Water and mineral-seeking fungi

– the symbioses of plant roots and mycorrhizas

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There is a commonly held opinion that fungi are good decomposers but are otherwise undesirable and should be eliminated like weeds.

This erroneous view is based largely on the risks to plant health posed by fungal diseases ranging from rust to rhizoctonia root rot.

Many fungi are hugely beneficial in cropping systems, working intimately with plants in ways that extend and improve the efficiency of root systems and the crops' ability to access water and nutrients from the soil. About 90% of all plant species, and most crop species, have roots that live together in prolonged symbiotic relationships with often mutually beneficial soil fungi called mycorrhizas.

This type of plant-fungi relationship, which is disrupted by many modern farming practices, is evident in the fossil record and has evolved over millions of years as plants and fungi have adapted to their changing environment.

Archaeological evidence, in the form of fossils of fungi growing within the roots of primitive plant, suggests the first land plants supported by mycorrhizal fungi began to inhabit dry land about 450 million years ago in the early Devonian period.

The term 'mycorrhiza' translates as 'fungus root', from 'myco' = fungus, and 'rhiza' = root.

Algae or plants that grow in aquatic habitats are able to take up nutrients from the water in contact with their surfaces. The early ancestors of modern land plants evolved with roots and soil fungi working together to access the nutrients and moisture they needed and enable them to survive environmental stresses caused by fluctuating availability of plant-available soil water and soil mineral nutrients.

The fungi in root-fungi relationships revealed in the fossil record are physically similar to a contemporary fungal group called *Zygomycetes.*

Today most crop and pasture species, and many broadleaf woody plants, form symbiotic *Zygomycete* associations with

HELPING OUT

Mycorrhizal fungi can transfer nutrients between plants.

In research in which a mature plant and two seedlings shared the same mycorrhizal fungal symbiont, the adult plant was exposed to radioactive carbon dioxide. After this exposure, radioactive sugars were found in the cells of the seedlings, indicating that carbohydrates photosynthesised in the adult plant were carried to the seedlings through the hyphal network.

arbuscular mycorrhizal fungi (AMF), vesicular arbuscular mycorrhizas (VAM) or endo-mycorrhizas that penetrate the walls of plant root cells. Other plant groups growing in different soil environments have symbiotic ecto-mycorrhizal relationships with ***Basidiomycete*** and and ***Ascomycete*** fungi that do not penetrate the root cell walls.

The total volume of soil occupied and accessed by the hyphae (soil mycelia) of mycorrhizal fungi is vastly greater than can be colonised by plant roots alone. These hyphae are tiny pipes that carry sugars, a source of energy derived from green plants, to the fungi, which simultaneously provide the plants with improved access to soil water and nutrients including phosphorus, nitrogen, zinc, copper, calcium and sulphur obtained from the soil by the branching fungal hyphae.

The fine, thread-like hyphae have a much smaller diameter and larger surface-area-to-volume ratio than plant roots and so are better able to adsorb nutrients and water from soil. Plant roots can occupy the spaces between soil crumbs but soil micro-organisms including mycorrhizal hyphae and bacteria in the rhizosphere (the thin layer of soil immediately adjacent to roots) are able to penetrate and access nutrients from within soil crumbs.

Two factors pose the greatest threats to mycorrhizas: intensive soil disturbance and prolonged vegetation clearance.

Minimal soil compaction from wheel, tool or foot traffic plus adequate soil aeration and drainage also maximise the potential for development and maintenance of high levels of mycorrhizal fungi and other beneficial soil organisms.

No-till, reduced-tillage, conservation-tillage or direct drill seeding technologies, controlled traffic farming systems and raised beds all contribute to soil conditions in which mycorrhizal fungi and other beneficial soil organisms can thrive.

Conventional tillage, on the other hand, inverts soils, buries weeds, increases soil compaction, decreases soil drainage and aeration, degrades soil aggregates and reduces levels of soil organic matter. This disrupts and inhibits soil biological networks, results in poorer physical and biological conditions in topsoils and increases CO_2 emissions from the soil.

Two factors pose the greatest threats to mycorrhizas: intensive soil disturbance and prolonged vegetation clearance. Both these threats are removed by direct-drill (no-till) stubble retention farming systems, with no-till minimising soil disturbance effects on mycorrhizal fungi populations and stubble retention minimising the risks posed by bare soils or extended fallow.

Extended rotations of non-mycorrhizal crops or weeds also pose a threat to mycorrhizal fungi populations.

Relatively few species of crops plants and weeds do not form mycorrhizal partnerships, but some of these 'non-mycorrhizal' species are important cash crops, cover crops or green or brown manures. Non-mycorrhizal plant species include all the ***Brassica,*** beet and amaranth families plus lupins and buckwheat. The evolution of 'non-mycorrhizal' plant species is a relatively recent adaptation, on the evolutionary scale, of flowering plants growing in highly disturbed soils such as landslides and river beds.

Growers wanting to maintain populations of arbuscular mycorrhizal fungi in their soils should ensure green/brown manure mixtures include species that host mycorrhizas and that they do not sow only non-mycorrhizal plant species such as lupins. Farmers growing non-mycorrhizal crops can address the threat they pose to the mycorrhizal fungi population by under-sowing then with a mycorrhizal host species 'companion crop' to maintain mycorrhizal fungi in the paddock. A mycorrhizal host used in this way would need to have little competitive impact on the cash crop and would ideally not flower at the same time as the cash crop. A short legume such as a subterranean clover offers many of these characteristics.

Research has shown that the diversity of plant species in a paddock is statistically correlated with the below-ground biodiversity of mycorrhizal fungi, with increased populations of soil micro-organisms including bacteria encouraged by energy-rich by-products from the decay of dead plant roots and fungal hyphae and from exudates of living roots and hyphae.

In a healthy soil environment most resources, including waste or exudates from groups within the soil community, are used or recycled by some member of the soil community. A diversity of plant communities and soil biological species ensures that all the 'roles' or ecological niches necessary for an efficient and regenerative ecological 'economy' are filled by an organism or group of organisms. Within a healthy ecological soil 'economy', producers (plants) and consumers (mycorrhizal fungi, soil bacteria vertebrate and invertebrates) live in intimate contact in the soil and may either aid or antagonise each other.

This inter-dependence, which often takes the form of a symbiosis, means there are no biological 'silver bullets' or isolates of single 'super' mycorrhizas. Rather, the biodiversity of mycorrhizal fungi ensures there are many species filling many ecological roles that contribute to multiple plant and soil benefits.

'Symbiosis' means 'living together of two organisms in close association'. However, contrary to the common perception, this 'close association' is not always mutually beneficial. Most scientific literature on the benefits of mycorrhizal symbiosis refers to the effects of symbiotic fungal-plant interactions as 'mutualisms' but the outcomes of these associations can range from highly beneficial to detrimental.

Greenhouse propagation trials conducted using corn seedlings during winter showed that AMF plant and fungal interactions can be 'parasitic' on host plants, with only the fungi benefiting from the relationship. This may occur because the plants have to share the precious photosynthates obtained during winter with the fungi and so grow less large than control plants grown in the absence of mycorrhizas.

Mutual benefits occur when two species work together to obtain nutrients neither can access on their own. Examples include lichens, which are consortiums of algae and fungi that are no longer able to live separately, and the obligate symbioses between ecto-mycorrhizal fungi and the roots of specific host plants including beech trees, pines, poplars and eucalypts. These plants cannot grow without the mycorrhizal fungi with which they interact.

Other plants and fungi can establish non-obligate symbiotic interactions that benefit them but are not essential to them. For example, almost all plant seedlings can be grown in a sterile, soil-free potting media. The seedlings do not need mycorrhizal fungi to grow in such environments, but when they are transplanted into soils where fungi are present they can form

RE-POPULATING THE SOIL WITH MYCORRHIZAS

Mycorrhizal fungi can be re-introduced to biologically depleted soils.

Several methods can be used, depending on the production system and other circumstances.

Using onion bags or 'planter bags' made of weedmat or similar material to collect 'eco-sourced' mycorrhizal hyphae from a healthy soil is probably the most relevant option for large-scale broadacre systems.

This is a convenient method to concentrate and collect these organisms and eliminates the need to dig or physically remove inoculant-rich soil from paddocks.

The first step in the multiplication or collection process is to fill the porous 'planter bags' with a suitable growing medium and seeds of a mycorrhiza-dependent plant or plants. Biochar, vermiculite or perlite all offer protective habitats for mycorrhizas.

The bags are placed on top of a healthy soil containing a good population of mycorrhizal fungi. When the seeds in the bags germinate and the plants begin to grow, mycorrhizal fungi from the soil will move through the underside of the porous bag to colonise the roots and growing medium in the bag. As a result, the material in the bag becomes a mycorrhizal 'culture' of the diverse species of mycorrhizal fungi in the soil under and around the bags.

At the end of the growing season the bags are collected and the material they contain is broken up to a free-flowing consistency and this mycorrhizal inoculants, which needs to be placed close to the seeds of a mycorrhizal host crop, is then applied through the seeder as part of the seeding process.

Such inoculants would typically be applied in paddocks that had been kept free of growth for an extended period, or where a non-mycorrhizal crop had been grown the previous season.

Seed balls, an ancient Chinese method of revegetation, may also be relevant in some broadacre situations. Seed balls are simply scattered about the site to be regenerated. To make them combine one part seeds, three parts compost or mycorrhizal inoculant and five parts clay.

In garden or nursery environments, transplanting seedlings colonised with mycorrhizal fungi from healthy living soil will inoculate the soil they are planted into with the fungi on their roots.

Direct inoculation, by placing a small amount of a healthy living soil near or around seeds, can also be effective. Nurserymen propagate 'pot-cultures' of mycorrhizas to increase the volumes of mycorrhizal inoculant for production of inoculated seedlings or cuttings.

non-obligate 'pro-cooperative' mycorrhizal symbioses that improve their ability to access moisture and nutrients and their subsequent performance.

AM fungi are obligate biotrophic symbionts of plants and these endo-mycorrhizal organisms cannot exist without access to living plants. Many fungi that form ecto-mycorrhizal and ericoid mycorrhizal symbioses are able to access nutrients from decaying matter and can be propagated without contact with plants.

Managing the soil 'economy'

In an ecological context, competition between two species is invariably mutually detrimental to both organisms, and in farming systems 'anti-competitive' practices such as weed control are viewed as useful tools to increase farmers' control of production in crop monocultures. However, weeding and conventional tillage, particularly prolonged vegetation clearance and intensive soil disturbance, are the two land use practices most detrimental to populations of soil organisms including mycorrhizal fungi.

Intensive soil disturbance disrupts or prevents AMF population maintenance or re-establishment, and in high-disturbance cropping systems with full tillage and high fertiliser inputs, non-host weeds or crops can disrupt soil fungal networks.

Weed removal reduces inter-plant competition for light, minerals and water, but prolonged vegetation clearance, whether that is achieved by maintaining tilled bare soils or spraying herbicides, has the potential to reduce soil organic matter and be detrimental to soil microbial and earthworm populations.

Populations of mycorrhizal soil fungi are maintained by living roots of host plants, crops and weeds, with the roots of many weeds able to support populations of beneficial soil organisms including arbuscular mycorrhizal fungi (AMF), so failure to re-plant or allow re-establishment of 'host' vegetation soon after the removal or death of living plants in a paddock increases the risk of the soil biology being dominated by microbes that are antagonistic to beneficial mycorrhizal fungi and general soil health.

The combination of the lack of a potential plant 'host' for the fungi and the obligate nature of AM fungal symbionts, which must have access to a host plant to survive, results in detrimental competitive interactions that inhibit the AM fungi

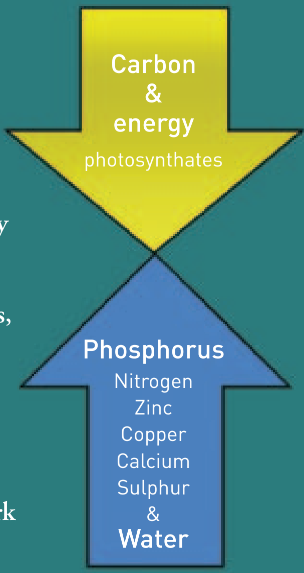
MYCORRHIZAL PLANT AND FUNGAL INTERACTIONS: BI-DIRECTIONAL NUTRIENT TRANSFER

Mycorrhizal plant benefits

1. Plant health
- improved P nutrition
- increased photosynthesis
- disease resistance
- increased drought tolerance

2. Plant community composition/increased diversity
- increased net primary productivity
- increased soil Carbon deposition
- increased quality and quantity of litter from roots, fungi and soil microorganisms

3. Improved nutrient cycling
- less need for mineralisation of organic matter to produce soluble minerals
- inter-plant nutrient transfer/ commensalism between plants sharing a common hyphal network



Mycorrhizal soil benefits

Improved soil structure. Micro-organisms inhabiting the plant root soil zone (rhizosphere) include mycorrhizal fungal hyphae and soil bacteria that assist the formation of water stable soil aggregates. This fungal mediated soil crumb making process has been described as the 'sticky string bag' effect.

Formation of soil macro-aggregates (> 0.25 mm diameter)

1. Biological mechanisms:
- mycorrhizal products influence microbial communitiesm e.g. bacteria
- fungal interactions with soil food web, e.g. nematodes, invertebrates

2. Biochemical mechanisms:
- release of mycelium products from living and decomposing hyphae, e.g. Glomalin
- decomposition products of hyphae

3. Physical mechanisms:
- hyphal enmeshment of soil particles/micro-aggregatess and organic matter
- hyphal alignment of soil particles – exerting pressure
- altered soil water regime – wet/dry cycles

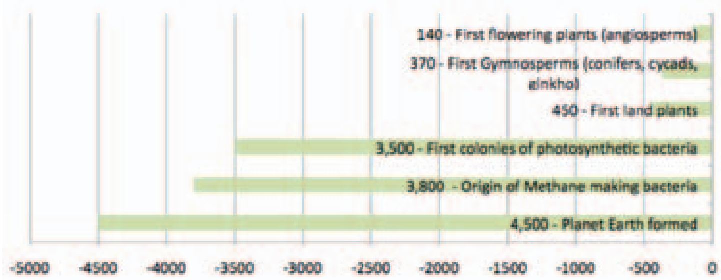
Formation of soil micro-aggregates (< 0.25 mm diameter)

- Micro-biota/biological mechanisms, bacterial by-products including glues and gums

Improved soil carbon sequestration

- Fungal-derived soil organic carbon (SOC) decomposes more slowly and thus has a longer residence time than bacteria-derived SOC or most plant-derived SOC and hence increases soil carbon sequestration

MILLIONS OF YEARS BEFORE PRESENT



SMITH & READ (2008), TABLE 17.1

and their potential benefits to mycorrhizal host plants.

Prolonged or repeated crop rotations of 'non-host' or 'non-mycorrhizal' plants that have their nutrient needs met by chemical fertilisers instead of via fungal symbiosis can also eliminate or reduce populations of mycorrhizal fungi to levels below what is needed to colonise a 'host' crop.

Even in mycorrhizal-dependent crops, soluble NPK chemical fertilisers reduce mycorrhizal fungi populations by inhibiting release of root exudates plants produce to stimulate biological activity to counter plant environmental stresses such as low nutrient availability, high levels of UVB radiation and drought or water stress.

These exudates act as biological signals to the community of soil organisms and may encourage establishment of fungal-plant mycorrhizal symbioses, so inhibiting their production by reducing the need for the plant to obtain nutrients via a VAM network can limit the potential of crops to benefit from relationships with mycorrhizal fungi.

Herbicide-resistant GMO 'non-mycorrhizal' crop plants such as 'Roundup Ready' canola or sugar beets inhibit the potential of non-resistant weeds to act as host plants for mycorrhizal fungi, thus magnifying the monoculture effects of traditional non-GMO non-mycorrhizal crops.

About 10% of all plants examined to date are 'non-mycorrhizal' plants that do not host of form symbiotic associations with mycorrhizal fungi, including:

- Brassica family – canola, mustard, turnips, swedes, kale, cabbage, broccoli, cauliflower
- Beet family – fodder beet, sugar beet, silver beet, red beet
- Amaranth family – 'red root' (pig weed)
- Lupins
- Buckwheat

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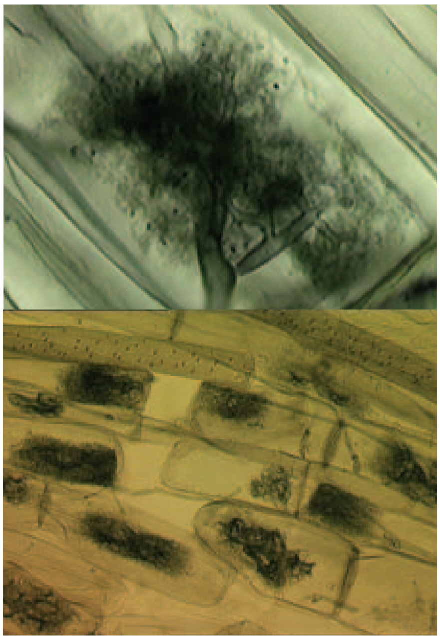
PINUS SYLVESTRIS SEEDLINGS GROWN IN A GLASS-SIDED TERRARIUM, SHOWING THE SOIL VOLUME OCCUPIED BY ECTO-MYCORRHIZAL FUNGAL HYPHAE COMPARED WITH THE AREA ACCESSED BY PLANT ROOTS ALONE. (PHOTO RE-PRINTED WITH PERMISSION FOR EDUCATIONAL PURPOSES BY D.J. READ, READING UNIVERSITY, U.K.)



PLANTS AND THEIR ARBUSCULAR MYCORRHIZAL (AM) FUNGAL PARTNERS TEMPORARILY FORM SMALL, TREE-LIKE BRANCHING STRUCTURES CALLED 'ARBUSCULES' INSIDE LIVING ROOT CELLS OF SOME PLANTS.
THE WORD 'ARBUSCULE' TRANSLATES FROM 'ARBOR' = TREE, + 'CULE' = 'SMALLEST FUNDAMENTAL UNIT'.

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