrates by eel-like lashing motions. Eventually, it may find a root belonging to any one of the 2000 kinds of plants that these nematodes attack. It injects the root with fluid from special glands it carries in its head. Almost immediately, the root forms giant cells, usually three to five of them, which surround and finally enclose the nematode. These knots on the root much resemble beads on a string, and occasionally each bead may be as large as half an inch in diameter.

The root-knot nematode feeds by sucking the giant cells, and it swells rapidly, first into the shape of a sausage, then into that of a pear. When it appears that the female nematode is about to burst, she lays her eggs inside the knot, usually 500 of them, although occasionally the number reaches 2000 eggs. What happens next is due entirely to chance. The egg may hatch while still inside the knot and the larva escapes through a crack in the rotting root. Or the root may decay first, depositing the egg as a free agent in the soil where it lies dormant until conditions for hatching become favorable. The egg is very resistant to inhospitable temperature and moisture conditions, and can survive many stresses.

The golden nematode which attacks potatoes—and has so far been limited in this country to Long Island, New York, although widespread in Europe—has a remarkable longevity in the soil. Like the root-knot nematode, it lays some eggs in the plant root—but it also deposits them inside its own body. In fact, it lays them in such tremendous numbers that its body becomes a mass of eggs sur-

rounded only by the leathery, golden cuticle of skin. The nematode is dead, but its body shelters the eggs inside a protective cyst.

The cyst is practically indestructible. It resists chemicals, dryness, dampness, boiling temperature, freezing temperature, even radiation (some nematodes have withstood doses of atomic radiation 1000 times greater than that needed to kill human beings). In fact, the simplest way to destroy the eggs in the cyst is to squash them with a hammer.

The eggs that were laid outside of the female's body hatch, and the nemas wriggle off into the world to find food and shelter. Few succeed, and if the nematode relied solely on this method of dispersal, its species would quickly become extinct. But the hope of the golden nematode's survival is to be found in the cyst, and it is the primary carrier of the species from generation to generation.

If the host—potatoes, tomatoes, and their relations—is again planted in the soil where the cysts were deposited, most of them will hatch the next year. But if no host plant appears near the cysts, very few will hatch, only an occasional one discharging its young in a futile quest for a host root. Most remain dormant, more than ten years if necessary. They lie in the soil and appear to be completely dead; yet as soon as a host plant grows in the vicinity, the signal to hatch is given.

What is this signal? It is obviously chemical, but the chemical is secreted in amounts too small to be detected by ordinary laboratory methods. This *root diffusate,* as it is called, goes into solution with the soil water, and eventually reaches the dormant cysts. The eggs in the cyst quickly hatch, secure in the knowledge that already in their vicinity are host plants, ready to be fed upon. But not all cysts hatch even when the diffusate reaches them; some remain dormant, apparently as insurance against a catastrophe destroying that year's crop. Biologists are not quite certain about the mechanics of this dormancy, but the hatching process might produce an inhibitor, perhaps similar to the inhibitors in termite caste-differentiation. This

inhibitor, also carried by the soil water, might halt further hatching, insuring that some cysts will remain in the soil for another year.

Root diffusates are open to much research, for no more than the bare facts are available at the present time. It appears that the nematodes are not only able to recognize traces of diffusate and separate them from the chemical reservoir of the soil water, but they can also tell the difference betwen diffusates from hosts which they prefer and those which interest them only mildly. Then, too, there may be more than a single chemical involved; for example, one chemical may stimulate the hatching while a different chemical directs the nemas toward the root.

The diffusate must be a potent chemical indeed, because hatching is stimulated even if it is diluted to the vanishing point. If water is merely drained through a pot in which a potato is growing, that water has enough diffusate to bring about the normal hatching of the cysts. The diffusate is produced only by vigorous plants: a tomato root growing at the rate of only 6/100ths of an inch a day has no attraction for nematodes; but a root with a growth rate of more than 8/100ths does. A tomato plant showing a root growth of only 6/100ths is a very weak plant indeed, and will no doubt soon die. To be attracted only to plants which have a fair chance to weather the hazards of life must be of tremendous survival value to the nematodes.

Attempts have recently been made to discover from which part of the root the diffusate comes. Few nematodes are attracted to the first 8/100ths inch of a growing root (this area includes the root-cap and the region of cell division) and, in fact, are often repelled by it. Between about 8/100ths and 30/100ths inch (the zone of elongation, the most actively growing part of the root), a large number of nematodes cluster around the root. So it appears that the diffusate is secreted from this zone. But plant physiologists are still unable to state what the diffusate is, and which tissues do the secreting. More important, it is unknown how such a self-defeating characteristic of roots could have evolved, much less survived.

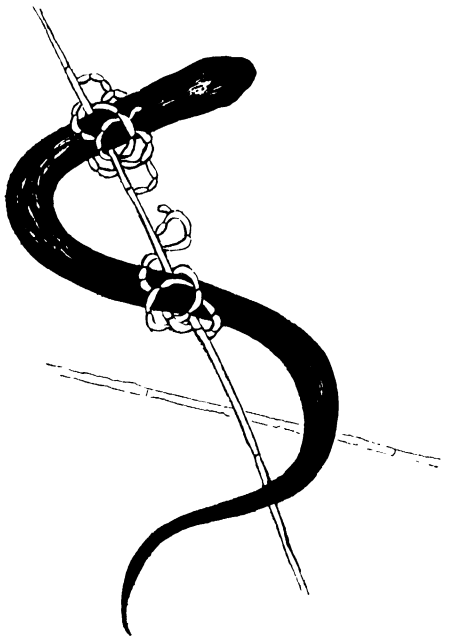
The Predatory Fungi

Nematodes are beset by many enemies in the soil—but it was not until about 1888 that an enterprising German research scientist first discovered that delicate soil fungi can trap the much larger, wriggling nematodes in a variety of snares.

That they are able to is due to the ingenuity of the snares. Some of the commonest of these predacious fungi work like flypaper and they are best demonstrated by watching *Arthrobotrys* under the microscope. Most of the time, when no nematodes are present in the soil, Arthrobotrys lives peacefully, consuming organic matter; it is an inconspicuous member of the fungus flora of soils and would be little noticed if it did not possess also a secret life. When nematodes are present, this fungus becomes a hunter. It sends out little loops in many directions that soon resemble a crumpled piece of chicken wire. Each of the loops is extremely sticky, and a wandering nematode quickly becomes fastened. Struggling to escape, the nematode brushes against even more loops; in a few hours it is tightly encased and dead.

To consume its meal, Arthrobotrys merely sends out a food pipeline which enters the body of the nematode, expands, and divides into tiny threads. The threads soon grow to fill the nematode's entire body, digesting the nematode from the inside out, sending the sustenance back to the parent plant. When feeding is completed and the nematode but a hollow shell, the thrifty fungus then digests the threads themselves. Witnessed under a microscope, the process is one of striking efficiency, for the nematode never has a chance. Sometimes so many nematodes are captured that the very network of snares is obscured by the carcasses being drained. Yards of Arthrobotrys can be found in a handful of almost any garden soil, and so can thousands of nematodes. The toll taken on even a small lawn must be overwhelming.

The flypaper snare has its intricate variations and specializations. Some predacious fungi, instead of growing loops, set out sticky



NEMATODE SNARED BY A PREDACIOUS FUNGUS

knobs much like fish hooks. And there are even some fungi which do their trapping while still only spores. When a sticky spore becomes accidentally attached to a passing nematode, it germinates, sending its strands into the nematode and consuming it; then it reproduces inside the corpse, launching more spores to ensnare more nematodes.

Another kind of trap is made like a noose. Three cells of the fungus grow into a curved shape, gradually enlarging until they form a stout lasso. The circle is just large enough for the nematode to insert its head into, and as soon as this happens the rings suddenly expand, closing the opening so tightly that the constriction of the nematode's body can be seen. The nematode is strangled, and there is not the least possibility of its escaping. In fact, the time necessary

for the three cells of the fungus to tighten on the nematode has been measured at less than one tenth of a second after contact.

We are now learning that predacious fungi are more widespread in the soil than formerly believed. So far, more than fifty species of predacious fungi have been identified, and new ones turn up every year. Not only are there fungi which attack nematodes, but others snare small crustaceans, amoebas, and rotifers. They belong to many unrelated fungus families; thus, at way-stations along the course of evolution, the habit of tiny fungi going on trapping expeditions has arisen.

In the study of predacious fungi, scientists are blocked by the chemical barrier to knowledge. When the nematode is caught in a sticky trap by the flypaper Arthrobotrys, why does it die so promptly, usually in a mere hour or two? The extremely tough and resilient nematodes have survived torture tests concocted by scientists for longer periods. One explanation is that some kind of poison, or anaesthetic, is administered, perhaps by the feeding tentacle.

Russian scientists claim to have found a poison secreted by Arthrobotrys, but their experiments have not been conclusive enough to gain acceptance by other scientists. The most striking evidence to date lies in a remarkable motion picture, showing the process of nematode-trapping, filmed by two French scientists. The microphotographs reveal that as soon as a nematode has been snared, a violent seething takes place in the fungus cell; materials within the cells appear to be streaming toward the point of contact. They may merely be bringing enzymes to aid in digestion, or possibly an anaesthetic.

Nor can the sudden swelling of the noose be very easily explained. It is known that the trigger initiating the swelling is simply contact. A nematode is not even required; the scientist can swell the cells artificially by gently brushing them with a fine needle. Very possibly the cells expand by a speedy intake of water, but the mechanism is unknown. There is much uncertainty, also, about the very formation of the rings. Grown in a nutrient dish, the fungus resembles most

other soil fungi and no traps are constructed. But when even a drop of water in which nematodes had once lived is added to the dish, in a few hours traps begin to form. Possibly the nematodes secrete a diffusate which results in their downfall. If so, the destructive nematodes, who are attracted to roots by secretions, would themselves be victims of their own secretions.

The Chemical Highway

Secretions from root systems also form a highway for the only other soil tenant who equals the nematode in destructiveness, the wireworm. This is not a worm at all, but rather the larval stage of the familiar click beetle found in many meadows and agricultural lands, and a close relation of the Japanese beetle. The adult beetles put on a performance of acrobatics that cannot be equalled by any other insect. If a click beetle is threatened while on a plant, it suddenly rolls itself into a tight ball and drops like a pebble to the ground, simulating death. After waiting a few moments for the danger to pass, the beetle is ready to scurry off again. Only in falling it probably landed on its back, so to right itself, there is a sudden click and the beetle shoots into the air for three or four inches. If it lands on its back again, as usually happens, it propels itself into the air once more, and will keep doing so until it lands squarely on its legs. The clicking mechanism is quite simple: there is a prong between the forepart of the insect and its broad belly which, when snapped, jerks it into the air.

Entertaining as they may be in the adult stage, the larval click beetles are notorious soil pests; England regards them as the worst insect destroyer of crops. The wireworms' life in the soil is one of continual destruction of plants, as they bore through the outer layers of seeds and roots to get at the succulent inner portions. A few kinds of wireworms may become mature in the soil in only one year, but three years are necessary for many, and more than six years for some.

They are extremely active in the soil, traveling up and down from layer to layer in response to living conditions. In the spring, they strike out for the surface as soon as the soil temperature reaches 50 degrees. But when the temperature rises as high as 80, they begin their downward movement, and usually stay below a six-inch depth. A few migrate upward again in September, but most remain in the lower soil horizons and often spend the winter a foot beneath the surface. Wireworms have unusual tiny organs on their head, and it is believed that these are for sensing changes in humidity; they are extremely responsive to moisture, and migrate quickly out of dry areas to congregate in those that are wet.

Studies have shown that wireworms respond to chemical compounds which are given off in trace amounts by growing roots. Not only do the secretions attract the wireworms to the succulent roots, but their act of biting into the roots appears to release more compounds which further affect their behavior. In the complex association of chemical substances and wireworms, tests have shown that amino acids cause them to group on a root, and that sugar compounds make them bite into it. But later in life, when it is time for the female to lay her eggs, the wireworms are repelled by sugar compounds.

Perhaps much of the life of the wireworm—and other insects as well—is governed not so much by internal mechanisms as by external chemicals. What "makes" an insect do something? In the past, many scientists have been prompt to attribute an action to an unknown cog within the machinery of an insect's instinct. Recent research, such as that carried on at Tufts and Johns Hopkins in chemo-receptors, may reveal that insects are not so precise in their behavior as once believed, but rather are tossed about by the waves of chemicals in their environment.

The Grass and Its Guest

Chemical substances in the soil also govern the life of the fifty or

so varieties of *Striga,* known around the globe as witchweed. Striga's depredations upon common grasses—and those grasses which are grown as crops, such as corn, sorghum, rice, and sugar-cane—are in some places worse than all other insect and fungus pests combined.

Witchweed begins its life as a microscopic seed, only a thousandth of an inch in size; as many as 500,000 seeds might be produced by a single plant. They are dormant seeds, capable of remaining alive in the soil for well over twenty years. But the compact mechanism of the seed does not spring into life until the root of a host plant probes within a tenth of an inch. What awakens the witchweed? Experiments have shown that the roots of the grasses they attack exude a stimulant, a hormone signal for the witchweed seed to germinate. And the stimulant does even more—it provides a chemical trail for the witchweed to follow right to the root. The hosts of witchweed are gracious ones; bewitched, they collaborate fully in their own destruction.

The tiny strand that the witchweed sends snaking through the soil does not dissemble. It declares itself to be nothing more than a sponger: the strand has no root-hairs by which the witchweed might make its own way in the world. Instead, the strand follows the chemical trail to the grassroot and, as soon as it makes contact, swells into a bulb that clasps its host in a deadly embrace.

The witchweed has chemicals in its arsenal. An enzyme helps the sucking organ pierce the grass' root, thrusting headlong through the cell walls and creating a tight connection with its food-and-water-carrying vessels. Now the witchweed is ready to live completely as an uninvited guest, shunting off for its own use the host's food supply. It grows more tentacles that attach themselves to the root.

Witchweed is an efficient parasite: in one case, twenty-two witchweed seedlings were observed sucking the lifestuff out of only a quarter-inch of corn root. As many as 500 witchweeds have been fastened to a single plant. Occasionally, though, the witchweed's orgy of hunger results in its own downfall: it kills off the host too

quickly and thus loses its own food supply. But in most cases the host remains alive within the shadow of death until early summer, both plants developing on the same root system. By then, the young witchweed has grown a thick underground stem and loaded it with stolen food supplies.

Witchweed is now ready to cast off the sucked-dry husk of its host, much as the spider hurls the empty corpse from its web. It has reformed, and emerges into the sun, welcomed into the society of higher plants. The fat grey tuber puts out a bright green stem and fuzzy green leaves—badges of respectability, for they mean that witchweed is laboring to manufacture its own food through photosynthesis. Witchweed takes its place along with the other toilers in the summer sun.

It grows to a height of a foot, and flowers in a burst of red blossoms that resemble nasturtiums, carpeting fields with crimson. It is so bewitching a plant that when the scourge appeared in the United States for the first time, in 1956 in North and South Carolina, residents there tried to transplant the little flowers to their garden beds.

Unlike the lofty forests, where so much of the activity is centered above ground, the grasslands afford panoramas of vast stretches of level soil, relieved only by the low vegetation. On the surface, the grasslands appear to be at peace, but the stream of life that flows under them is a carrier of secret chemical forces.

7. *Triumph of the Seed*

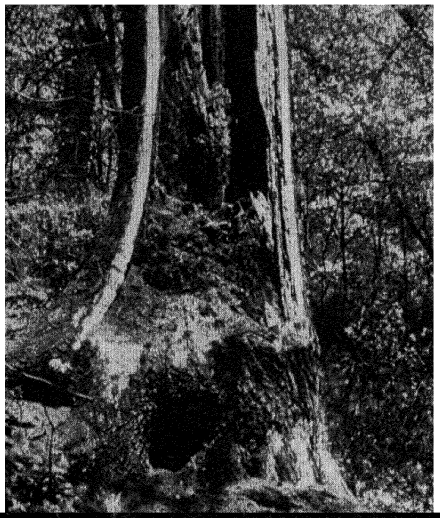
EVERY YEAR showers of countless seeds fall upon the grass, the legacy of a declining year to the soil of the next. Each of these seed motes represents evolved plant life in its most compact form. It arises from the union of two cells, male and female, and it is an embryo clothed with many-colored coats. Within the coats is a master plan for development of that species, but no more than a blueprint which may be altered at the initiative of each seedling. Typically, the seed contains one or more primary leaves, mere specks in the seed, not resembling mature leaves, but indications of what will come. There is an axis for balance, and the semblance of a bud. The radicle indicates that there will arise a primary root.

The earthworm's capsule gives rise to another earthworm, of form the same, and a replica in color and size. It grows to a predetermined size, then awaits the end in the fullest stage of its perfection. Not so the growth of a plant from seed. It is growth of disorganization, the sprouting of life without form. The primary root system goes where it can, and no two root networks of the same species ever follow the same courses. Roots never cease growing until death: the root-tip is always young, and it leaves behind the trail of age.

Many plants store food for the embryo under the seed coat. Sometimes the reserves are packed away in the fruit or a nut, or they may arise from a special tissue, grow to surround the embryo and cradle it in nourishment; the legumes store their provender in the incipient leaves themselves. With these provisions, the embryo is launched on

WINGED TERMITE REPRODUCTIVES, assisted by wingless nymphs in pushing aside the soil particles, head for the surface for their brief flight into the sunlight. After dispersing and finding mates, they return to a world of unremitting darkness in the soil.

NURSE-ANTS are in constant activity, moving the young to different parts of the nest to find the best conditions of temperature and moisture.



A DEAD FOREST GIANT returns to the soil the materials it used during its growth. The interior has already been decomposed by fungi, termites, and carpenter ants. A strong wind will soon topple the tree, making its trunk accessible to more soil-dwellers.

LEAVES ON A FOREST FLOOR are broken down by the action of the soil inhabitants, returning the substance to the soil where it may be used for the leafing out of a future spring.

what can only be a voyage of disaster, for but a small fraction of seeds ever survive the hazards of germination and growth.

As soon as it leaves the parent plant for its trip to the soil, the seed prepares for the worst. All excess water is bailed out, and the tiny embryo pulls itself into a smaller space, as if to husband the flickering spark of life. The coats of the seed grow hard and resistant to nearly everything—water, heat, pressure, abrasion. The internal chemical works metabolize at minimum capacity to maintain the scant reserve of food.

Inside their mailed coats, the embryos of some seeds can survive for an extraordinary time. Indian lotus seeds, discovered in a dry lake bed in Manchuria, were dated at approximately 1000 years of age by radioactive carbon measuring. The seed coats were as impervious as the day they left the parent tree. But when the coats were broken open by botanists, the seeds germinated and flowered—a bud that was conceived in the days of the mandarins awakened in a twentieth century laboratory.

Seeds insure the survival of their species by dormancy, so that a catastrophe one year does not affect the sleeping seeds of that species. The delay in germination sends the seeds into a fourth dimension, time. Even those that lie dormant for but a year or two enable their species to survive a severe winter. A lawn may be cleansed of weeds, yet they appear again the next spring: usually, these were not blown in but were in the soil all along, perhaps for a decade. This was proven over fifty years ago when United States Department of Agriculture researchers undertook a lengthy experiment. Over 100 species of seeds, from wild as well as domesticated plants, were buried in the soil and then periodically inspected. The research workers learned, first of all, that depth of burial did not affect the life span of the seed; some, uncovered after a decade from a four-foot interment, still sprouted. After twenty years, the seeds were dug up, and practically all of the wild plants germinated.

So resistant are many seed coats that scientists have been unable to destroy their powers of germination. The scientists have boiled

the seeds for days, frozen them at sub-zero temperatures, vacuum-packed them, submitted them to tremendous pressures—and still they sprouted. In 1940, the London Museum of Natural History was hit by a bomb. A cache of seeds, gathered from all over the world, was subjected to fire and floods of water. Many germinated, including some that had been collected 150 years previously.

Most cases of dormancy are due to an impermeable seed coat. No germination can occur until the seed has imbibed water, the force that sets the seed into action. But there are many causes of dormancy, as seen in some of the commonest weeds like shepherd's purse, pigweed, and mustard. These have coats that permit water and oxygen to penetrate, but the strength of the coat does not allow the embryo itself to enlarge. The embryo imbibes water and strains at its bonds, and if water were constantly available it could remain inside its coat for about thirty years. But if the coat dries out just once, the seed will germinate when wetted again. The drying-out process apparently brings about changes in the cells of the coat which rupture it.

Delayed germination results, too, from the fact that in certain seeds the embryos themselves remain dormant, even after the coat has burst. Although botanists have removed the seed coat by hand and planted the naked embryo, it still does not germinate. Some of the commonest plants exhibit this form of dormancy, such as dogwood, hemlock, and pines among the trees, iris, lily of the valley, and many others. What these seeds need is a long period of "after-ripening," which usually means lying in the soil for at least a winter. Witchweed seeds, for example, require two years of after-ripening.

Actually, though, most seeds germinate very rapidly and are notoriously short-lived. The seeds of willows and poplars survive for only a few days, and must germinate at once. Elms germinate best within two weeks after ripening, and their ability to sprout decreases sharply after that period. The seeds of a silver maple are shed in the first days of summer, and their water content then is 60 per cent;

they will live only until their water content drops to about 30 per cent, which can happen in scarcely a week or two during the dry summer.

Most seeds germinate just beneath the soil surface, but seeds of forest trees sprout underground, covered by the raw humus of the soil surface. The necessary element in germination is water, slowly filtering through the seed coat or entering through abrasions, filling the cells and causing them to burst. Germination is aided, too, by microorganisms on the seed coat which gradually decrease its resistance, and the temperature and moisture fluctuations in the soil.

Temporary Tenants

"Go to the ant, thou sluggard," advised King Solomon, "consider her ways and be wise; which, having no guide, overseer, or ruler, provideth her meat in the summer, and gathereth her food in the harvest." Not only Solomon extolled the harvesting activities of ants, but so did a procession of classical writers, including Hesiod, Horace, and Virgil. Pliny found them working overtime, during the night, at the harvest and praised their labors. The *Misna,* a codification of traditional Jewish laws begun after the birth of Christ, in the very first section discussed the apportionment of the ant granaries among the human discoverers: "The granaries of ants which may be found in the midst of a growing crop of grain shall belong to the owner of the crop; but, if these granaries are found after the reapers have passed, then the uppermost part of each heap shall go to the poor and the lower to the owner."

In spite of the ancient testimonials to the fact that ants gathered seeds and laid by stores for the winter in granaries, as recently as the last century entomologists still doubted the wisdom of King Solomon. There was not a scrap of evidence that ants did any such thing. In fact, the dispute became so energetic that in 1869 the president of London's Linnean Society (the same group to whom Darwin and Wallace had announced their theories on origin of the species eleven

years previously) proposed that the subject be investigated by the membership.

There is no report that any member in the audience became enthused, with the exception of J. Traherne Moggridge, a curious poker-around in soils, who recalled that in the south of France he had seen ants carrying seeds. Could these ants also store seeds in immense granaries underground, as the ancients had claimed? He set out for France in the hope of again finding the valley where he had observed these ants. He located the valley, the ants, and finally, after much digging, the granaries. Moggridge announced that Solomon was right after all, and he published his studies in 1873 in *Harvesting Ants and Trapdoor Spiders.*

Now it is known that harvesting ants are indeed widespread, found almost wherever there are drylands on every continent. In the Sahara, Auguste Forel many years ago discovered an ant granary at a depth of five feet, and presumed there were more even deeper. They have been collected throughout the Palestinian deserts and are very common in the drier grasslands of the United States.

The habit of storing seeds has arisen among many different groups of ants. Some use it almost exclusively as a food source, while others—such as the fire-ant of the southeastern states—put by only small provisions of seeds. In the uncertain conditions of the drylands, seeds are a very efficient food source: like vitamin pills, they provide concentrated nutriment, easily stored inside the nest. Most harvesting ants will also eat meat when they can get it, but small insects are often a chancy commodity, so the harvester must rely heavily on its granaries.

The mounds of the harvesting ants are among the most conspicuous objects of the western landscape. A fair-sized one may be a dozen feet in diameter, but there have been reports of some with diameters of thirty-five feet. The mounds are completely devoid of vegetation, every twig and leaf having been deliberately removed. Since a blade of grass to an ant is, proportionately, like a Douglas fir to man, land clearing by harvesters represents a major achievement

in insect forestry. The clearing of vegetation is important to the success of the granaries, because the roots might intrude into the storage chambers; also, vegetation collects moisture, and dampness might coat the stored seeds with mold. To further increase the runoff of water from their mounds, some harvesters pave them with gravel brought up from the depths.

Some harvester colonies reach immense populations, up to 50,000 individuals. The worker ants (usually there is no soldier caste, each worker possessing a sting as powerful as that of a wasp) scurry aimlessly about, for they have no particular hunting grounds. Even after a worker has come upon a productive foraging ground, she usually does not return there, nor is the discovery of a supply of seeds communicated to the other foragers.

These ants are exceptional in that odor plays little part in their lives; it is understandable that this should be so, since the dusty drylands soil quickly covers an odor trail. Experiments have revealed that the harvesters rely completely upon sight and memory to find their way. But, oddly, once their sight has brought them to what appears to be a seed, they use only smell to determine whether the seed is really a seed.

They not only carry back seeds that have fallen to the ground, but also collect them from growing plants. Moggridge reported watching one ant climb a stalk and bite loose the seed pod, letting it drop to the foragers waiting below. So numerous are the seeds brought back by the foragers that a single granary often contains enough to fill a milk bottle. The ants gather the seeds from many sources, and sometimes twenty different species of plants are represented in a single granary.

An ant mound can be identified as belonging to a harvester species if it is surrounded with heaps of garbage left over from the husking operations. Inside the nest, a special corps of the larger workers do the husking, their powerful jaws scraping away the hard coats of the seeds; they seldom, if ever, emerge into the sunlight, their millstones constantly at work on the grist brought back by the

foragers. The refuse of their threshing operation is carried outside the nest: seed husks, dried vegetable matter, inedible seeds, all are deposited on the garbage heap.

Occasionally, a ring of plants not usually found growing in the vicinity sprouts up around the harvester mounds. For many years, some entomologists believed that the ants actually maintained these as their own cultivated row crops, in the same way that other ants tend mushroom gardens. But these ants cannot be credited with such foresight. The rings of exotic plants arise simply from errors in the threshing operation: a viable seed occasionally gets mixed in with the day's garbage and grows readily on the fertile compost of the dump.

Although they do not actually cultivate crops for seeds, they are still professional in the business of harvesting, threshing, and storing the hoard. Because of their expert engineering in maintaining the dryness of the mounds, very few seeds are attacked by mold. And the dryness discourages germination. But occasionally a torrential downpour wets the granaries, so on the first sunny day the ants carry their stores outdoors and lay them in the sun to dry out.

The seeds remain in excellent condition in the granaries, without the enormous losses that occur to man's surplus hoards in grain elevators. Moggridge collected seeds from twenty-one nests, and of the thousands he gathered, only twenty-seven showed traces of germination. Surely the engineering of the mounds for dryness cannot alone account for the arrested growth. Rather, it appears that when the seeds do begin to germinate, the ants bite off the radicle, or first-root, not only halting further germination but also converting the starch in the seed into edible sugar.

The Soil Incubator

Those seeds which are not gathered by the harvesting ants, eaten by birds and animals, or fall prey to the hosts of microbial disease, will germinate and put out foliage. As soon as the young leaves poke

above ground, they are beset by a variety of additional enemies, and in some seasons none are worse than the grasshopper hordes.

The hungry grasshoppers have been incubated by the same soil that gave life to the seed, and in many ways grasshoppers parallel the seed's development. In the early fall, the female grasshopper seeks out fields where the soil is workable. On her abdomen she bears a group of prongs, simple tools with which to bore holes in the soil for her eggs. After selecting a drilling site, she closes the prongs, their ends meeting to form a sharp wedge, and drives them all of the way into the earth. Then she spreads the prongs, pushing the soil crumbs apart, and plants perhaps 100 eggs. She gives the eggs what protection she can by spraying a frothy liquid into the hole: the liquid hardens into a sponge, cushioning any impact on the nursery, assuring a supply of trapped air for the young, and also providing insulation. The grasshopper makes four or five such borings, each enclosing a capsule of eggs.

The eggs display varying degrees of dormancy, somewhat similar to seeds. If laid in a favorable location in warm latitudes, some will develop at once and shortly give rise to young grasshoppers. Others begin their development, but halt it at the onset of cold weather, so that the young do not emerge until the following spring. Most grasshopper eggs, though, do not hatch until they have first endured the rigors of a freeze. This simple requirement prevents hatching during a sudden warm spell, such as a prolonged Indian Summer in the fall, which would bring a brood to life only to be killed by the winter freeze. By insisting upon the eggs' first being frozen, the grasshopper has insured that they will hatch only in the hospitable spring.

Those plants which survive the onslaught of the grasshoppers, and most of them do, set seeds which return to the soil and reenact the cycle of life in the grassland. In this, they are assisted by the pollinators, many of them bees. Although honeybees are the chief pollinators of many agricultural crops, the 5000 species of wild bees account for much of the variety and beauty of the natural landscape, and it is believed that they make up 90 per cent of this coun-

try's bee population. They are a very diverse group and comparatively little is known about them, no more than 250 of the wild-bee species having been adequately studied.

Most wild bees nest in the soil, and they select a wide range of sites. The earth may be moist or dry, very loose or packed; occasionally they even work into crevices in solid rock. But wherever the nest is made, it is always a simple affair. A primary tunnel enters the ground for an inch or two, from which short branch tunnels lead to the brood cells. Subtle variations can be seen in nest-building technique among each of the species. In some, the brood cells are clustered like a bunch of grapes; in others, they stretch out from the primary tunnel like fingers. The brood cells receive somewhat more care in construction than the tunnels, since they must be protected against drying out. This the female does by applying a sealer to the walls of the cells, usually in the form of bits of leaves or plant fibers.

Whereas honeybees lay their eggs in empty cells and the young are fed by workers, the wild bees almost never see their offspring once the egg cells have been stocked. They lay their eggs on a mass of honey-moistened pollen, and this is the only provisioning the young will get. There are no worker castes, and the eggs hatch into about the same numbers of males and females.

Each female builds her own nest and provisions it without assistance from any other bee. Solitary though they are, they are still very gregarious: in a large wild-bee town, there may be as many as one-and-one-half million nesting in an acre of land. The burrows may be dug barely an inch apart, and somehow each female is able to locate her own nest in the swarming confusion. Fights among them are rare and they appear to make good neighbors.

Midway between solitary wild bees and social honeybees are the bumblebees, the giant *Bombus*. Their patterns of sub-social behavior are very old, fossils having been found in Baltic amber, and demonstrate an arrested sort of social life which has persisted to modern times. Unusual, too, is their distribution, quite the opposite of their insect relatives like ants, wasps, and other bees: bumblebees are

decidedly more numerous in the cold temperate climates than in the tropics. They even occur in goodly numbers in the Arctic regions and are often seen around flowers in Greenland.

Each spring the large Bombus queens, resplendent in their bright coats, unsoiled by the winter hibernation spent in the soil, search for nectar from dogwoods and early flowers. They finally set to work, investigating and rejecting countless matted clumps of dead grass and rodent tunnels. For like the yellowjacket queen, Bombus chooses a former rodent nest, a hole already excavated, the major earth-moving job completed.

But unlike the yellowjacket, Bombus is not a fussy homemaker. She does not bother with redecorating, but rather sets immediately to work to found her village. She constructs a pot made of wax from her body; this contains the honey hoard which she brings back from foraging trips. Alongside the honey-pot she constructs another bowl, this one to hold her eggs. There are usually less than eight eggs in the first batch and the queen broods them constantly to protect them against the spring cold. Only occasionally does she lift her abdomen from the egg cell to drink from the honey-pot or to go on an expedition to renew supplies. The eggs hatch in a few days, and now the queen broods and feeds the larvae.

Three weeks after the first eggs were laid, the workers cut their way out of their cocoon coats, assisted by the queen. Their bodies still wet, their wings unfurled, they crawl to the honey-pot and drink deeply. In a day or two the wings harden and their thick bodies take on the familiar fuzz of the bee; they are now able to search the fields for pollen and to care for the young. The queen settles down to egg-laying and directing the building of her home. For the nest must be enlarged, combs constructed, new storage tanks for honey built.

Occasionally the queen makes a trip into the sunshine, but it becomes a rarer and rarer event as the season progresses. Now she lays a brood of eggs every day, and the nest's population grows. It will never become as large as a honeybee colony, but a thriving

Bombus town may reach a population of a thousand, and villages of several hundred are quite common. Workers of the first brood live only a week or two, and even those hardier workers born after the colony has been launched and sufficient food is available, still wear themselves out in a ceaseless four weeks of labor. By the end of its life, the worker's once glorious coat has worn thin; gone now is the black-and-gold velvet and the darting flight.

The sending forth of kings and queens is the highest moment of the colony. After that the decline is rapid, although lacking the orgy of the yellowjacket city. The Bombus queen dies, as do the workers one by one, leaving the nest to the scavengers. The life of the city lasts but three to six months, depending on species and location; during the remaining months Bombus is represented on the planet only by the young queens. After their mating flights they are drawn back to their former citadel, and they contest the scavengers for a piece of soil in which to hibernate. There may be dozens of queens, quietly sleeping through the harsh winter within a foot or two of the parent nest.

It is by no means true that all the workers of a Bombus colony are offspring of a single queen, as Dr. Otto Plath of Boston University proved many years ago. Dr. Plath, this country's leading bee-watcher, learned that queens which have founded colonies are often killed by invading queens, and the future workers may be the offspring of the new monarch. He examined numerous nests where he found eight to ten dead queens and presumed that many of these, possibly all, were previous rulers supplanted by interlopers.

The outcasts of the bumblebee tribe are the cuckoo bees, parasites who lay their eggs in thriving Bombus colonies. The bumblebee workers have become expert in warding off a cuckoo queen. As soon as she is detected in the bumblebee nest, a battalion of workers strategically groups itself around her and blocks the exit. One by one the workers dart toward the cuckoo queen and place a droplet of honey on her body. At first she accepts the gifts of sweet nectar, but soon she becomes bathed in a sticky mass. At last she drags her-

self out of the nest, her velvet dripping with the goo of an insect tar-and-feathering, a bedraggled contrast to the proud queen who invaded the colony.

This gentle method of warding off attack is used only against the cuckoo and workers of some other species of bumblebees. Against any other invader—whether it be an unwelcome parasite or even a mouse trying to reclaim its diggings—the sting is promptly and efficiently used. The bumblebee possesses a terrible weapon that can be inserted repeatedly, unlike that of the honeybee who stings once and loses both sting and life. Not only is the bumblebee quicker on the draw, but her venom is considerably more powerful than either the honeybee's or the wasp's. Any intrusion near her nest is taken as a threat to the entire village and the attack is prompt, vicious, and often feline: an enraged worker not only stings repeatedly but also resorts to scratching and biting.

Bombus is to be feared only in the vicinity of her nest. In the open, while foraging, she is gentle and slow to take offense. She can be teased unmercifully, annoyed in every way except being directly touched, and the stiletto remains in its buckler. I have disputed blossoms with Bombus and found her timid. In fact, her timidity seems to increase in direct proportion to her distance from the nest. Testing a bumblebee's reactions at various distances, I have narrowly escaped being stung as far as three feet from the nest; at four feet, I am merely buzzed in a loud warning; further away than that, I am ignored.

Bumblebees, like ants, have many guests, and none is more enterprising in gaining admittance than the beetle *Antherophagus,* a tiny scavenger found in nearly every Bombus town. This beetle is a common one around the blooms of some of the showier flowers, such as hollyhocks, and there it patiently sits, with jaws extended, waiting for a Bombus worker to come collect the nectar. As the bee sticks out its long tongue, the beetle grabs hold with its jaws; if the beetle misses, it will as soon grasp an antenna or a leg. Antherophagus cannot be shaken off: it took Plath about fifteen minutes to capture one

bumblebee worker and during all of this time Antherophagus hung on; even when the bee and beetle were dropped into a killing jar, the guest still did not loosen its hold. The bee porter can do nothing but carry the beetle back to the nest, where it finds sanctuary in a dark corner. Other workers are also carrying beetles back, and eventually male and female Antherophagus meet in the dark nest. They continue to live out their lives there, feeding on the debris of old honey-pots or leftover drops of nectar.

It is a strange world, that of Antherophagus, yet when we see the spry little beetle on a meadow flower it is like a visit from an inhabitor of a faraway land, inarticulate, but by its very existence speaking of a successful journey. And so we of the aerial world may catch occasional glimpses of the wayfarers from the soil. We may admire their forms, ponder their life histories. Yet we can but divine their roles in the intricate web of grassland life; for no creature of the soil stands alone—all are interwoven, their pasts and futures, in the economy of a piece of earth.

IV.

THE DESERTS

8. *Adapting to Adversity*

DESERT SOILS occupy at least a fifth of the land surface of the globe, an area equal to that of Africa. The desert is one of the most hostile environments known, and is characterized by strange and wonderful adaptations on the part of the animals and plants who live in it. Some of the desert soil-dwellers display modifications whereby, if they have not made the desert a hospitable place, they have at least been able to endure life in it.

Water is the limiting factor common to all deserts, and the average rainfall is often only a few drops a year. The *minimum* rainfall may be no water whatever for long stretches of time, as many as two or three years. Not only must the droughts be taken into account, but also the other harsh tests of nature in the desert—sudden frosts, dust-devils, torrential storms.

That any living things survive at all is a wonder, yet they do, as can be emphatically seen in a trip to a unique natural history establishment, the Arizona-Sonora Desert Museum, west of Tucson. Here are collections of desert creatures, botanical trails and, most marvelously, an underground zoo that allows the visitor to watch the soil-dwellers of the Sonoran Desert, the mammals and reptiles, roots of living plants, all carrying on their lives undisturbed.

The tunnel in the desert is a walk 175 feet long, and by the end of it the visitor has learned that the desert soil is indeed populated. Even the terrestrial creatures must constantly return to it to escape the harshness of their environment. Coiled in dark corners, behind inconspicuous glass walls, are the desert reptiles, awaiting the cool of night to emerge for their hunting. Here, too, are underground quar-

ters for prairie dogs, ferrets, skunks. The porcupine slumbers in his den until dusk, and if the visitor looks carefully, he may see the little trade rat (also known as pack rat); this rodent busily pilfers the porcupine's food stores, carrying away much more than he could ever use and storing it for himself.

Microorganisms, too, are present in the desert soils, although in much fewer numbers than in forests and grasslands. Studies made in desert soils have revealed about 90,000 microbes in a teaspoonful of soil, a small fraction of the hordes in a typical forest soil; practically all of these are bacteria, with only a few actinomycetes and fungi. Small as the actual numbers are, much diversity of species exists.

Microorganism counts have revealed the amazing fact that protozoa exist in desert soils, and that they belong to the same groups usually found in fresh water. A pioneering study made about forty years ago in the vicinity of Cairo, Egypt, showed that these microscopic animals were everywhere in the dry sand, but enclosed in protective cysts. They emerge from their cysts when the rains fall, and return to the protective envelopes as soon as the sands dry up. Even after eight months of unbroken drought, the investigators were able to collect more than fifty species of protozoa which hatched as soon as the sands were moistened.

Turning over the small stones on the surface of deserts soon after a rain reveals an amazing number of small animals. Many of the familiar soil dwellers of moister environments have found refuge there, woodlice and millipedes, mites and roaches and earthworms. The life histories of the desert forms have not been sufficiently investigated for us to be quite certain what happens to these animals during the dry seasons of the year. But they have only two choices: some will burrow underground until they reach moisture (like desert termites which plumb the depths for 100 feet and more), others will go into an inactive stage to await favorable conditions once again. Whatever their methods, and they do vary greatly, even the moisture-loving organisms have adapted to the realities of the desert life.

The Search for Water

The Great American Desert of the Southwest is distinguished among the deserts of the world for the variety of its plant life. For example, one botanist found only a dozen kinds of plants in a month-long collecting trip through the North African deserts, yet in a small area in just one of the American deserts he turned up many times that number. The Old World deserts have already been ground down into a uniform monotony; the American deserts are still geologically young. Someday our desert areas will also be levelled, and gone will be the canyons, mountains, and plains which have provided a rich assortment of habitats for many kinds of plant life.

Many deserts seem headed toward a final geologic form, the great shifting sand dunes, such as may be seen in the Sahara. It is nearly impossible for a plant to gain a foothold in the shifting sands: the seed must first arrive, blown in across wide spaces of inhospitable sand; then it must remain viable until water permits it to germinate; finally, the seedling must survive the shifting dunes which lay bare the roots to the scorching sun and whip the leaves to shreds.

Occasionally growth does begin in a sandy desert, for although the chances are but one in many billions, a prodigal nature has provided the billions of opportunities. How does life enter a desert? Often it starts in a little pocket or depression where a rain has soaked the surface and temporarily held it against blowing. There, some seeds may quickly germinate and hold their own for a time as the sheltered depression begins to dry up. The spindly plants soon die, but they leave behind a clump of organic matter, able to retain the moisture of a subsequent rain, preparing the way for another pathetic handful of plants.

Certain species of plants have adapted to the shifting sands, and none is more successful than the date palm, the trademark of the oasis. Its secret lies in quick-growing roots which are sent into the depths while the palm is still very young, quickly establishing both a foundation and a connection to underground water. Even in the

blinding glare of Death Valley one will come upon the deep-green mesquite, a lush shrub that appears to more properly belong in a rain-forest. Its source of water is often 100 feet down, pumped up in copious quantities by the searching roots.

The mesquite is not drought-resistant, but is a water-seeker. So is the most widespread and familiar plant of the sandy deserts, the yucca—a low-lying handful of daggers which hold, as balanced on the palm, a tall stalk of blossoms. The roots of the yucca have been shown to descend as deep as fifty feet. But water-probing roots alone do not explain why the little yucca is still not buried under a shifting dune. Rather, the yucca responds to the dunes as if it were a boat bobbing on a sea of sand. As the sand begins to cover its leaves, the crown of the plant lifts itself higher and higher.

The dryness of the desert is not endless, and inevitably the period of rainfall must come. That is when the desert suddenly blooms, as if overnight; it is a rapid change, because the plants have been husbanding their energies for this one triumphant moment in which to send out flowers and make seed. The most conspicuous blooms of the desert after a rainfall are the gaudy colors of the annuals, evening primroses and sunflowers and other representatives of familiar groups.

In the constant jockeying of life to find a place in the desert sun, the annuals have not adapted their leaves or stems or roots to desert conditions. These ephemerals have banked the whole survival of their species on the ability of the seeds to germinate quickly, carpeting the soil with an incredible array of blossoms that set more seed hurriedly, then wither. The annual seed is capable of making fine distinctions between rainfalls: many germinate if the rainfall is an inch or more, but will not do so if it is less than that. However, the layer of soil surrounding the seed is exactly as moist after a three-fourths-inch rainfall as it is after a two-incher. How, then, can the seed so accurately measure precipitation? Further, the seeds are sensitive to the direction from which the water comes: water rising from below, as by capillary attraction, does not cause them to germinate;

but the same inch's worth, sprinkled from above, will. How can a seed, scattered upon the soil at random, tell direction?

Dr. Frits W. Went, formerly of the California Institute of Technology and one of the outstanding botanists of the century, has found a chemical answer to the problem of the cogent desert seeds. The seed coats possess chemical inhibitors which successfully prevent germination until they are removed. The only way they can be removed in the desert is by washing off—and the only way that something may be washed off is when the water comes from above. Thus, water rising by the blotting-paper action of capillary attraction will not affect the inhibitor at all. Dr. Went's theory also explains the ability of the seed to gauge precipitation, for a certain minimum amount of water falling on the seed coat is necessary to wash off the inhibitor. Further research may reveal unsuspected complexities in the relationship between inhibitors and desert seeds. For example, some of the inhibitors are not removed by the rain directly; the rain must first be sufficient to set the soil bacteria into action, and the bacteria then eliminate the inhibitor.

Overshadowed in the sudden display of annuals after a rainfall are the perennials, some of the loveliest of the desert blooms, including representatives of the iris and crocus and amaryllis families. During the long periods without rain, they have stored up their resources in a tuber or fleshy root underground. The metabolism of the tuber is extremely slow during dry weather, but in the presence of moisture the tuber reacts quickly, shooting up leaves and stems. When the soil dries out once more, the perennials evade the drought by retreating underground.

There is yet another method for the survival of desert vegetation. The giant saguaro cacti of Arizona—their tall spires resemble candelabra forty feet or more high, their pulpy stems are as thick as a man's trunk—possess an elaborate mass of surface roots, only a few inches below the surface, tightly packed and extending for yards around the cactus. The roots form a catchment basin, and when the

rains finally come they can hold practically every drop that falls, often half a ton of water at a time, and store it in their pulp.

From a low-flying airplane, the forest of saguaro cacti appears to be evenly spaced upon the landscape. To survive, the saguaros must colonize an area that is exclusively their own, one that furnishes them sufficient soil into which to extend their long feeding roots. The desert-wise naturalist is also reminded of the familiar creosote bush, similarly spaced and with the same wide-reaching bowl of surface roots. With the creosotes, recent research has provided a reason for the spacing: chemical warfare underground. The roots of established creosote bushes secrete toxic substances which inhibit seedlings from developing in their spheres of influence.

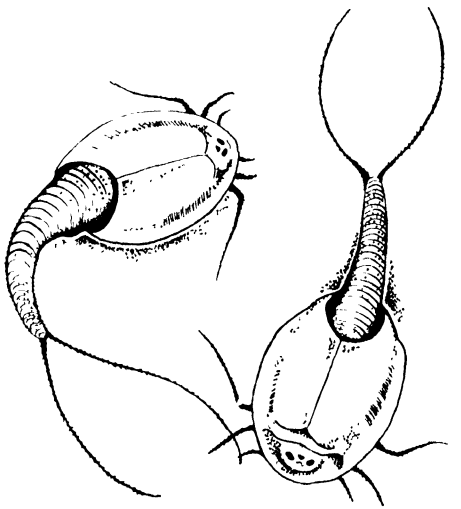
It appears that the creosotes are living out their lives beyond the laws of natural selection. Those with extra-strong roots or stiff stems or reproductive vigor have no advantage in survival over any other creosotes. All possess the toxic weapon in their roots and, rather than being drawn into a struggle for existence, merely practice birth control.

Unusual Desert Dwellers

The occasional rainfalls suffice most desert plants for germination and reproduction, but the water demands of soil animals are more frequent if they are to remain active. One of the most important water sources in deserts is dew, and it is only recently being investigated in Israel as well as the United States Department of Agriculture's Coshocton, Ohio, Hydrology Laboratory. The importance of dew to desert insects was first noted around the beginning of the century by travelers in the North African and Asia Minor deserts. Beetles were observed which were active throughout the year because they were able to obtain their water almost completely from the drops of dew caught in the angles of plants.

Many desert animals center their lives on the "washes," dried-out stream beds which carry water only after the occasional rains send it

pouring down from the mountains. Crabs and crayfish often follow the water retreating into the sands of washes, moving first into the mud and, as that dries out, burrowing ever deeper under the dry bed. One of the most successful animals of dry washes, particularly those that have a high salt content, is the brine shrimp *Apus*. So well



BRINE SHRIMP

has Apus solved the problem of living in a river that is a river for only a few weeks out of the year, that it is found in deserts all over the globe.

Apus resembles a small horseshoe crab and represents a group of crustacea which have remained unaltered for about 200 million years. In fact, the climatic changes of the earth have passed them by. About 200 million years ago, the earth was subjected to extremes of drought and deluge. Even though the climate of the planet is now more equable, the Apus shrimp has continued its ancestral way of living—seeking out the contradiction of wet places in dry deserts.

Apus can endure long periods of drought in the egg stage, and the

eggs survive for many years without rain; a North African egg remained viable after fifteen years of dry storage. But when the rains do come, Apus is capable of extremely rapid growth: one from the Central Australian desert reached a length of two and one-half inches in only two weeks. A heavy rain may make the mud alive with them, as many as 200 to a square yard. Biologists have recently learned that Apus lays two kinds of eggs: one is thin-shelled and hatches almost at once, as the shrimp makes a bid for one more generation before the wash dries out; but most of the eggs are thick-shelled and able to withstand prolonged dryness and wide temperature changes.

Living much the same life as Apus are the desert frogs and toads, other unlikely organisms to live in arid soils. The Horn Expedition to the Australian desert, many decades ago, found toads extremely numerous and able to survive without water because of a few simple adaptations. Many constructed deep burrows under the temporary streams where the soil was still fairly soft and moist. At night—the period of highest humidity and lowest temperature—they emerged from their burrows to search out insect food. One Australian desert frog fills its bladder and body cavity with water—when available—so that it can survive the dry season.

Other species construct permanent burrows in which they enclose themselves for many months, even laying their eggs there. The eggs go through the normal developmental period, in fact up to the very point of the tadpole's emergence. But that final stage is not reached until the rains come. At the first fall of water, the tadpoles are released, provided with ample time to complete their life cycle before the soil dries up once more.

The eastern spadefoot toad, *Scaphiopus,* has a counterpart in the western deserts and semiarid regions. These "rain frogs," as they are called, bear a thin frog-like skin that appears adapted only for an aquatic existence; yet in some desert environments, where not another amphibian may be found, Scaphiopus is extremely widespread.

Scaphiopus owes its success to the fact that it has pegged its

breeding cycle to rainfall, and not to temperature or duration of daylight, as most other animals probably do. It breeds only when the rain is torrential, no matter in what season it falls. When the rains come, Scaphiopus can take advantage of them, for its young develop more rapidly than those of any other amphibian. The eggs hatch in less than a day, and the entire journey from tadpole to adult spadefoot is completed in perhaps a week and a half. The adults inflate their tremendous vocal pouches, raise a courting hubbub, mate in a shockingly rapid fashion, and then disappear suddenly from view.

After their brief appearance, little is known of the rain frog's life underground. There has been a long-standing controversy among scientists whether the spadefoot remains locked in its burrow for many months, or even years, awaiting rain, or whether it occasionally returns to the surface. It appears from some studies made by Dr. Arthur Bragg of the University of Oklahoma that these frogs do remain fairly active, but only at night, and quickly disappear from view if disturbed.

A Strange Water Supply

Rodents can exist in deserts because so many of the plants there have fleshy roots, bulbs, and tubers; thus even during droughts, the animals are provided with a constant source of food. The most common of the desert rodents, whose nest entrances are usually identified by the piles of cactus spines under chollas and creosotes, is the little trade (or pack) rat. These rats protect their nests by erecting fences of spines around the entrances, and spend much of their time repairing and strengthening the bristles.

The trade rat is possessed by a gnawing kleptomania: it collects and brings back to its nest practically anything it finds—wrist watches, bottle caps, keys, bullets, matchboxes. Usually, when a camper misses a possession, he often finds in its place another article, from which has arisen the fiction that trade rats always leave something in exchange for what they have stolen. But there seems to be

no idea of fair swapping in the rat's cunning. It probably already has a stolen object in its mouth pouch, and to cart off the newer object it must jettison the previous prize.

The desert rodents have no special structures to compensate for the scant water supplies available. A rodent living in a tropical rainforest has a water content of about 65 per cent of body weight. A rodent living in an arid desert must maintain exactly the same water content. The little trade rat must take its water where it finds it, and that is usually in cactus pulp and in water-storing desert plants. The trade rat is thus restricted only to deserts where there is succulent growth.

There is, however, another rodent—the kangaroo rat which much resembles its Australian namesake—which is found in deserts so barren that there is practically no vegetation whatever, nor is dew available. Furthermore, these rats are homebodies who do not stray more than a few hundred yards from their mounds: they do not undertake extensive foraging trips to find juicy plants. Zoologists became more uncertain about this rat's water supply when they brought specimens into the laboratory: the rats were fed nothing but dry seeds, yet their water content remained at about the normal 65 per cent.

Much of the mechanics of the kangaroo rat's water supply is now known, largely through the extensive research of Knut and Bodil Schmidt-Nielsen, a husband-and-wife team of zoologists at Duke University. First of all, the kangaroo rat feeds on dry seeds which contain hydrogen; when the rat oxidizes the hydrogen, water results. A small amount to be sure, but water nevertheless. There is nothing mysterious about this, since nearly every animal similarly oxidizes its food and obtains water. The only difference is that other animals supplement this scant amount with drinking water, while the kangaroo rat does not.

The Schmidt-Nielsens estimated that the 100 grams of dry barley seeds they fed their kangaroo rat over a five-week period resulted in fifty-four grams of water through oxidation. Also, they added to this

amount about thirteen more grams, the slight amount of moisture that even a dry seed absorbs from the air. (In the precarious water balance of the kangaroo rat, there is an advantage in storing seeds in an underground burrow where the humidity makes them moister than they would be if stored in the outside air.) In a five-week period the kangaroo rat is supplied with a total of sixty-seven grams of water, a very small amount for an animal its size, but all that is available.

Yet it is more than sufficient if the animal is similarly able to reduce its water loss, which it does. It has a very efficient kidney that can eliminate wastes with virtually no water loss; in fact, its urine is about twice as salty as ocean water. Evaporation of water through sweat glands is at a minimum also, as with most rodents. The primary loss of water from the rat's body comes through the simple act of breathing, due to the dryness of the air that is inhaled.

The Schmidt-Nielsens made a balance sheet of water income and outgo and learned that the kangaroo rat lives a very precarious life indeed. At zero humidity, common in the desert, the animal would show a deficit after five weeks of about seven grams of water, sufficient to kill it. At 50 per cent humidity, a high figure rarely reached in the desert, the rat has a profit of about 24 grams. Water income and outgo are in balance at a temperature of about 75 degrees, with humidity around 15 per cent.

If the average climate of the desert remained at 75 degrees and 15 per cent humidity, the rat could be assured of a constant, if scant, water supply. However, the desert is slightly drier than that. To compensate, the rat is nocturnal. During the day it escapes the high heat by staying in its moist burrow; when it comes out to feed at night, the air is more humid, sufficiently so to reduce its water loss. Income and outgo balance each other; the rat has neither too much water nor is it in need.

The only physical equipment provided the rat in meeting its water conservation problems is the efficient kidney. All of its other adaptations are in behavior rather than physical make-up, and only

by making use of the moist climate of the soil has the rat succeeded in winning out over its most uncertain existence.

Living Storage Tanks

Ants are extraordinarily abundant in arid areas, and entomologists believe that their tribes originated in deserts and then spread to other environments. A fungus ant, counterpart of the rain-forest mushroom-growers, is even found in the Arizona deserts, and a less likely homestead for mushroom growing does not exist. The desert fungus-growers differ from their tropical relatives in a number of ways, the most apparent being that they are rarely abroad, and even when they do venture out seem rather sluggish. Their whole metabolism is geared to a much more leisurely sort of gentleman farming than that practiced by the Attas.

But how are they able to maintain the constant high humidity necessary for a mushroom crop? Perhaps to preserve moisture, the desert fungus ants often close their nest entrances for days, even weeks, at a time. They also accommodate themselves to desert conditions by the shape of their mounds. Whereas the harvester slopes her mound to get rid of water, the desert fungus ant builds hers as a retaining basin, higher at the periphery and lower at the entrance hole. The desert fungus ant appears to utilize the method of the saguaro cactus in catching all of the rainfall in its immediate vicinity.

Some ants spread the occasional fertility of the desert throughout the year by storing plant liquids. These are the honey-pot ants, among the most enterprising of the ant tribe, a group that has conquered the desert without a single adaptation of its body.

The honey-pot ants find an occasional aphid or scale insect to relieve of its honeydew, but their food is primarily furnished by the dwarf-sized scrub oaks. On these grow tiny galls which exude droplets of white nectar. The problem faced by the honey-pot ants is that there is a large but intermittent supply of this nectar. How can they store the surplus for periods of need? The difficulty has been

solved by at least three large groups of ants around the world, one of them related to the familiar carpenter ant of the forests.

What they do is use some of their own workers as living storage tanks. Every ant has a crop that can be distended to store honeydew until it can be carried back to the nest and passed into the communal stomach. But only the honey-pot ants have carried this ability of all ants to its full potential: they have selected some of their members as permanent casks into which the returning foragers empty their crops.

There is no anatomical difference between a swollen honey-pot cask, called a replete, and a sister worker. Repletes are ordinary workers who were drafted into service by chance. A group of workers may return from foraging, their crops filled, and find that all of the storage casks are loaded to the brim. They wait for a young worker to amble by and seduce her into accepting a drop of the sweet nectar. The callow ant begs for more, and finds that it is freely given. Soon all of the workers have unloaded their crops into the hungry youngster. She gorges herself, but will pay for her gluttony. She has taken a road from which there is no return.

The continual addition of nectar into her crop stretches it more and more. The organs of the abdomen become compressed as the elastic tissues of the stomach swell and strain. The worker will never again return to normal. Soon she is unable to walk; later she becomes so swollen that she cannot even stand. She hangs with the other repletes, clustered like grapes, from the roof of the underground chamber, patiently receiving even more nectar, regurgitating it when it is needed to feed the colony.

Honey ants inhabit deserts around the world. The American species, found from Mexico City to northern Colorado, works its repletes the hardest of any: their abdomens swell until they reach a diameter of half an inch and become perfectly rounded balls. Some thriving nests contain as many as 300 living storage casks, and each of the repletes stores about nine times her weight in honey.

The existence of honey-pot ants was confirmed by Reverend Henry C. McCook while exploring in Colorado's Garden of the

A HONEY-POT ANT REPLETE

Gods in 1879. He found their nests to be marvels of architecture: they are always built in the hardest soil in the area so that the ants can better sculpture the extremely large chambers needed for the repletes. The site must also be a dry one, for excessive moisture would make the living honey-bags mildewy.

One nest which McCook selected for complete exploration required that two men work for three days with mallet and chisel to unearth it. The length of that nest was nearly eight feet, and in the construction of the honeycomb of galleries and passageways, about thirty-six cubic feet of stones, gravel, and earth were excavated. The galleries for the honey-bearers were about six inches long and four inches wide; their walls were scraped smooth, but the ceilings were left in the natural roughness, providing a better hold for the repletes hanging there by their front legs.

The Dance of the Tarantulas

A few hundred years ago in Italy was perpetrated one of the cleverest frauds ever to make use of a form of wildlife. It originated

near the city of Taranto in southern Italy, and from there swept across much of southern Europe. A cult was dedicated to curing the bite of a large wolf spider, popularly called a "tarantula" after the name of the Italian city, by wild music and an ecstatic dance (which has persisted to this day, in the tarantella).

But the cult was based on an error in natural history; this fearsome-looking creature is quite harmless. Scientists have taken great pains to convince the timid tarantula to bite at all, and when it was finally goaded into doing so, the effects were no worse than those from a mosquito bite. Obviously, there must have been some reason for the fraud, and one has been offered by a British scholar. He discovered that the rituals for the cure were nearly the same as those used by the ancient priestesses of Bacchus. In short, these were heathen rites persisting into Catholic Italy; the Church was mollified when the tarantula was offered as the excuse for the rituals.

Tarantism has left its mark upon the education of generations since, and the tarantula has become a most feared animal. Fearsome spiders they appear to be: extraordinarily large, averaging an inch or so, with some measuring nearly four inches and weighing two ounces. A tarantula can easily be distinguished from a true spider by the fangs: a spider's are set horizontally and move together like ice-tongs; the tarantula's are extraordinarily large and point downward like the tusks of a walrus. The tarantula's fangs are shiny, thick weapons and to insert them the animal must lift its whole body, as if it were driving in a pick.

Tarantulas have venom at the base of the fangs, but it usually is very mild stuff. Because of their large size and powerful fangs, their need for poison is slight. Then, too, it is nearly impossible to convince them to bite, and much tickling, poking, and annoying of the creatures is first necessary. They are quickly tamed and make excellent pets. Sheltered in a human household, they may live to twenty-five years of age and, while they will gorge themselves when food is available, they can live for two and one-half years without eating.

Most tarantulas are clothed with long hairs, iridescent and beau-

tiful in coloration, remarkable for their diversity of patterns. These hairs are the primary senses of the tarantula, for they apparently do not possess hearing and smell, and their eyesight is extremely foggy. The tarantula knows its world through the hairs which clothe it, and a very efficient job they do.

If the tarantula is hungry, merely touching these hairs launches it into a furiously swift pounce. By the location of the hairs that have been stroked, ever so lightly, it can aim its attack with precision even in complete darkness. But if the tarantula has recently finished a meal, touching these hairs results only in a swift kick at the annoyance. I have watched an Arizona tarantula in the American Museum of Natural History's "spider zoo" while a lone larva, the last of the day's provender, strode back and forth beneath the tarantula's fangs and wound through its legs. The only attention it received was an occasional swipe from one of the eight legs of its host. Of course, when the tarantula's hunger returned, the larva undoubtedly met with a completely different fate.

The United States possesses a rich fauna of tarantulas, with scores of different species spread across the southern states. They are most common, and reach their largest sizes, in the deserts of the Southwest. All are inhabitants of the soil and, once they have found a burrow to their liking, they often remain there for the rest of their days, exploring no more than a few feet into their neighboring world. Their subterranean habits, combined with the fact that they are nocturnal, make them very rarely seen.

The specialists among the burrowing tarantulas are the trapdoor spiders who, millions of years before many garden spiders learned to spin their webs, were constructing comfortable burrows protected by trapdoors of their own manufacture. Little was known of trapdoor spiders until they were thoroughly investigated by J. Traherne Moggridge, about the same time as he was looking into the affairs of harvesting ants.

Moggridge found at least four different kinds of burrows, ranging from a very simple tube capped with a heavy door to the more

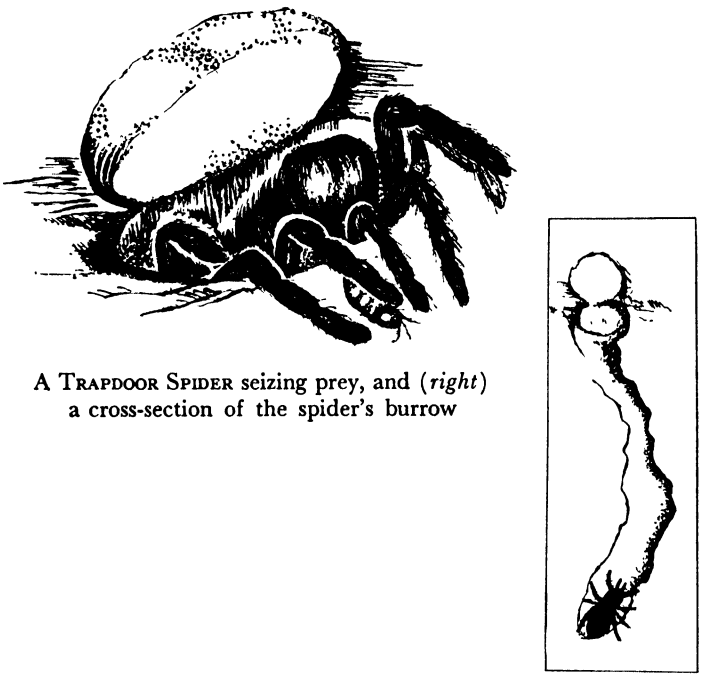
elaborate nests which had series of trapdoors and tubes. The simplest kind of burrow is fashioned by the common trapdoor spider of California, a small, stout, black tarantula with extremely short legs. It is well-equipped to carry out its digging operations: on the front legs are pickaxes which do most of the heavy work; the fangs have tiny rakes attached to them which are efficient tools for moving pebbles and scraping off the rough edges of the handiwork.

Trapdoor spiders exist almost exclusively in the dry western states, although there are a few species found in the moist Southeast. The most common is the California trapdoor spider. She works quickly and expertly, first excavating the outlines of her tube, then carrying the excess dirt away from the burrow. At one place in the tube she widens it to allow room to turn around, but otherwise the width of the tube is just enough to permit her passage. Finally, the burrow is made comfortable—for the spider will spend the rest of her life in it —by smoothing and lining it with copious amounts of silk.

The burrow is not completed until the door has been turned, a precision wafer which fits the tube as a cork in the neck of a wine bottle. It is made of alternate layers of silk and earth, and is so heavy that it falls closed of its own weight. On the underside of the door the spider fashions two grooves into which she can insert her fangs; if an attempt is made to disturb her, she holds the door closed, pressing her body against the sides of the tube for leverage. I have tried to pry nests open with a penknife, and my blade has bent practically to the snapping point before I was able to do so. On the other hand, if she wishes to open it, she can exert strong pressure; I have piled coin upon coin over her door, and still she managed to force it open.

Each evening, after dark, the trapdoor spider opens the door slightly and waits for insect prey to blunder within range. She appears to be well fed, for the desert night, with its high humidity, brings insects from their shelters; inevitably, at least one must pass within range of the spider. She becomes alert at the vibrations of an approaching meal, then springs out to capture it. But she always

leaves one of her legs still inside the tube to prop it open; otherwise the gate may lock on its keeper. The insect is pilloried by the fangs and pulled into the tube; the door bangs shut, throwing darkness on the details of the insect's death.



A TRAPDOOR SPIDER seizing prey, and (*right*) a cross-section of the spider's burrow

Although extremely secretive, trapdoor spiders are common throughout many arid areas; even under the hard, baked sands of Arizona's Sonoran Desert, one species fashions a nest similar to that of the California variety. Perhaps the most unusual burrow of them all is constructed by the folding-door tarantula of the south Atlantic seaboard states. Its door is similar to those on the old-fashioned saloons: two semicircular portals swing on hinges and meet in the middle.

The trapdoor spider artfully uses camouflage: she gathers bits of earth, twigs, and dead leaves and fastens them to the top of her door with silk. The precaution is necessary, for her citadel is protection against every enemy save one, the "tarantula hawk," giant wasp of the genus *Pepsis* who specializes in tarantulas and tarantulas only. Pepsis is the largest of all the wasps, with a three- or four-inch wingspread. Its metallic body, usually of bright blue, shines as it courses over the desert sands in the full light of day, searching for any tarantula foolish enough to be abroad, or seeking out the camouflaged trapdoor.

For the first month or so of her adult life, the female Pepsis flits over the desert blooms and drinks from the sweet galls. But all the time the eggs inside her ovary are developing; as they press against her, a change comes over the wasp. No longer is there time to bask in the sun; work must be done. She flexes her stinger, an immense and glistening weapon which has until now been unused. She is going hunting with a feminine urgency.

The adult wasp lives only on plant juices, but her young are eaters of fresh meat. Each species of Pepsis must search out a particular species of tarantula, one in which her ancestors were specialists, and upon which she fed as a larva in the darkness of her burrow. It is not known how Pepsis chooses exactly the right species of tarantula, for she came into the world an orphan, and never gained instruction in the different kinds of tarantulas; but she never makes a mistake. Perhaps there is some chemical response when the correct species is found (Pepsis does inspect the prospect carefully with her twitching antennae), but there is as yet no evidence for it. Or perhaps she carries in her memory the flavor of her own first meal.

Eventually Pepsis finds a tarantula, either by catching one out of its burrow or by digging her way through the burrow entrance. She inspects the prey closely, tapping it with her antennae, deliberately and calmly circling it. Then Pepsis unflinchingly walks under the tarantula's fangs for an examination of its underparts. All this time

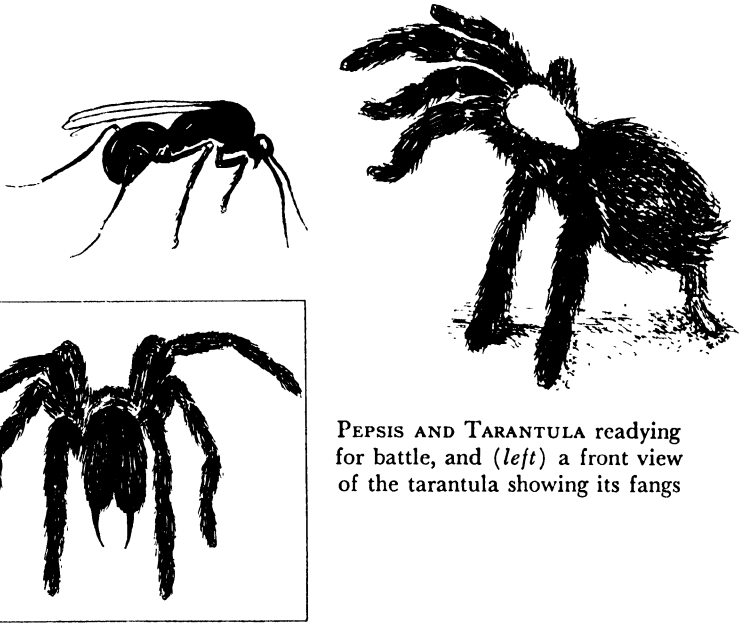
the tarantula remains meek; its fangs far outweigh the wasp's stinger, yet, for some unknown reason, they are never raised.

If the wasp is satisfied that the tarantula is of the correct species, and will make a meal for her young, she steps back a few inches and digs a grave. The tarantula makes no effort to escape and even appears to be interested in its own interment. Occasionally the wasp pops out of the grave, as if again to take the measurements of the tarantula.

Finally, with the grave eight inches or so down, and of the correct dimensions, Pepsis is ready to proceed with the burial. But first she must immobilize the tarantula. Immobilize, not kill—for dead prey would spoil before the eggs hatched, and she wishes her young to have a fresh meal. How does she do it? In the tarantula, there is an articulation membrane between the first leg, maxillae of the mouthparts and the sternum. It is an inconspicuous part of the tarantula's anatomy, and one that even graduate students in invertebrate morphology might never know existed. But Pepsis is a surgeon who knows the body on the operating table well. This is the spot where she will insert her poisoned stinger; it is the gateway to the nervous system of the tarantula. But to reach this chink in the tarantula's armor, Pepsis must walk under the fangs.

Few biologists have witnessed the final battle between Pepsis and tarantula, but one of those who have is Dr. Alexander Petrunkevitch of Yale. According to his observations, Pepsis walks directly toward the tarantula, the enormous sting extended, perhaps in her excitement a drop of venom protruding from the tip. Now, at last, the tarantula realizes her predicament. She shies away, but the wasp continues to bore in. Finally the wasp lunges and they lock their legs, rolling over and over on the ground, Pepsis' stinger searching for the vulnerable spot.

The battle may continue for minutes, or it may be over at once. No matter its duration, the wasp is always the victor. She finally finds the chink and inserts her dagger, pumping in the venom. The tarantula is slowed down, but not completely paralyzed; it raises its



PEPSIS AND TARANTULA readying for battle, and (*left*) a front view of the tarantula showing its fangs

fangs and waits for Pepsis to approach once more. Again she does so, head-on, right under the fangs. She again inserts her stinger, and battle drains out of the tarantula.

All that remains is to drag the body to its grave and toss it in. Pepsis lays an egg on the tarantula's abdomen and seals the burrow; she has left her larva with a single meal that shall provide it with all its food needs. The tarantula lies in its tomb, still alive and occasionally twitching, but unable to move. When the egg hatches, the growing larva eats daintily and avoids any essential organs, for the tarantula must not die until the meal is completed.

Does the tarantula feel pain? Or is the anaesthetic so effective that it looks on only as a bystander, feeling nothing? Some would like to believe the latter, but it probably is not true. For there are other hunting wasps besides Pepsis which have been more closely studied. Their burial grounds have been opened by entomologists and the

plunder withdrawn; in many cases, the prey showed consciousness and reacted to stimuli. The tarantula no doubt also survives until the final moment.

Finally, the larva has digested all of the meat and there remain only the tarantula's essential organs. The grub, now grown to enormous size, closes its jaws on a vital spot, and death finally comes to the tarantula. The larva is surfeited and innocently goes to sleep. It will emerge from the pupal stage as an adult huntress, ready to continue its species' cycle of life.

Why did not the tarantula dispatch the wasp at the outset, as it might easily have done? Why did it not attempt escape? Why did it resist so futilely, as if in the knowledge that its final act had already been written? There are no certain answers to these questions.

But in the death of the tarantula there is a symbol of soil life. For in the soil are working many mechanisms, paradoxes, mysteries which cannot be explained. As the shifting particles of soil disclose new truths to the scientists, with every truth there emerges, also, the question—why?

V.

MUTUAL SURVIVAL

9. *Living Together and Living Apart*

IN THE SOIL, no life is sufficient to itself. Many varied patterns are woven by the inhabitants, the threads of their brief existences crossing and recrossing to make up the fabric of soil life.

What interrelationship could be more complex than that of Clostridium wedded to two bacterial partners which remove the oxygen from its tiny atmosphere, leaving it only the nitrogen it needs? Or the protozoa which have been sheltered for millions of years inside the stomachs of termites, each partner doing for the other something it cannot achieve alone?

In observing life underfoot, we cannot fail to note the endless variety of partnerships that have been entered into. Many of the plants and animals have joined their resources and created completely new entities. There are the tree roots that have allied themselves with mycorrhizal fungi, and legume roots that work in partnership with bacteria to obtain nitrogen from the atmosphere. Other kinds of fungi are cultivated by termites and ants. The lichens demonstrate how an alga and a fungus can combine so that they may colonize a new habitat, bare rock.

It was while studying lichens about eighty years ago that Anton de Bary, a distinguished botanist, coined a new word for these partnerships—*symbiosis,* which means "living together." But de Bary chose a difficult time for putting forth symbiosis as a fact of life: his theories were swamped by the enthusiasm of the Darwinian revolution. "Survival of the fittest" and "the war of nature" ruled much of the biological thinking of that period. In the hands of popular writers, the living world was characterized as a place where the ob-

ject of every creature appeared to be to eat, parasitize, suck dry, squirt poisons on, capture, and otherwise put an end to other forms of life. Ignored were the cooperative patterns of living things—the organization of the body itself, its stability and harmony of different parts. Unanswered was the question: if a war of nature has existed, how did the parts of the body organize themselves in the first place?

In the soil, however, and probably also in the other great environments for life on the planet, it is not so important who eats whom—but rather who lives with whom. If there is any secret to survival on the part of the beings underfoot, it may lie in mutual cooperation rather than destruction of other organisms.

A close look at the two environments often characterized as the heights of injustice between living things—the dark jungle and the dry desert—suggests that the concept of relentless competition has been overemphasized. Dr. Frits Went points out that on a visit to a jungle anywhere, two facts are apparent: first, there is a great diversity of vegetation, with hundreds of different kinds of plants all living together; second, there are few forest giants. If the jungle were solely a pit of fierce struggle for existence, then opposite conditions would prevail: there would remain only the few successful species in the war of nature, and these would have grown to tremendous heights.

In the steamy tropical jungle, success is determined by finding a place in the sun, for it is light that is in short supply in the dense forest. Yet, there is only a handful of plants in the jungle which kill off other species to find light, and these are the strangler trees, mostly varieties of fig. Rather, the trees possessing a slower growth rate do not die; their development is merely retarded. Studies made in some of the dense Pacific jungles have revealed trees that have put on little growth in half a century but are very much alive.

Neither in the desert do the strong wage ceaseless war on the weak, but all grow up to the carrying capacity of that kind of soil, usually limited by the amount of water available. If many seeds fall on the

same spot, most of them germinate, sharing the scant water supply equally and growing equally spindly.

Most plants simply are not equipped for warfare. Whatever struggle is practiced in the jungles and deserts takes place before germination and can best be described as birth control. The shade of an established jungle tree often prevents germination of another tree; many desert plants exude toxins which prevent germination of nearby seeds. But once a seedling survives the infanticide, there is relatively little mortality. Today we are not witnessing many forms of plant life struggling with each other, but rather well-organized botanical communities.

In finding niches to inhabit in the soil, some organisms have chosen to adapt to the non-living world, such as the nitrifying bacteria which have hitched their economy to the presence of ammonia. Others have become specialists in using decaying organic matter. These forms have carved out biological bailiwicks that are their very own, and have little concern about trespassers. But most organisms have met their world head on—either by living off some other organism, or by joining with another organism in symbiosis to produce a unique relationship which is greater than either acting separately.

Many have chosen the first course, parasitism, which was defined by Jonathan Swift this way:

> So, Nat'ralists observe, a Flea
> Hath smaller Fleas that on him prey.
> And those have smaller Fleas to bite 'em
> And so proceed, *ad infinitum.*

In parasitism, one partner is always the gainer and the other the loser. True symbiosis, on the other hand, divides the benefits between both partners. But between the extremes of parasitism and symbiosis are many shades, and the dividing line is not often clear.

An example is the strange life of the Honey Agaric, *Armillaria,* a common toadstool whose fungus strands are a parasite of many trees.

It had been widely studied in Europe for many years; then a Japanese botanist named Kusano made still another discovery about it. In Japan, it enters into a symbiotic relationship with an unusual sort of orchid, *Gastrodia elata*. This orchid develops a very large underground tuber which much resembles a potato, but it is completely rootless. It remains in the soil, a bundle of amassed food reserves, until suddenly and unpredictably it blossoms into a flower on a stem three feet high.

What makes it send up shoots is invasion by the Honey Agaric. That way, it makes contact with the soil, receiving its food through the fungus strands. The fungus is apparently repaid for its trouble by gaining a small amount of nutriment from the tuber. It is a bewildering arrangement, for no one can explain why the fungus fails to digest the orchid's entire food hoard, killing it as it does most other plants it attacks. Instead, it parasitizes Gastrodia only to the extent that it brings in food, then it ceases its attack.

Even the pinpoints of microbes have found ways of joining together for mutual benefit. For example, there are two soil fungi, both of which require Vitamin B_1 to live. This vitamin has two halves—and one of the fungi needs only the thiazole part, while the other fungus requires only the pyrimidine portion. Each fungus is able to manufacture the lacking half on its own. By entering into a partnership, these two fungi have been able to satisfy all of their vitamin needs—even while growing in the complete absence of Vitamin B_1. The way they do it is that each fungus furnishes to the other one the half of the vitamin molecule that it lacks.

The living together of diverse organisms is still a complex problem in biology and many of the mechanics of it are obscure. Yet, possibly, symbiosis has played a more important role in the origin of species than it is generally credited with. About 30 years ago, Dr. Ivan E. Wallin, professor of anatomy at the University of Colorado School of Medicine, put forth that thought in his book *Symbionticism and the Origin of the Species*. Briefly, he stated that it is symbiosis which has insured the creation of some new species of life on the globe.

Although this theory never gained acceptance by his fellow scientists, it does come from a reputable source. It may indicate that there is more to living together than is at first apparent.

In the cells of almost all plants and animals are minute and strange bodies known as mitochondria; it is believed that they supply energy and serve as the powerhouse of the cell. Some cells may possess as many as a thousand of them. Dr. Wallin supposed that the mitochondria are the remnants of bacteria once united symbiotically to the cells.

He then took a broad look at the living world and found symbiosis nearly everywhere. His examples covered many pages and included bacteria, algae, protozoa, the sponges, worms, the coelenterates, insects, and so forth. (In addition, many new symbionts have been discovered in the past thirty years.)

If symbiosis has always been as widespread as it appears to be today, some of the forms of life on the planet may well have started out as two separate entities which joined together. They may now have progressed beyond the stage where the individual partners can any longer be identified. For example, biologists can still demonstrate that a lichen is made up of a fungus and an alga. But in a million years or so will they still be able to divide a lichen into its separate parts? Or will the origins of the partnership have been lost beyond identity? The latter is very possible. What may happen someday in the future might well have occurred in the past. In short, some forms of life might not have come into being as single organisms, developing under the constant tests of natural selection. Rather, they may have originated in the union of two organisms which found that they could survive very well by living together.

Dr. Wallin does not suggest that every example of symbiosis results in a new species, or that it played any part in the origin of the first life on the planet. He does state that it is of primary importance in the origin of *new* species. Dr. Wallin cannot garner enough evidence to make a totally convincing case, but neither is there enough evidence to totally refute him. The truth, whatever it is, is buried in

the mysteries of time, and an answer may not be forthcoming for incalculable ages.

Antibiosis—or Living Apart

Antibiotics are chemical poisons produced by many soil microbes. In the excitement over their discovery, it appeared that here was chemical warfare among living things at the lowest possible level, the microbes. The vision of specks of cells destroying each other by squirting out penicillin entered the popular mind and has persisted. There is no evidence that antibiotics do any such thing in altering the populations of soil microbes.

The study of antibiotics is due in large part to the career of the Nobel Prize-winner, Dr. Selman A. Waksman of Rutgers University. Beginning in the early 1900's, he poked in the soils and compost piles of New Jersey, studying the antagonistic relations of microbes. With precise research, Dr. Waksman solved many of the basic biological problems involved in microbial antagonism—and his discoveries, undramatic as they were at first, laid the scientific foundation for a study of antibiotic substances.

Dr. Waksman was particularly intrigued by a little-known group of soil organisms called the *Actinomycetes*. In size and numbers they resemble the bacteria, yet their methods of growth and reproduction appear to be that of the fungi. They are strange organisms, occurring in numbers as high as a few million in a teaspoonful of soil. In fact, the smell of the good earth when the plow has turned it over is merely the odor of Actinomycetes.

In this group of borderline bacteria-fungi, Dr. Waksman searched for his antibiotics. He had reasoned that they must be there, and now necessary was the drudgery of isolating them. Thousands of soil samples were collected, of which but one might yield a potential antibiotic. This one then had to be cultured and tested, perhaps finally rejected, and the search would begin again. It was painstaking work indeed, but in 1943 Dr. Waksman isolated from a pinch of soil

an organism known as *Streptomyces griseus*. It produced the well-known antibiotic streptomycin.

Since then the pace of antibiotic research has increased. In 1949, terramycin was found in a bit of earth from the grounds surrounding a drug company's laboratories. Many of the Actinomycetes are now known to produce antibiotics, and a description of the fungi doing so runs to well over seventy pages of small print.

Most antibiotics are *not* produced naturally in the soil, and in the cases of the few that are, the amounts produced are so small that little lasting effect is observed. There is no evidence that the production of antibiotics has anything to do with competition among organisms for living space or food. For example, the fungus *Penicillium* produces large amounts of the antibiotic penicillin when it is cultured artificially in the laboratory. But the production of penicillin has not given this fungus any preferred place in the soil; there are groups of other fungi, which do not produce an antibiotic, found much more abundantly in the soil than Penicillium.

What, then, is the function of antibiotics for the microbes that produce them? The fact is that no purpose can be found. The organisms capable of producing antibiotics are very widespread in nature, but the antibiotic substances themselves are rarely produced outside of the laboratory. The situation is similar to that of agriculture, where a plant or animal is bred to strengthen an innate capacity, thus giving a useful variety. "I am merely domesticating a new form of wildlife," states Dr. Waksman. All that is known presently is that antibiotics exist—and the mystery of their importance may never be completely revealed.

10. This Enduring Earth

THE SOIL is the seat of abundance on earth, a massive machinery for keeping the chemical stuff of the planet in constant circulation. There can be no life without soil, and no soil without life—they are inseparable. Every complex thing that lives and then dies returns to the soil where it is reduced to the simplest common denominators.

All living things are whirled about on a wheel which, from age, brings forth youth once more. For the birth of an elephant, a mastodon may have died; for an oriole to take wing, a pterodactyl may have been brought to earth. The planet was created with a fixed amount of raw materials and there are no more: through the ages of geologic change, through the succession of plants and animals that have staggered up the tree of evolution, the raw stuff of this planet has remained very nearly the same. "All destructions ordered by God are mere quarryings of His building materials," wrote a French abbot.

The wholeness of what we call life is like a delicate fabric with many simple threads. The wonder is not that so many threads are necessary in the fabric, but rather that the fabric manages to exist at all. The economy of the planet is founded upon plant life, and plants can absorb only the most chemically pure and simple food substances. Each of the threads weaves a vital pattern in serving up the food in a form in which it can be used. Some organisms tear down the abode of life, others rebuild it in more modern architecture.

Corruption is the mother of vegetation—that is the cycle of life in the soil. The soul, possibly, enters a new life; the body most em-

phatically does. We each have in us something of the dinosaur, the beasts of the field, and perhaps a molecule from the viper that our grandfather crushed under his boot. The beings that dwell in darkness under the soil are the great equalizers of life. The tree and its fungus-root, a bacterium and its devourer, a corn plant and its witchweed parasite, all go into the melting pot together and arise triumphant, a living thing.

"A man may fish with the worm that hath eat of a king, and eat of the fish that hath fed of that worm," said Hamlet, in his wonder at the cycles of life. A single atom of the earth's substance passes through a fantastic variety of shapes and through the systems of many forms of life. Carbon, hydrogen, nitrogen, oxygen, sulfur, phosphorus, calcium—these and many others are in constant circulation throughout the planet. Some of the cycles are short and unvarying; others are intricate—all are vital.

The carbon cycle is of the utmost importance because all of the carbon contained in the atmosphere, if not replenished by the cycle of matter, would be utterly exhausted in about fifteen years. A single large tree locks up in its massive structure the equivalent of carbon found in the total atmosphere over as much as twenty acres of the earth's surface. Were this carbon not returned to the soil—as it is year after year in the steady rain of leaves and twigs and eventually dead trunks themselves—a forest might exhaust much of the earth's supply of carbon.

The nitrogen cycle is the most essential for life on the planet. It presses into service representatives from nearly every family of living things, sharply diverse in their food requirements and living conditions, yet each a measured link in a great chain.

Nitrogen is brought to earth primarily by the nodule bacteria on legume roots. It is now in the soil, in the form of nitrates which a plant absorbs into its chemical works and converts into proteins. The plant tissue may then be eaten by a land animal, and the atom of nitrogen embarks on an immense journey through the complicated food chains of the aerial world, lodging in the tissues of many differ-

ent kinds of animals and birds. At some link in the chain, it is shed in the form of droppings and returns to the soil.

The soil microbes attack it. The atom of nitrogen is removed from its compound and once again reduced to a simple nitrate in the soil, available for another generation of plants. In this process of denitrification, some nitrogen may once more be lost into the atmosphere, set free by certain soil bacteria. Perhaps in a million years or so, that nitrogen atom might return again to the soil through the action of the legume bacteria. So the cycle of life spins on.

A small-scale version of what happens each year in returning life to the soil may be witnessed in any compost pile. Each step in the decomposition of the compost is unique and there is no repetition: the organisms cross the stage in predetermined order and do not reappear for encores. First come the pioneering sugar fungi, then cellulose- and lignin-destroyers. The next stage, which may be one of bacterial decay, cannot be seen with the naked eye, but it is indicated as the heap shrinks in size and its temperature rises, due to the intense metabolism of the soil microbes. Once the tough cellulose material has been digested by the fungi and bacteria, the heap is sufficiently broken down to be consumed by insects. Finally, the remains are worked into the soil by the burrowing animals and earthworms.

What remains after the soil creatures have done their work is humus, a substance which no one knows very much about, in spite of the fact that man has revered it since early Classical times for the fertility it seems to bestow. Humus itself does not feed anything in the soil; it is in reality the end product of all the forces of the soil life acting upon organic matter and leaving their imprint. It is a biological dead end, but the *process* of humus formation is what releases energy, minerals, and carbon dioxide for plant growth.

In an undisturbed soil the humus remains unvarying both in its structure and the amount present. But is not more humus being produced all the time? It is, but as new humus is added to the soil surface the older humus is oxidized into nothing but air and a few

pinches of salt. There is a time in the growth of soils when they become mature, their outgo of humus balanced by the income. When this happens, the soil has become like a fortress against any sudden change. Its humus maintains the particular plants which created that kind of soil in the first place. It perpetuates its own kind and, barring catastrophe, a mature natural soil remains very much the same in the kind of life it supports.

Thus the particles of soil, which began perhaps on a mountainside, have matured. The soil lies fertile in the valleys, secure in its well-defined profile, insulating the harbored life against change. Like a mold it lies, into which new grains pour every day and old grains are carried seaward; unchanging until another great upheaval in the earth buries it under seas or exalts it into mountains; the entire cycle to be endlessly repeated, like mimeographing a page from geologic time.

Appendix: Readings

General Information About Soils

The World of the Soil. E. John Russell. Collins, London, 1957

Soil Conditions and Plant Growth. E. John Russell. Longmans Green, London, 1950

These two books must be the cornerstone of any reading program about soils. Sir John Russell began his pioneering studies of soil around 1900, and for thirty years was director of Britain's Rothamsted Station, most famous of the world's centers for the study of soil. *World,* although supposed to be a popular book, is hardly easier reading than the classic *Soil Conditions,* and it is suggested that the reader plunge into the earlier volume for its riches of agricultural and soil knowledge.

Soils and Men, the Yearbook of Agriculture, 1938. United States Government Printing Office, Washington

A monumental survey of information about soils, but containing many inaccuracies and out-of-date information. However, it is still one of the best volumes for a general introduction to soils.

Soil. G. V. Jacks. Nelson, London, 1954

A short and excellent introduction to soils by the director of Britain's Commonwealth Bureau of Soil Science.

Forest Soils. H. J. Lutz and R. F. Chandler. John Wiley & Sons, New York, 1946

A painstaking text for advanced students, it contains by far the best bibliography available on all phases of soil.

Geological Background

Down to Earth. C. Croneis and W. C. Krumbein. University of Chicago Press, Chicago, 1955

Authoritative, and delightful reading.

The Earth as a Planet. Edited by G. P. Kuiper. University of Chicago Press, Chicago, 1954

Much of the recent research in geology is available only in this book, in the form of contributions from many of the world's specialists. It is highly scientific, but can be chewed on, if not digested, by the reader who has read *Down to Earth* previously.

General Soil Biology

Soil Zoology. Edited by D. K. McE. Kevan. Butterworths, London, 1955

The only general work available on all phases of soil animals. The volume consists of the proceedings of a symposium attended by leading experts in soil biology.

Animal Life in Deserts. P. A. Buxton. Arnold Co., London, 1923

The pioneering work in the field which, although primarily concerned with the Palestinian deserts, is still widely valuable.

General Soil Microbiology

My Life with the Microbes. Selman A. Waksman. Simon & Schuster, New York, 1954

The autobiography of the Nobel Prize winner which documents the thesis that our culture should allow poor immigrants like Dr. Waksman to putter around in the soil.

Soil Microbiology. Selman A. Waksman. John Wiley & Sons, New York, 1952

Technical, but not too difficult for the lay reader. In fact, Dr. Waksman explains as simply as possible the intricate lives of the soil microbes.

The Microbial World. R. Y. Stanier and others. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1957

The best of the newer books about microbes.

Principles of Insect Pathology. E. A. Steinhaus. McGraw-Hill, New York, 1949

A textbook that can be savored by any serious reader and that gives valuable insight into the intricate relationships between insects and microbes.

Social Insects

American Social Insects. C. D. and M. H. Michener. Van Nostrand, New York, 1951
The most sparkling and reliable commentary on insects possessing the social habit.

Ant Communities. Henry C. McCook. Harper & Bros., New York, 1909
Written by a pioneer student of ants, this book provides fascinating reading even though it is out of date in several respects.

The Ant World. D. K. Morley. Penguin Books, Baltimore, 1953
The best of the recent popular books, by a British authority.

Our Enemy the Termite. Thomas Snyder. Comstock, Ithaca, 1948
Dr. Snyder was for many years head of the United States Department of Agriculture's research program on termites and is this country's leading authority. Most of the facts you will want to know about distribution, castes, life history, identification—even control, if necessary—are in this book.

Dwellers in Darkness. S. H. Skaife. Longmans Green, London, 1955
The life history of a species of termite, by a South African specialist. This book stands as a superlative example of how to record the doings of an insect in a fascinating and accurate way.

Bumblebees and Their Ways. Otto Plath. Macmillan, New York, 1934
Virtually the only book on this subject available for the lay reader.

The Hunting Wasp. John Crompton. Houghton Mifflin, Boston, 1955
An up-to-date interpretation of wasp studies made by Fabre and other naturalists.

Wasps Social and Solitary. G. W. and E. G. Peckham. Houghton Mifflin, Boston, 1905
Wasp studies carried out by two American enthusiasts. A classic in entomology.

Tarantulas, Spiders, and Mites

American Spiders. W. J. Gertsch. Van Nostrand, New York, 1949
An interesting, authoritative book by the specialist at the American Museum of Natural History.

Introduction to Acarology. E. W. Baker and G. W. Wharton. Macmillan, New York, 1952
There is little knowledge about mites, but that little is here authoritatively presented.

Spiders, Scorpions, Centipedes and Mites. J. L. Cloudsley-Thompson. Pergamon Press, New York, 1958
Valuable information about mites and a number of other little-studied forms of life.

Earthworms

The Formation of Vegetable Mould. Charles Darwin. Appleton & Co., New York, 1882
So thorough were many of Darwin's observations that the last seventy-five years have added comparatively little additional knowledge.
New Biology No. 21: Famous Animals: The Earthworm. B. L. Roots. Penguin Books, Baltimore, 1956
A concise summary of much present information.

Nematodes

The Invertebrates (Vol. 3). L. H. Hyman. McGraw-Hill, New York, 1951
Soil & Fresh Water Nematodes. T. Goodey. Methuen, London, 1951
These technical discussions are the only works available about the nematodes.

Burrowing Mammals

American Mammals. W. J. Hamilton, Jr. McGraw-Hill, New York, 1939
The sections on soil mammals are brief, but present a valuable summary of the most important points.

Seeds

Physiology of Seeds. W. Crocker and L. V. Barton. Ronald Press, New York, 1957
All you might want to know about seeds.

Fungi

Molds and Man. Clyde Christensen. University of Minnesota Press, St. Paul, 1951

A delightful introduction to the fungi, including mycorrhizae, predacious fungi, symbiotic relationships.

Mushrooms and Toadstools. John Ramsbottom. Collins, London, 1953
Covers the field, and is magnificently illustrated.

The Friendly Fungi. C. L. Duddington. Faber & Faber, London, 1957
Dr. Duddington is one of the handful of knowledgeable experts on the predacious fungi.

Mycorrhizae

Trees and Toadstools. M. C. Rayner. Rodale Press, Emmaus, Pennsylvania, 1947
The best popular account, written by Britain's expert.

Biology of the Root-Infecting Fungi. S. D. Garrett. Cambridge University Press, Cambridge, England, 1956
Dr. Garrett is one of the world's authorities on soil fungi. Although written for the specialist, it contains much valuable information for the lay reader.

Mycotrophy in Plants. A. P. Kelley. Ronald Press, New York, 1950
The definitive work on the subject; very technical.

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