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I

What Lies Beneath

It's a wonderful place for an orchard, but a terrible place for growing fruit. In central England, far from the buffering effect of the sea, the trees are blighted by late frosts. Freezing air flows like water, but here, on this flat plot, dammed by rows of houses, it gathers and pools, drowning the orchard in cold.

Every year, as the trees come into blossom, my hopes crack open with the breaking buds. Roughly two years out of three, they wither with the flowers. Frost curls into the branches like poison gas, shrivelling and blackening the stamens.

By autumn, the orchard is a living graph of spring temperatures. Apple varieties blossom at different but regular dates. Unless a freeze is especially hard, it damages only the open flower. From the trees with and without fruit, you can tell when the frost struck, almost to the night.

Every variety belongs to the same species: *Malus domestica*, which translates literally as tamed evil. The reasons for the age-old defamation of a lovely tree are complex, but one is likely to be etymological confusion: a dialect name for fruit – *μᾶλον*, or 'malon' – appears to have slipped from Greek into Latin, where it was, so to speak, corrupted: into *malum*, or evil.

This single species, too good to be true, has been bred into thousands of different forms: dessert apples, cooking apples, cider apples, drying apples, in an astonishing range of sizes, shapes, colours, scents and flavours. We grow Miller's Seedling, which ripens in August and must be eaten from the tree, as the slightest jolt in transit bruises its translucent skin. It is sweet and soft, more juice than flesh. By contrast, the Wyken Pippin, hard as wood when picked, is scarcely edible till

January, then stays crisp until the following May. We grow St Edmund's Pippin, which has skin like sandpaper and is dry and nutty and aromatic for two weeks in September, after which it turns to fluff, and the Golden Russet, whose taste and texture are almost identical, but only in February. The Ashmead's Kernel, crunchy, with a hint of carraway, my favourite apple, peaks in midwinter. The Reverend W. Wilks puffs up like wool when you bake it, and tastes like a smooth white wine. The Catshead, roasted at Christmas, is almost indistinguishable from mango purée. Ribston Pippin, Mannington's Pearmain, Kingston Black, Cottenham Seedling, D'Arcy Spice, Belle de Boskoop, Ellis Bitter: these fruit are capsules of time and place, culture and nature.

As every tree requires subtly different conditions to prosper, some do better here than others. Some varieties are so finely adapted to their place of origin that they perform disappointingly on the other side of the same hill. By choosing breeds that blossom at different times, we have sought in this orchard to spread the risk. Even so, in bad years, when frost strikes repeatedly, we lose almost everything.

But yes, despite the many broken dreams, it's a wonderful place for an orchard. When I arrived this morning, its beauty made me gasp. The first apple trees have come into flower: the pink buds uncurling to reveal their pale hearts. The pear and cherry trees are in full sail, carrying so much white blossom that their branches lift slightly in the breeze.

I walk the rows of trees, smelling them. Every variety has a different, faint scent: some of the blooms smell like hyacinth, some like lilac, some like *Daphne* or viburnum. I believe I can tell when a flower has been pollinated: the perfume, no longer needed to attract bees and hoverflies, is immediately cut off. The pear blossom, pure white, with twenty black stamens like tiny cloven hooves, stinks revoltingly of anchovies. The cherry petals are beginning to flake from the trees, drifting and feathering in the light wind. The new grass is streaked with shadow. Wood pigeons growl in the plum trees. To have all this within a few hundred metres of our home feels like an astonishing luxury; a luxury for which, between the five families who share it, we pay just £75 a year.

The orchard occupies three adjoining plots on an allotment site. Since 1878 in England, local governments have allotted land for people to cultivate vegetables and fruit. In principle, since 1908, we have all had the legal right to grow.*

What this legislation inadvertently spread was anarchy, in its true sense. In other words, it created thousands of self-organized, self-governing communities, otherwise known as commons. Though the local government owns the land, it is managed and run by the people who work it. Our site in Oxford is divided into 220 plots, cultivated by people who have arrived in the city from all over the world. We cross-pollinate each other's knowledge with grains of peculiar experience.

Seventeen years ago, the allotments seemed to be dying. Only one-tenth of the plots were occupied. The remnant community was desperate for people to take them on: otherwise, the local authority would reclaim the site for housing. They leased me two and a half adjoining plots, one of which was covered in monstrous brambles, snaking three metres into the air. I spent a month cutting the stems with a bush knife and hacking out the rootballs with a mattock. Beneath them sleeping beauty lay. Meadow grasses, cowslips, oxeye daisy, germander speedwell, vetch, knapweed, wood avens, scabious, yarrow, ribwort plantain, cat's ear and hawkbit sprang from the soil. The seeds must have lain dormant for decades. I persuaded a couple of friends to join me, and we planted the plots with heritage fruit trees: mostly apples, with a few plums, cherries and pears, a medlar and a quince.

Just as the trees became productive, I left Oxford and moved to Wales. Abandoning the orchard was among my few regrets. My friends passed it to others, who in turn passed it on. Five years later, unexpectedly, for family reasons, I returned. I didn't want to be back. But soon after I arrived, one of my best friends in the city told me that some people who had recently moved away had passed him a beautiful orchard, planted on the allotments a few years before . . . He couldn't manage it alone, and remembered that I knew something about fruit trees.

It felt like coming home.

Now, though it covers less than one-tenth of a hectare, the orchard sometimes feels like half my world. It is the living calendar that marks my year. We have brought in three other families, creating a miniature

* In practice, in some cities, the waiting list now stretches to twenty years or more.

commons within a commons. Every couple of months, we organize a work day, with a break for lunch beneath the trees. In late winter and spring, we prune the apples and pears. In May and September, we mow the grass. In June, we thin the fruit. In October, we harvest the apples, store the sound fruit and, if the crop warrants it, spend a frantic day chopping, scratting, pressing, pasteurizing and bottling the rest, turning some into juice and some into cider.*

In midwinter, we wassail the orchard. Wassailing is a scientific procedure deployed to ensure the trees produce a good crop the following season. The methodology consists of singing and drinking cider. According to a well-tested hypothesis, the crop the trees bear is directly proportional to the effort expended: '*For more or lesse fruits they will bring, / As you do give them Wassailing.*'[1] The hypothesis is not upheld.

Then we begin the cycle again.

By mid-morning I'm six feet from the ground, with a bowsaw and long-handled pruning saw. Our lovely allotment neighbour, Stewart, has decided he is too old to manage his fruit trees, so he has passed his row, which abuts our orchard, to us, completing our three plots. His old trees are in a sorry state, the limbs congested and either sweeping the ground or rising so high that the fruit they bear is unharvestable. So I'm standing in the cherry tree, among branches so packed with blossom that you can barely see the bark, committing a desecration.

Whereas apples and pears can be pruned in the winter, stone fruit has to be pruned when the sap is rising in the spring or early summer. Otherwise, you expose the trees to infection by canker, leafcurl or silverleaf. This means you must perform the awful sacrilege of carving

* Counter-intuitively, apple juice is a modern product. Traditionally, the entire pressing was used to make cider (which in Britain means the alcoholic drink), though 'make' misleadingly suggests an active process. Juice starts fermenting immediately. Proper cider contains nothing else. The apples provide the sugars, the flavour and, attached to their skins, the yeast. By Christmas, it's drinkable, though still sweet and fizzy. By February, it has settled into a smooth, subtle, well-balanced brew, in my dispassionate opinion the finest alcoholic drink ever to have ruined human lives. By the end of May it is a little too dry. By July it lives up to the Latin name for apples: you could use it to remove graffiti. To prevent juice from becoming cider, you need to pasteurize it. This requires energy, to bring the liquid to 70°C. Until recently, energy for heating was in short supply. The only juice people drank came straight from the press.

up a tree in flower or fruit. The snowy branches crash to the ground in a blizzard of petals.

Though this violation offends me, I love pruning. It has almost become an end in itself, as much sculpture as management. When you have completed the big, structural cuts, you trim the remaining twigs back to a bud that points in the direction you want the new growth to follow. As the tree spreads, it assumes the shape you have bidden it to take. I favour the Spanish, or goblet, style, moulding the tree into a broad cup. If you get it right, this exposes every leaf to sunlight and the flow of air, eliminating woolly aphids and mildew without the need for chemical controls.

As I move through the tree, I find myself thinking about the likely history of this land. When we turned the soil, we found pieces of the white clay pipes that labourers smoked, some of them patterned with stipples, rings and vines, bearing the mould-lines and fingernail marks of those who made them. We found broken field drains, a donkey shoe and modern oyster shells, which were sometimes hard to distinguish from the fragments of fossil *Gryphaea* we also turned up: a gnarly, hooked Jurassic oyster known in these parts as Devil's Toenails. When the seas were abundant, oysters, even in central England, were the food of the poor. One day, I found half a pearl, bored for the string on which it had hung.

Before it was surrounded by the city, then allotted equally to the townsfolk, this land was farmed, probably – to judge by the combination of field drains and dormant wildflower seeds – in rotation. Some of the surrounding place names contain the suffix -ley or -leys, which often means a temporary pasture, on which hay and forage are grown between arable crops. The oyster shells, concentrated in one part of our orchard, suggest that a tree might have stood there, beneath which the labourers sat to eat their lunch, as we do today. I picture them sprawled in their broad hats, scythes propped against the trunk, between the knuckled roots of a great oak.

We too mow the grass here only with scythes, partly to avoid using fossil fuels, partly to spare the frogs and voles. At first, we hacked at it. The harder we tried, the worse it looked. But one day, I noticed another allotment neighbour, an eighty-year-old Serbian refugee called Angela, watching us incredulously.

Despite all she has witnessed and survived, Angela manages always to find pleasure in life and goodness in people. True to her peasant roots, she presses her surplus vegetables on us, explaining that no one knows what real vegetables are these days, and we won't know how to cook them properly, but that's not her problem, as once she has given up her vegetables they are in the hands of God. We give her apples for roasting, medlars (that are better appreciated in the Balkans than they are here) and plums for brewing.

Eventually, she could bear it no longer.

'No, stop! You do it all wrong!'

She took the scythe from my hands. She felt the weight of it, lifting and lowering it slightly as if communing with the tool.

'I do this from when I little girl. I show you.'

She settled the blade into the sward then appeared simply to twitch her broad hips. The grass fell flat. She trundled up the row without breaking sweat, leaving a perfect lawn, the math laid to one side as if every stalk had been combed into place. (Math means mowing, or the cut grass produced by mowing. The stubble that remains is the aftermath.)

Now I look down from my perch in the cherry tree to the ruined limbs on the ground. I have left just four branches on the tree, more or less at the points of the compass. It looks mutilated. But it will heal. I climb down and start to process the prunings. Nothing here is wasted. We leave the heavy branches at the allotment gate, where people take them for firewood: fruitwood cuts neatly and burns sweetly. I use the sawdust in my smoker: whatever I cook in it takes on the soft dark flavour of the wood. We use some of the slimmer twigs for pea sticks, and stack the rest. After five years, the prunings break down into a rich, dry compost. We spread it around the dripline of the trees.* One spring a family of hedgehogs emerged from our stick pile. The babies were curious and unafraid. One of them waddled up to me, sniffed my outstretched hand, then tried to bite it.

* The dripline is the ring of ground beneath the outermost extent of a tree's branches. Because the tree acts as an umbrella, much of the water that lands on it drips to the ground along this line. As a result, the tree's feeder roots are concentrated here. If, as some people do, you stack the compost around the trunk, instead of feeding the tree, you are likely only to rot it.

Trying to grow fruit, or vegetables, as I did in prodigious quantities when I lived in Wales, reminds me every day of the constraints of biology and climate, and of the way these constraints have begun to flicker. While I have noticed no consistent change in the frosts that strike the orchard, which are all noise and no signal, other patterns have become impossible to ignore, especially the extremes of drought and rainfall that now afflict our fruit trees, the rest of the nation and much of the world. Working this tiny patch of land has helped alert me to the scale of the predicament we face, as the conditions that enable us to grow sufficient food begin to shift.

I finish stacking the pile and put my saws and loppers and helmet away. Then I take from the shed a different set of tools, to do something I can scarcely believe I have never done before. I have explored woodlands and rainforests, savannahs and grasslands, rivers, ponds and marshes, tundra and mountaintops, coastlines and shallow seas. But I have never explored, deliberately and thoroughly, the ground beneath my feet.

There are times when I struggle to understand myself, and this is one of them. Why, when I have spent over half a century immersed in the living world, seizing – or so I believed – every opportunity to discover wildlife and understand the ecologies that surround me, have I failed to explore the ecosystem that underlies so many others? Why, when I have spent thirty years growing food, have I neglected the substrate that provides, directly or indirectly, roughly 99 per cent of the calories we consume?[2]

Like many people, I like to imagine that I find my own path. But we are all influenced, to a greater extent than we are usually prepared to admit, by social consensus. We think along the lines laid down by others, follow paths already trodden. We see what others see, and ignore what they ignore. We might argue passionately about the small number of issues on which the spotlight falls, but, implicitly and unconsciously, we agree to overlook other topics, often of greater importance. Few are either as important or as dark to us as soil.

A few metres from the cherry tree, I push my spade into the sward. I keep my tools sharp so, though the soil is heavy and rooty, the sod slices cleanly. I cut a small square of turf and lift out half a spit,* about a kilogramme of soil. Then I settle onto my stomach in the grass and start working through it.

England is, or so I believed until I began researching this book, a dispiriting place to be a naturalist. Its visible wildlife, while once much richer than it is today, was never as varied as the wildlife in other parts of the world, especially the tropics. Now it is a threadbare remnant. This country has lost all its large land predators and most of its large herbivores. Our food webs are ragged and windowed, missing many of their strands. Uncultivated land is scarce, and even this is often mismanaged and polluted. In large parts of the country there is not much to see. Or so I thought.

I now realize that I was looking in the wrong place. While life above ground here is suppressed and depleted, below the surface lies one of the richest ecosystems on Earth. Soil at these latitudes is more diverse than the soil almost anywhere else. One scientific paper suggests there may be an inverse relationship between the diversity of plant life above ground and animal life below.[3]† The soil beneath a square metre of the orchard may contain many hundreds of thousands of animals, ranging across thousands of species. It took me a while to absorb that. Several thousand species beneath one square metre.

English soils could be as diverse as the Amazon rainforest,‡ and as little studied. Scientists estimate that only 10 per cent of small soil animals have so far been identified.[4] In this orchard, there are probably thousands of undiscovered species. Many are likely to be unique to their regions: there are scarcely any microarthropods (small scuttling creatures) common to soil communities in different parts of the world.[5] We know even less about their relationships. For example, ecologists puzzle over something they call the Enigma of the Oribatids.[6] It might

* A spit is the length of a spade's blade.

† If this is correct, one likely explanation is that in the tropics, high temperatures and high rainfall lead to higher levels of inorganic nitrogen in the soil and higher acidity, both of which may suppress the number and range of microbes on which many soil animals feed. This does not mean that reducing biodiversity above ground enhances biodiversity below ground – far from it.

‡ Not counting the Amazon's own soils.

not sound as romantic as the Riddle of the Sphinx, but I find it as fascinating. Oribatids are one sub-group of a sub-group of the mites, which are in turn a sub-group of the Arachnids, the class that includes spiders. They are tiny and crablike and at first sight unremarkable. But in one handful of soil there might be a hundred oribatid species, all, apparently, occupying the same niche. Ecologists are accustomed to single species in single niches, as one outcompetes the others to become dominant. But here an astonishing number of related animals, in a wide range of shapes and sizes and colours, live alongside each other, apparently doing the same thing. How can this be?

Leonardo da Vinci remarked that we know more about the movement of the celestial bodies than about the soil on our own planet. This remains true today.

The first things I see are a fragment of bone, a bleached snail shell, a withered plum stone and a fragment of blue ceramic. Then I look more closely and notice a woodlouse and a little transparent millipede, its legs curling and uncurling in waves along its body, red dots along its sides like shields on a Viking longship. A chestnut centipede rushes past, carriage by carriage, into a dark siding. There are caramel beetle larvae and clusters of translucent globes, containing the faint white crescents of snail embryos. The labyrinthine stalks of seedlings work through the soil matrix, trying to find the light.

I crumble a pinch of soil into a fine sieve, then place it, in full light, over a funnel that leads into a test tube filled with gin. I prop up the test-tube rack with sticks, to prevent it from falling over, and leave it to cook in the sun.

Then I break off a lump of soil, take out my 40× magnifying loupe, and find the focal length. As soon as I do so, the earth bursts into life. The first thing I see is a springtail: a soft olive creature, rounded and slightly furry like a knitted toy, fleeing from the light. Now I've seen one, I see them everywhere: there are little grey ones less than a millimetre long; tiny white ones; a three-millimetre giant in iridescent grey and pink and blue; a humpbacked, amber species like a tiny drop of honey.

Springtails look a bit like insects, but they occupy a class of their own. Their abundance is astonishing: sometimes 100,000 or more beneath a square metre of ground. They can be male, female, hermaphodite (a bit of both) or parthenogenic, which means they can reproduce through immaculate conception. They live almost everywhere, even the Antarctic, and have survived every extinction event of the past 400 million years. In many parts of the world, they knit together the entire soil food web: in other words, they are the channel that connects much of life on land. But most people are unaware of their existence.

As I follow the springtails, a monstrous beast fills the lens. I start back. It takes me a moment to realize it's an ant. When I look around, I see I'm on the edge of the myrmecosphere, which means the soil zone influenced by ants. Close to my shoulder is one of the hummocks, about 40 centimetres high, that the yellow meadow ants started building almost as soon as I had cleared the brambles.

These anthills are like concrete. When I'm mattocking out plum suckers or resurgent brambles, I know when I've hit the edge of one, as the tool stops dead, jarring my hands. The ants bring clay from the subsoil and mix it with their saliva, making a cement strong enough to support their galleried and storied domes, the equivalent, if scaled to human inhabitants, of 100-metre towers. Into their cellars, which can extend a metre underground,[7] they carry aphids, which feed on the trailing roots of plants, and produce the honeydew on which the ants subsist.

They are ecosystem engineers, influencing all the life within their zone. In the orchard, I've noticed that germander speedwell, a little blue flower, selectively colonizes the roofs of the anthills, while the grass growing around them is thicker and darker than the grass elsewhere. The ants concentrate nutrients in and around their skyscrapers, inadvertently feeding the creatures that have adapted to live alongside them. The south-east face of every anthill is flat, and angled like a solar panel to absorb heat in the mornings.

Soon after spotting the ant, I find a white crustacean, just a millimetre long. When I look it up, I discover that it's an ant woodlouse. Unlike its relatives, it can live among these fierce creatures without being torn apart and eaten. Still more impressively, it persuades them to feed it, stroking them with its antennae and begging until they regurgitate the pellets of food they usually share among themselves.[8] Yellow ants are almost blind, and the woodlouse appears to fool them by masking itself with their scent. Its smell and the caresses of its antennae convince them that it's a hungry member of the sorority. If, however, the disguise is rumbled, and the ants attack, it lifts the two horns on its bottom and squirts glue into their faces, jamming their jaws.

I expose a long pale centipede, terrifying under magnification, like a medieval Great Worm. It snaps its fangs,* through which venom flows, then slithers away with a horrid combination of sinuosity and scuttling. By comparison, a docile, flat-bodied millipede, pinkish brown, armoured with wide, overlapping mail, guarding her clutch of eggs, is as comfortably rustic as a farmyard hen. Little white potworms squirm out of the light.

Mites are everywhere, round and crabby. In soils like this, they are even more numerous than springtails: in some places, there are an astonishing half million per square metre.[9] Some, like hermit crabs, have tiny feet that barely emerge from their carapaces, others, long groping forelegs. They are brown, pink, mauve, yellow, orange or white. In the soil, there seems to be a white version of everything. The white animals generally live at greater depths, where everything is blind (barring a crude ability to distinguish light from darkness), so there is no need for disguise. All that an animal creates incurs a cost in energy and resources, including colour and eyes. If they can do without, natural selection ensures that they will.

I take the test tube from its rack and hold it against a sheet of black paper. With my lens, I can just detect tiny white filaments: nematode worms, driven from the soil by the light and heat of the sun, down the funnel and into the gin. These too are fantastically abundant, and critical to soil food webs. When conditions are right, they can multiply twelvefold in one day.[10]

I feel huge and violent and slow as I break into the soil's hidden chambers. All of its animals hate the light, and they move with surprising speed when it falls on them. Otherwise, in this voracious jungle, they would be immediately snapped up. I see the carnage that soil predators have left: the hollow scutes of millipedes, the wing shields of beetles, empty snail shells, the armour scattered after battle.

Then I notice something that looks like a creature from a Japanese anime: long and low, white, with two fine antennae at the front and

* Technically these are modified forelegs, called forcipules.

two at the back, poised and sprung like a virile dragon or a flying horse. I half-expect to find a miniature Studio Ghibli heroine riding on its back: by now, nothing would surprise me. It has six legs, but it isn't a springtail, and resembles no insect I've ever seen. When I look it up, I discover that it's a bristletail, or dipluran. It belongs to an entire class of life – a group with the same rank as insects or mammals – of which I knew nothing.* How could it be, after a lifetime immersed in natural history and a degree in zoology, that I have never heard of such a thing? But this is not the most spectacular exposure of my ignorance.

Soon afterwards, I spot an animal that at first I take for a tiny white centipede. Now that I'm looking, I see loads of them. When I peer at one closely through the lens, I notice that instead of the fifteen pairs of legs or more a centipede possesses, it has twelve, and rather than an armoured head bearing wicked curved jaws, it has the soft round face of a herbivore or detritus eater. Leafing through a textbook on soil ecology, I find a photo, and the answer astonishes me. It's a creature called a symphylid, a member not just of a class I had never encountered before, but, according to some authorities, an entire phylum.†

A phylum is a big deal. Human beings belong to the family Hominidae, the great apes. This family, in turn, is part of the Primate order: apes, monkeys, lorises, tarsiers, bushbabies and lemurs. This order is a subset of the class we call Mammals, encompassing everything from shrews to whales. The mammals are one component of the phylum Chordata, which brings us together with birds, reptiles, amphibians, fish, lancelets and sea squirts. Now I find myself looking (some sources say) at a phylum, a grouping comparable to the Chordata, and probably much more numerous, which until today had been unknown to me.

I'm struck by an astonishing thought. I can see, in this half-spit of soil, more of the major branches of life than I've seen in the Serengeti, or in any other ecosystem. Here are insects and crustaceans, mites and spiders, chilopods (centipedes) and diplopods (millipedes), springtails

* The taxonomy of soil animals keeps changing, so by the time this book is published, it might be out of date. At various points over the past few years, diplurans have been treated as a class, a sub-class and an order.

† Again, this position keeps shifting. Sometimes the symphylids are considered a class, sometimes a phylum.

and earthworms, nematodes, molluscs and creatures I never knew existed.

The soil can support such abundance because of its gigantic surface area. In the extreme case – the finest clays – a single gram (half a teaspoon when dry), would, if all its surfaces were laid out flat, cover 800 square metres, an area slightly larger than our orchard. Just as importantly, far from being the undifferentiated mass I once perceived, soil is a cosmopolitan city of zones and structures, in which distinct cultures inhabit adjacent parishes. One of these zones is the myrmecosphere, the ant borough, itself divided into subordinate precincts. But even more ecologically important are the narrow wards surrounding the roots of plants, known as the rhizosphere. It is upon this zone that humanity depends. As I pull the clod apart, the roots are so dense that it feels like fabric tearing.

I turn my attention to a tiny root hair. To the naked eye, it's a single strand, as thin as cotton thread. But under the lens, I see it is caged and frosted by much finer hairs, glittering like crystals in the sunlight. Every rootlet has them, even around the growing tips, which at this time of year cannot be more than a day or two old. Some look like whiskers, some are woven so tightly that they remind me of frayed nylon mesh around an ironing cable. They are filaments – hyphae – of the fungi whose lives are knitted into the lives of plants.

These are not, in most cases, fungi whose fruits we will see, though mushrooms and toadstools also form relationships with plants. The great majority – perhaps millions of species – live only within the soil, and many of them lace through and proliferate from the plant roots on which they depend. Most plants rely on these fungi to gather minerals and moisture from the soil.[11] The plant feeds the fungi with carbohydrates and lipids* that it makes through photosynthesis; the fungi feed the plant with nitrogen, phosphorus and other elements they scour from the ground and transport with far greater efficiency than plants can manage. Their tiny filaments creep into pores and

* The chemicals that are the building blocks of fats and many other crucial compounds.

crevices too tight for even the finest root hairs to explore, and the enzymes and acids they release break mineral bonds that plants cannot split.

This mutually beneficial, symbiotic relationship is as old as the first land plants, some 460 million years.[12] When algae emerged from the water, they had no roots: in the ocean, they could absorb nutrients directly from the water. To survive, they needed to form relationships with the fungi that had long colonized the land and were, in effect, nothing but root. Just as we now know that we are not the singular beings we assumed ourselves to be, but a community composed of billions of microbes and the multicellular system that houses them, so we must now see plants not as rugged individuals but associations of unrelated creatures, combining forces to create life forms so complex that we are only beginning to understand how little we know.

In every gram of soil in places like our orchard, where plants are well established, there is around a kilometre of fungal filaments:[13] one kilometre in less than a teaspoonful. The filaments of each fungus form a dense net called the mycelium. In some forests, the mycelium of a single fungus can extend through several square kilometres of soil, though most are much smaller. They are constantly growing and retreating, forming new relationships, changing the terms of established ones, meshing with each other, shifting nutrients from one place to another, securing their own survival while serving the plants that host them. Some of them stitch together the roots of hundreds of plants.

The discovery that sugars sometimes move from the roots of strong, healthy trees into the roots of weak or sick ones generated great excitement among people who saw it as evidence of altruism in plants. But, as Merlin Sheldrake suggests in his wonderful fungus book *Entangled Life*, a more likely explanation is that fungi are, in effect, farming their hosts, shifting food from one plant to another, to ensure that all those on which they depend remain alive.[14]

Sheldrake also explores the possibility that the fungal mycelium is a form of intelligent life. It possesses directional memory. It can navigate labyrinths. It can send messages from one end of the network to another, changing its responses far from where it receives a stimulus. After discovering that fungal hyphae can conduct electrical pulses at intervals similar to those moving through an animal's sensory nerve cells,* some researchers see the millions of junctions within a mycelium as decision gates or processors, and the network as something resembling a computer.

Fungi are crucial to the health of the plants with which they grow. Perhaps to an even greater extent than their green partners, they mesh the soil together,[15] defending it from erosion, absorbing the rain that falls on it, locking up the carbon it contains.

All this, you might think, is remarkable enough. But what I cannot see, even with my loupe, is still more extraordinary.

Here is a fact that changes everything we once thought we knew about the living systems that sustain our lives. Of all the sugars that plants make through photosynthesis, they release between 11 per cent and 40 per cent into the soil.[16] They don't leak them accidentally. They deliberately pump them into the ground. Stranger still, before releasing them, they turn some of these sugars into compounds of tremendous complexity, with impossible names such as

2,4-dihydroxy-7-methoxy-2H-1,4-benzoxazin-3(4H)-one

Making chemicals like this requires energy and resources. At first sight, tipping this expensive brew into the ground looks crazy: in human terms, like pouring money down the drain. Why would they do this? The answer unlocks the gate to a secret garden.

These complex chemicals are not dumped randomly in the soil, but into the zone immediately surrounding the roots,[17] the rhizosphere. They are released to create and manage a series of marvellously intricate relationships with the creatures on which all life stands: microbes.

Soil is crammed with bacteria. Its earthy scent is the smell of the chemicals they produce. Petrichor, the smell released by dry ground when it is first touched by rain, is caused in large part by an order of bacteria called the Actinomycetes. The reason that no two soils smell the same is that no two soils have the same bacterial community. Each, so to speak, has its own terroir. Biologists call soil microbes 'the eye of

* Roughly four action potentials per second.

the needle', through which the nutrients in decomposing materials must pass before they can be recycled by the rest of the food web.[18]

Microbes live throughout the soil, but in most corners, most of the time, they exist in limbo, waiting, in a state of suspended animation, for the messages that will wake them up. When a plant root pushes into a lump of soil and starts pumping out signalling chemicals and sugars, it triggers an explosion of activity. The bacteria responding to its call consume the rich soup the plant feeds them and proliferate at astonishing speed, to form some of the densest microbial communities on Earth. There can be a billion bacteria in a single gram of soil in the rhizosphere.[19]

These bacteria gather and unlock many of the nutrients on which plants survive. Bacteria in the rhizosphere, alongside the fungi with which the roots are meshed,* and other microbes, capture iron, phosphorus and other elements in the soil and make them available to plants. They break up complex organic compounds, allowing them to be absorbed by the roots.[20] Uniquely, bacteria can turn the inert nitrogen in the air into the minerals (nitrate and ammonium) that are essential for making proteins. No part of the food web can survive without bacteria.

Soil bacteria also produce growth hormones and other specific chemicals that help plants grow. The complexity of some of the compounds the plant releases into the soil is explained by the fact that it seeks not to awaken bacteria in general, but the particular bacteria that are most effective in promoting its growth.[21] Plants speak in chemical languages that only the microbes to whom they wish to talk can understand.

The language changes from place to place and time to time, depending on what the plant needs.[22] When plants are starved of certain nutrients, or the soil is too dry or too salty,[23] they will call out to the bacteria that can overcome these constraints. Some biologists describe this as their 'cry for help'. In response to these chemical cries, a specific community of bacteria proliferates around their roots.

When you take a step back from these facts, you see something that

* Bacteria also appear to stimulate the relationships between plants and fungi, and, in some cases, to destroy the toxins that inhibit fungal growth.

transforms our understanding of life on Earth. The rhizosphere lies outside the plant, but it is as essential to its health and survival as the plant's own tissues. It is, in effect, the plant's external gut.[24]

Some of the similarities between the rhizosphere and the human gut, where bacteria also live in astonishing numbers, are uncanny. In both systems, the microbes break down organic material into the simpler compounds the plant or the person can absorb. Though there are over 1,000 phyla (major groups) of bacteria, the same four phyla* dominate the rhizosphere and the guts of mammals.[25] Perhaps these four bacterial groups have characteristics that make them more prepared than others to cooperate.

In humans, the infant immune system is less active than that of adults, enabling a wide range of bacteria to establish in our guts. Similarly, young plants release fewer defensive compounds into the soil than older ones, allowing a broad variety of microbes to colonize their rhizospheres.[26] Human breast milk contains sugars called oligosaccharides. At first, scientists struggled to understand why mothers express these compounds, as babies can't digest them. It now seems that their sole purpose is to feed the bacteria with which the child will grow. They selectively cultivate a particular bacterial species† with a crucial role in helping the gut to develop and calibrating the immune system.[27] Similarly, young plants release large quantities of sucrose into the soil, to feed and develop their new microbiomes.

Like the human gut, the rhizosphere not only digests food, but also helps to protect plants from disease. Just as the bacteria that live in our guts outcompete and attack invading pathogens, the microbes in the rhizosphere create a defensive ring around the root. Plants feed beneficial bacteria species, so that they crowd out pathogenic microbes and fungi.[28]‡

Sometimes plants deploy chemical warfare, releasing compounds that poison or suppress harmful microbes, but encourage helpful ones.[29] So precise are some of these chemical attacks that they can knock out a pathogenic variety of a bacterium species, but not a beneficial genetic

* The Firmicutes, Bacteroidetes, Proteobacteria and Actinobacteria.

† *Bifidobacterium longum infantis*.

‡ The effect is called colonization resistance.

variant of the *same species*.[30] Sometimes plant and bacterium work together against a common enemy, both producing the same defensive chemical.[31] Sometimes the distress flares fired by plants provoke friendly microbes to attack their rivals with antibiotics.[32] Sometimes, if a harmful fungus has managed to invade the roots, the plant will stand down its usual defences and allow certain bacteria species to invade as well, which then fight and suppress the fungus inside the root tissues.[33]

The pathogens fight back, hitting the plant's auxiliary microbes with lethal 'effector proteins'.[34] Some pathogenic species have evolved to thrive on the compounds that are meant to suppress them. Some fungi and insect pests use the plant's distress signals to locate and attack it.[35]

Plants also cry out for help from larger creatures. When insects attack their roots, they release volatile chemicals into the soil that attract certain species of nematode:[36] the tiny white worms I found in my test tube. These nematodes use their sharp beaks to pierce the skin of underground caterpillars. Then they wriggle into the body cavity and regurgitate the luminous, symbiotic bacteria that live in their guts. The bacteria produce an insecticide that kills the larva and antibiotics, which wipe out the microbes already living inside the insect. Then they digest the caterpillar from the inside, and the nematodes eat the proliferating bacteria.

The nematodes' population explodes, sometimes producing 400,000 young within the rotting hulk of a single caterpillar.[37] They burst from its sagging skin into the soil, seeking new prey. These prey might be easy to find, because the luminous bacteria make the caterpillars they infect glow blue. The glow seems to attract other caterpillars, which can then be attacked in turn.

After the Civil War battle at Shiloh, Tennessee, in 1862, thousands of injured soldiers were left lying in the mud, in some cases for two days and two nights, as the number of casualties on both sides was so great that it overwhelmed their armies' capacity to retrieve and treat them. Many died from their injuries and the consequent infections. But at night, some of the injured men noticed a strange blue glow emanating from their wounds. Their ghostly penumbra could be seen from a distance. Field surgeons observed that the soldiers who luminesced healed more quickly and had a higher survival rate than those who didn't.[38] They called it the Angel's Glow.

An explanation for the Angel's Glow was proposed 139 years later, when a seventeen-year-old high-school student, William Martin, acting on a hunch, persuaded his friend Jonathan Curtis to help him investigate.[39] Their paper, which won a national science prize, argued that the soldiers appear to have been attacked by insect-eating nematodes in the soil contaminating their wounds. The nematodes regurgitated their bacteria, and the antibiotics these microbes produce are likely to have destroyed the other pathogens infecting the wounds. Because the luminous bacteria have evolved to infect insects, whose body temperature is lower than that of humans, the students speculated that only hypothermic soldiers were inoculated. When they were brought in for treatment, and warmed up, the bacteria that had saved them died, preventing complications. (A related species, adapted to mammalian temperatures, causes severe infections.)[40]

Many of the antibiotics used in medicine were developed by soil bacteria[41] for use in their brutal underground battles, most of which are fought in the rhizosphere. As some of these crucial drugs begin to lose their efficacy – because the germs we seek to kill with them become resistant – we urgently need to discover new ones. The rhizosphere is likely to be a rich source. Using genome mining – prospecting a creature's genetic code for clusters of genes that make complex chemicals – researchers have already started to discover new antibiotics in the bacteria that live with plants.[42] As only half the major groups of soil bacteria have so far been grown in laboratories,[43] we have little idea of what the rhizosphere might offer.

Another way in which microbes in the rhizosphere – their 'external gut' – protect plants from attack is to stimulate the plant's immune system. If its leaves are attacked by fungi or insects, one of the plant's first responses might be to release hormones into the soil, crying out for help to the bacteria living there. This looks like a strange way to react: the bacteria cannot move out of the soil to attack the pathogens on the leaves above. But they bounce the plant's signal back with a chemical message of their own, which fires up its immune response.[44]* This allows the plant to produce defensive chemicals in its leaves, and to shut the pores (the stomata) through which fungi might invade.[45]

* This process is called Induced Systemic Resistance.

It seems like a cumbersome way of fighting off a pest. But because the plant's immune system co-evolved with bacteria, and is trained and primed by them throughout its life, it can't work any other way. This process, too, is similar to relationships in the human gut. Bacteria in the colon, some of which are friendly, some pathogenic, and some of which switch between roles, educate our immune cells, and send chemical messages that alert them when pathogens attempt to break through the colon's protective mucus layer and attack the gut walls.[46]

We now know that a combination of excessive hygiene, the overuse of antibiotics and a shift from varied diets containing plenty of fibre to less diverse, low-fibre diets damages our gut biomes, reducing the number of species they contain. This harms our dietary health and immune systems. Similarly, in the last few years agricultural scientists have discovered that plants seem to be less capable of fighting off attacks by certain pathogens when they grow in damaged soils with a low diversity of microbes.[47] Where the soil has been harmed by too much fertilizer, by pesticides or fungicides, excessive ploughing or crushing by heavy machinery, their cry for help is more likely to be exploited by parasites and pests. In both cases a dysbiosis is caused.[48] This is a medical term, meaning the collapse of our gut communities. But it could be applied to the unravelling of any ecosystem.[49]

An interesting line of research suggests that soils with a rich and well-balanced microbiome suppress pathogenic bacteria that cause disease in people,[50] making the transmission of human diseases through food less likely.[51] Our health depends, in ways that are obvious and ways that are not, on the health of the soil.

Researchers have discovered that, like healthy and unhealthy gut biomes, soils can be either 'suppressive' of disease or 'conducive' to disease. When plants die, they can bequeath a legacy of the bacteria they have cultivated in the soil, protecting those which grow in their stead. Some researchers are now experimenting with the agricultural equivalent of faecal implants. Just as doctors take stool samples from healthy people and transplant them into the guts of unhealthy patients, some agricultural scientists speculate that implanting suppressive soil into unhealthy, 'conducive' ground could suppress pathogenic bacteria and fungi.[52]

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Something catches my eye in the hole I dug. It's a huge lobworm, dangling into the void, doubtless wondering where its burrow has gone. I feel suddenly guilty. I have learnt that earthworm burrows can last for many years, sometimes decades, and are used, like our homes, by successive generations.[53] They form part of another, crucial soil structure: the earthworm zone or drilosphere.

Every hectare of stable, grassy land like this might be reamed by 8,000 kilometres of earthworm burrows.[54] The burrows tend to aerate the soil and help water to trickle through it. One experiment showed that after worms were introduced to soil from which they had been missing, within ten years the infiltration rate of the water landing on the ground almost doubled.[55] This means that less water flashes off the surface, so less soil is carried away, and more water reaches the roots of plants. One estimate suggests that worm burrows halve the rate of soil erosion. But their effects vary from place to place and season to season. In other cases, earthworms can make the soil less porous, or raise erosion rates, by bringing loose soil to the surface.

Earthworms can pull down into their burrows almost all the leaves and stems and twigs that fall on the ground.[56] Like birds, they swallow small stones and pieces of grit, and use them to grind up these pieces of dead plant in their gizzards. The bacteria that live in their guts help digest them, and some species then excrete everything they can't absorb onto the surface of the soil, in the form of casts.

The combined effect of this activity is extraordinary. In places like this orchard, earthworms can bring to the surface 40 tonnes of soil in every hectare, every year.[57] In tropical savannahs, the turnover can reach 1,000 tonnes.[58] Dilapidated buildings slowly disappear into the ground not because they sink, but because the soil, continually squirted from the surface by worms, rises around them.* Because of the organic material the earthworms eat, their casts are much richer in minerals than the rest of the soil. By grinding up dead plants, they make their nutrients available to bacteria and fungi, which make them available, in turn, to living plants. Where earthworms exist, the

* This effect was noted and measured by Charles Darwin in his wonderful book *The Formation of Vegetable Mould through the Action of Worms, with Observations on their Habits* (1881).

weight of plants and animals above ground, on average, is 20 per cent greater than where they don't.[59]

Earthworms also release plant growth hormones,[60] though it is not yet clear whether they do so directly or provoke bacteria to make them. Sometimes worms make plants more resistant to parasitic nematodes[61] and sucking insects, either by unlocking nutrients or by triggering their immune systems with chemical signals.[62]* In turn, plants might use their chemicals to control the behaviour of worms.[63] The harder we look at any ecosystem, the greater the complexity we discern.

In my lump of soil, I find a leathery ochre case shaped like a lemon, about seven millimetres long. It reminds me of the dried, inflated pigs' bladders once used as footballs. Using my loupe, inside it I can see a pulsing red streak, alternately weak and strong, like blood pumping through a vessel. It's a baby worm, developing inside its cocoon. Earthworm reproduction is as weird as everything else in the soil. After earthworms mate (any worm within a species can mate with any other, as all are both male and female), the saddles around the middle of their bodies thicken and harden. Then a casing containing the eggs and sperm slides off the saddle and over the worm's head, pinches together at both ends when it slips off, and forms the cocoon.

When I started working through this lump of soil, I was reminded of something that I couldn't quite place. Now it comes to me: it feels like the first time I snorkelled. Then, as now, when I broke the surface I found myself in a new world, imperceptible from above. As soon as I remember this, the soil begins to look like a coral sea. Like the sea, with its reefs and open water, it has more structured and less structured zones: places of intense biological activity (such as the rhizosphere, the drilosphere and the myrmecosphere) and the bulk soil through which large predators roam: centipedes and beetles instead of sharks and dolphins.

Like coral reefs, the most structured regions are rich in symbiotic relations. Just as coral is a combination of minerals derived from rocks, and animals, plants and microbes cooperating and competing to form structures from these minerals, soil is an ecosystem built by

* At other times they seem to make plants more susceptible to pests.

living beings from dead materials.[64] On its biological relationships, the soil's health and fertility – and thereby the survival of most of the world's terrestrial life – depends. It may not be as beautiful to the eye as coral, but once you begin to understand it, it is as beautiful to the mind.

In truth, we scarcely know it. So neglected has this ecosystem been, so little money and effort has been invested in comprehending it, that we are only beginning to unearth its complexities. The small funds available for studying soil life have mostly been spent on finding new ways to kill it: in other words, to destroy agricultural pests. As one of my university lecturers told me, 'I study insects because I love them. But the only funding I can get is to kill them.' By contrast to the many professional groups investigating other living systems, there is no soil ecology institute anywhere on Earth.

Soil, which we once saw as a homogeneous mass, is composed of structures within structures within structures. Earthworms, roots and fungi create clumps of soil, glued together with the fibres and sticky chemicals they make, called aggregates.[65] Within these aggregates, tiny animals like mites and springtails create smaller clumps. Within them, bacteria and their microscopic predators – creatures I cannot see even with my loupe, such as tardigrades, ciliates and amoebas – form still smaller aggregates.

Between these clusters are holes of different shapes and sizes. Around them are films of water and the complex chemicals released by plants and animals. Each of these clusters and voids and films has its own properties, creating millions of tiny niches that different species can exploit.

In 2020, scientists proposed what could be seen as the first steps towards a Theory of Soil.[66] This means that they began to understand what soil is. That might sound like a strange statement. But it has taken us until now properly to grasp that the substrate on which our lives depend is a biological structure.

Microbes create aggregates by sticking tiny particles together with the carbon-based polymers, or cements, they excrete. In doing so, they stabilize the soil and assemble habitats for themselves. Over time, this process builds an ever more complex architecture: pores and passages through which water, oxygen and nutrients can pass. In other words, soil is like a wasps' nest or a beaver dam: a system built by living creatures to secure their survival. But unlike those simpler structures, it becomes an immeasurably intricate, endlessly ramifying catacomb, created by bacteria, plants and soil animals, working unconsciously together. In other words, soil behaves like Dust in a Philip Pullman novel: it organizes itself spontaneously into coherent worlds. These are built on the principle of fractal scaling. This means that the structure is consistent, regardless of the magnification used to observe it.

The self-organized, adaptive world that microbes, plants and animals build to suit themselves helps to explain soil's astonishing structural resilience in the face of droughts and floods: it survives crises that would otherwise reduce it to amorphous powder. But these findings could also explain why soil can start to break down when it's farmed. When farmers or gardeners apply nitrogen fertilizer under certain conditions, the microbes respond by burning through the carbon in the soil, much of which is stored in the polymers that build the catacombs.[67] Without cement, the structure – and the system – begins to disintegrate. The pores cave in. The passages collapse. Oxygen and water can no longer permeate. Because soil is fractally scaled, as the micro-structure breaks down so does the meta-structure: it becomes sodden, compacted, airless. Paradoxically, plant roots in over-fertilized soils can struggle to reach the nutrients they need.

Multiplying soil's spatial complexity is its complexity through time. The opportunities in a speck of soil can change dramatically from hour to hour, as it dries out or becomes saturated, as bacteria consume the organic matter it contains, as a root hair breaks into it and releases sugars and complex chemicals, as a worm engulfs and excretes it, as an ant colony sticks it together with saliva, or as a larger soil animal, like a mole, a rabbit or a badger, digs it out and turns it over.

These fluctuations in space and time create what some ecologists call 'hot spots' and 'hot moments':[68] places and instances of intense biological activity. These endless variations contribute to a marvellous biological concept: the Hutchinsonian hypervolume.[69, 70] This describes the multi-dimensional opportunities that permit the survival of different creatures.[71] Broadly speaking, the more complex a system is across space and time, the greater the diversity it can support.

The massive Hutchinsonian hypervolume of healthy soil might