

SOIL, SYMBIOSIS & US

The key to healthy soil is the vast web of complex symbiotic relationships held within it.

“The agriculture of ancient Rome failed because it was unable to maintain the soil in fertile condition. The farmers of the West are repeating the mistakes made by Imperial Rome”.

Sir Albert Howard (*An Agricultural Testament*, 1940)

“Few things matter more to human communities than their relations with the soil. The biology of soil is of fundamental importance to the sustainability of life on earth...soil remains the least understood, and perhaps the most abused, habitat on Earth”.

Richard Bardgett (*The Biology of Soil*, 2005).

THE GARDENER'S JOY is to straighten up after a day spent tilling the soil, gently massage his aching back and heave a satisfied sigh as he surveys the land he or she has prepared for planting. The weeds have all been transferred to the eco-friendly composter and the new seedbed is smooth and even, ready to nurture flowers or food. Equally satisfied, the farmer leans on the field gate, deeply content with his even sward of vigorous seedlings, hopeful of maximum yield. In either case a fine crop can be assured by the addition of fertiliser and some well-directed pest control. Why is it necessary to add anything? Because something is missing: the microbes that mediate in nutrition and biodiversity, and reduce the impact of pests and disease to levels an ecosystem can tolerate.

It was whilst digging my own garden that I at last received the inspiration to begin this article that has been fermenting in my brain for several years. I prepared a beautiful tilth, but all the time I worked my mind was troubled because I knew full well the damage I was doing to the gift that is intact soil. As I worked, I could sense the death by chopping and desiccation I was dishing out to countless organisms which, if I had employed more considerate methods, could have assisted me with the plant growing process. I was ashamed, but I carried on regardless. Why?

One reason was lack of practical application to what I know and believe about the no-dig gardening regimes promoted by the Good Gardeners' Association (to whom I am, for goodness' sake, an adviser!). Also, I gave in to six thousand years of almost innate convention, 'progress' begun when man first embarked on the agricultural way of life. As ever by habit, I reached for the tools all gardeners keep in the shed and used them. That is blatant contradiction of my conviction that if, from earliest times, we had understood how soils worked and developed agriculture in sympathy with soil organisms, we would never have chosen to use intensive agricultural practices. Food production and the environment in which we live need not be in the sorry state they are today. Would it be crazy to suggest that, contrary to commonly held belief, the plough should be pretty high up in the list of man's worst inventions? Tillage may

make life relatively easy - with heavy machinery, even easier - but it doesn't account for the way plants really grow and living soils function. Tillage - and these days greed to get as much out of the land as we can squeeze - has created the necessity for chemical assistance.

AS A RESEARCH ECOLOGIST I had access to microscopes, advanced ecological methods and the new wizardry of molecular genetics which enabled me to peer into the invisible world of the soil. Using my imagination to make pictures out of scientific data, I can 'see' and appreciate that it is an incredibly diverse, highly developed, interactive community of micro-organisms which not only look after their own world, but also - the evidence is powerful - actually seem to *control* above ground ecological processes. I'm not the first to speak out for soils, yet those who have cried out: "Look after the soil!" have largely been ignored. Even if we ignore the implications (and seem not to care about the consequences), plenty of us know full well that when we remove plants, animals and other visible organisms from the above ground regions of an ecosystem, it becomes impoverished, both in biodiversity and in functioning. It is now certain that the same is true for soils, but not only do invisible, almost unimaginable soil communities vanish when soils are disrupted, negative feedback means that everything above ground suffers too, and of course that is bound to include us.

Were it not for *Homo sapiens*, much of the land surface would be covered in trees; forest that is home to a huge variety of plants plus fungi, protozoa, bacteria, animals and plenty of unknowns. Many British farmers, assert that it is their duty to manage the countryside "... or it will revert to wilderness", but before man (when it truly was wilderness, not the desolation that follows modern farming), it coped perfectly well, so who used to till the soil, plough the land? Who added the fertiliser and who controlled the pests? Nobody. Wild land looks after itself, requires no additional inputs *and* is more productive than many well-tended crop. We ought to learn something from that.

Proper wild ecosystems are self-sustaining, with a social structure based on cooperative interaction and nutrient recycling. Within them, symbiosis is a major driving force. "No man is an Iland, intire of it selfe, everyman is a peece of the Continent, a part of the maine;" (John Donne, 1624). Ditto every living organism on the planet, for all are involved in a worldwide, multi-layered web of symbiosis. Even what we think of as an individual owl, daisy, beetle or mushroom are all symbiotic communities. Symbiosis is absolutely everywhere. Unfortunately, it has been erroneously exemplified as an occasional curiosity and highly misrepresented by over simplification.

SYMBIOSIS is usually defined as two organisms combining for mutual benefit. Firstly, drop the idea of mutual benefit. Benefit of symbiosis to its components can vary in any temporal and spatial dimension. Sometimes benefit can be more or less equal, but it is frequently a one-sided affair, at least for a while, after which benefit may swing to another member of the association; a previous consumer might become net contributor. Symbiosis is infinitely variable, from mutualism, *via* commensalism (single partner benefit) to parasitism. Even partners seemingly parasitised at one stage in a symbiotic relationship might receive benefit at another. What we do not count as features of symbiosis are a participant's chronic detriment or death.

Also, forget about involvement of just two organisms. Symbiosis can occur between any number of organisms greater than one, at any scale from what we might look on

as an individual to continent-wide organisation. Even if you reduce your view to consider a single human, he or she *is* a multi-species symbiosis with - and this is a conservative estimate - 500 or so different bacteria, protozoa, fungi and yeasts. Every cell, which we consider to be ours alone, contains mitochondria which were once free-living bacteria that invaded millions of years ago, settled and stayed on as symbiotic partners. Without a kilogramme of gut organisms and ubiquitous intracellular mitochondria, eating and breathing would be a waste of time and we would be dead. A similar, extraordinary picture emerges if we look in detail at a wild flower, a single tree, a grove of trees or a forest with all of its understorey plants, animals, microbes and soil. The trees, shrubs and herbs of woodland stand on the ground. Have you noticed that, under normal conditions, they don't fall over? Their roots attach them to the ground; they are rooted in soil. Maybe soil matters.

SOIL CONTAINS several times the number of species found above ground. Intact soil is the most diverse interactive web of interdependent organisms on Earth, but it is solid, dark and impenetrable. Most soil organisms are invisible. Since we cannot look into soil, to see what is going on and understand it, we ignore it. In that ignorance, we destroy the very life of soils as we remove trees for our use and clear away all the other nuisance vegetation so that we may "plough the fields and scatter the good seed on the land".

Soil organisms, in mind-bogglingly complex interaction, support the above-ground flora and food webs upon which we rely for our existence, whilst the same above-ground flora supports soil communities. I do not wish in any way to belittle the role played by all the others, but I must leave them aside while I focus on a particular type of symbiosis, the one I know about: Mycorrhiza. This tongue twister combines two Greek words *μυκαζ-ριζα* (*mikas-riza*), literally 'fungus-root'. In a mycorrhiza, specialised fungi invade plant roots where they form an interface for the exchange of nutrients. I must simplify, because the mycorrhiza story is too involved to describe here in full. The ecology of mycorrhiza is perplexingly complicated, so much so that many people who think about it, even some ecologists, decide it is too complicated to include in their picture of the world, and what is more, then they just leave it out. That is a shame, because it matters a great deal (understatement).

MYCORRHIZA is probably one of the most important life processes on land. Its most usual function is to facilitate the supply of phosphate to plants. This essential nutrient generally occurs at extremely low concentrations in natural soils and is mostly held tightly by soil particles, unavailable. Don't worry, *'twas ever thus* and mycorrhiza is the remedy. No, remedy is the wrong word. It's the norm. For instance, the roots of Britain's favourite wild flower, bluebell (*Hyacinthoides non-scripta*), operate in an environment where phosphate is available at less than 0.1 part per million in soil solution. Bluebells cannot survive if non-mycorrhizal, for their short, thick roots are incapable of exploring the soil for inaccessible nutrients. Evolution and symbiosis have taken care of the problem. At Pretty Wood in Yorkshire, bluebell roots are colonised by at least eleven different mycorrhizal fungi, most of which are unculturable, unidentifiable and new or unknown to science. They range out beyond the root system, some of them gathering otherwise inaccessible phosphate on the behalf of their plant partners. It works very well.

This is not a new idea, even in evolutionary terms. In the primeval, aquatic habitat, primitive plants found phosphate acquisition uncomplicated, but it was not so when they experimented with life on land. Therefore, when they first embarked upon their

land-based lifestyle together around 500 million years ago, plants and mycorrhizal fungi collaborated to form a novel symbiosis which enabled them both to live on land and diversify. From the start, mycorrhiza was the normal way of life for land plants, and it still is for an estimated 90-95% of plants in all ecosystems on every continent. Mycorrhiza was, always has been and still is ubiquitous. *Please read the last two sentences again to absorb what they imply about the universal importance of this symbiosis.*

From the outset, man's intervention set in motion a series of disasters for naturally sustaining, symbiotic communities. Yes, worms, rabbits, tree wind-throw and earthquakes all disturb the soil, but only in isolated patches that all the constituent species can rapidly recolonise. This sort of disturbance is built into soil ecological processes for it releases localised bursts of nutrients promoting soil heterogeneity and ecosystem biodiversity. Agricultural tillage often affects vast areas, repeatedly exterminating soil organisms by exposure and, in the case of the fungi which form wide-ranging networks, also fragmentation. Destroy mycorrhizal fungi, and plants that are dependent upon them die, whilst populations and communities of adaptable plant species will be compromised. The fungi themselves are not so adaptable. They are entirely dependent upon their plant partners, for they are unable to produce a basic foodstuff, carbohydrate, themselves but they do obtain it through the symbiosis. If separated from their plants, they cannot survive. Therefore, if you remove the fungi, plant populations disintegrate and if you remove the plants you kill the fungi. Whether you take the viewpoint of the plants or the fungi, it is symbiosis that keeps them alive and symbiosis that is disrupted by man who must share the consequences.

As a quick aside, and to illustrate a parallel of mycorrhiza, corals are symbiotic with carbohydrate manufacturing 'dinoflagellates'. A rise in sea temperature of around 2°C is sufficient to separate this vital partnership. As the oceans warm, coral reefs, which support marine communities important to both planet and man, become bleached and die. Full stop.

MYCORRHIZAL PARTNERSHIPS can be highly specific. Not only is there specificity between certain plants and certain fungi (some of either can be also be generalist and promiscuous) but, with variability in time and space, the way partnerships function can also be very specialised. Therefore, if components of a community are removed, community structure is soon compromised. Remove a lot of them and community structure will collapse. Large-scale ecosystem collapse has already been predicted, and has occurred if only we could see it. Here is a mechanism which might help explain what is happening. Ecosystem collapse must be occurring with the progress of deforestation and intensive agriculture, and not just because wild plants are exterminated.

Remove a diverse forest community and collateral extinctions below ground mean that thereafter the soil can support no more than a few adaptable weed species - until the soil community has been rebuilt, which requires the presence of reserves of all the original organisms beyond the margins of the devastated area. If the area to be recolonised is large and potential recolonisers locally extinct, restoration is likely to take a long time or fail. Hence, it will take centuries for a landscape to reassemble itself. Eventually, after a very long period of recovery, it might begin to resemble something we humans would accept as natural, but it probably won't be, particularly if some extinctions were widespread rather than local. *We* can't reassemble complex ecosystems properly ourselves because we don't know what they were originally.

Planting countless millions of trees of the sorts we are able to grow does not make real forests.

Ice sheets sweep away everything living, but when they retreat, soils and ecosystems rebuild rapidly. It took northern lands less than 10,000 years to recover reasonable biodiversity after the last ice ages. Tropical rain forests - the sort that support up to 200 tree species per hectare - took a lot longer to develop, though ice once affected their continents as they drifted about the globe millions of years ago. Today, we can see how rapidly soils and communities form when quarries, exposures of bare rock, a clean canvas, are abandoned and left to nature.

Agricultural land, particularly in the 'developed' world, is probably a worse starting point for ecosystem restoration than bare rock thanks to contamination, not just by pesticide residues. At low concentrations, soil phosphate is a nutrient in biological communities that can recycle it efficiently. In agricultural circumstances, where populations of mycorrhizal fungi are impoverished, we find we have to keep adding phosphate to soils so that crops will grow. Therefore, when it is added in large quantities as an artificial fertiliser and not utilised or recycled, phosphate becomes a pollutant. Only phosphate in soil solution is available to roots unaided, and even then it does not flow in soil in the way that, say, nitrate solution does. Excess becomes attached to soil particles - stuck so that only specialist fungi can gather it - or is out of reach to the root system. Phosphate-rich soils favour non-mycorrhizal plants and, therefore, ecosystems become permanently changed, usually not for the better.

When we add phosphate to crops, even the few, tough, generalist mycorrhizal fungi that have survived mechanical assault are physiologically excluded from roots by their plant hosts, cutting off the last remains of the phosphate acquisition service they would receive free of charge in an intact natural community. Thereafter, plants must gather their own phosphate. The majority cannot, but some can: pioneer, weed and crop species.

GRASSES ARE perhaps the most successful plants in the world. They have refined the highly branched, fibrous root system so that a single plant might have kilometres of fine roots that can explore the soil for phosphate very efficiently. In contrast, a bluebell has just 2 metres of short, thick roots. Grasses do not need to be dependent upon mycorrhiza for their phosphate supply and many manage on their own. That is what makes grasses such good crop plants. When man exterminates plant support microbes, all he has to do is add water and fertiliser to dead soil and a grass monoculture will thrive (e.g. wheat, barley, rye, maize, sorghum, rice). Other fibrous rooted crops which are 'facultative' mycorrhizal plants (e.g. potato, sunflower, flax, alfalfa, soya, even poppies) also seem to do well in monoculture by adaptation away from biological nutrient uptake to artificial inputs. However, monocultures are very vulnerable to diseases and we must invent and use dangerous chemicals in order to protect them.

Many weeds and pioneer plants have to be non-mycorrhizal because their life cycle is necessarily rapid, transitional and unpredictable. If they are to colonise new places such as volcanic ash fields, post fire or disturbed land efficiently, they cannot rely on the right symbiotic fungi arriving at the same time as their seeds. Like grasses they have evolved the fibrous root system or an alternative phosphate acquisition strategy which enables them to do without mycorrhiza. The most successful weeds are in the non-mycorrhizal cabbage, beet and goosefoot families which also happen to include

some of the most amenable crops (e.g. rape/canola, cabbage and its many variants, sugar beet, quinoa, 'green manure').

Imagine the consequences for soil organisms of non-mycorrhizal, single species cropping for an entire year or several. In the past, crop rotation and fallowing used to assist soils recover from unsympathetic crops, but nowadays farmers repeatedly plant, for instance, rape or rape/wheat, season after season, without resting the soil. This effectively deprives mycorrhizal fungi of carbohydrate for several years, which is fatal for them. That is fine if farmers (and we) wish food to be grown on dysfunctional soils to which all the crop needs is added. If, alternatively, we would rather cultivate functional soils, we must strive to maintain the diverse plant-microbe soil communities upon which soil and crop are dependent and through which they can thrive. That will require the return of biodiversity to agricultural land.

Recovery of soil communities will require diverse plant cover which will not form until it has access to and the support of a diverse mycorrhizal fungus community. It is impossible to avoid a chicken and egg dilemma emerging here. Plants and fungi (and all the other components of ecosystems) will need to evolve such complex communities, a process which, if we must interfere, we will need to facilitate with knowledge and care. In many places, the starting point will be far from ideal: vast expanses of uniform, phosphate-soaked, abiotic soils, devoid of meaningful vegetation to be re-colonised from distant, patches of wild country and tiny nature reserves.

IF WE WANT to reconstruct complete ecosystems, why not add mycorrhiza when we plant? If only it were that easy. Of course we could grow the plants - couldn't we? Actually, I think if we were called upon to replace all of the plants that used to be in an area of lost rain forest, first we would not know what most of them were, and then if we took seeds, cuttings etc. from analogous forest, we would certainly find many died in the greenhouse. In our gardens and farmland we grow only what we can grow in simple systems and dismiss the majority as intractable.

Like plant seeds, mycorrhizal inoculants are available to purchase, but they contain only generalist, easily cultured fungi - essentially fungal 'weeds' - which might show benefit in simple cropping regimes, but they do not represent the majority of mycorrhizal fungi found in the natural world, most of which are unknown and many of those that are cannot be cultivated. Even if we had them, would we know how to use them?

It's as if we were to build a medieval cathedral, relying on our memory, a pile of illustrated guide books and all building materials we needed so long as we bought them at B&Q.

We have to stop thinking we can save the planet by fencing off a few choice nature reserves - which will gradually deteriorate anyway, influenced by change and detriment seeping in from beyond the fence - whilst we deconstruct the rest and naïvely plant millions of trees in eroded, depauperate and phosphate polluted, moribund soils. N.B. A non-mycorrhizal tree is a dead tree! In a study in North America, a single tree was found to be associated with in excess of 100 mycorrhizal fungi. We can't manufacture that.

"Good science is what we learn from nature. Let it teach you ... Work with a living system, to help support life." (William Marks, quoted in *Resurgence* 228). We must use wisely what knowledge we have and accumulate more about what our world is

really like. We must stop presuming that, when we have satisfied our lust for free resources from the environment, that we can somehow simply rebuild it. Like nature, it's not that simple. Ecosystem destruction must cease immediately; no ifs or buts. We should stand back and let regeneration occur naturally, for we do not yet have the wisdom to do it ourselves.

NATURE HAS PROVIDED us with food production processes she has proved over millions of years in collaboration with Evolution. Yet we choose to ignore, interfere with and damage them, arrogantly making remediation - which is expensive in time, money, transport, raw materials, environmental distress and common sense - the basis of our agriculture, rather than co-operation. It seems that before we begin to grow food, we must first deliberately make the land unfit for purpose. However, if we took just two measures we could eliminate the need for the toxic evils of modern agriculture: 1. Cease crop monoculture and mimic the mixed cropping methods used in Eastern countries (which mimic Nature). 2. Reduce tillage to a practicable, soil-conserving minimum.

It would be rather like 'co-opting' ourselves into existing symbioses, collaborating with and assisting the organisms that support the plants that provide us with food. When we cultivate the land, we could acknowledge the natural history and purpose of elegant natural mechanisms such as mycorrhiza, tailoring our methods to suit them rather than exterminate them and then have to devise crude alternatives to replace them. Symbiosis will prosper. Our environment will benefit. We will thrive.