Symbiotic Synergies: unravelling the grand biochemical dance between plants and fungi

By Roman Lorello

Soil

The limits are endless. An underground, oxygenated chasm. Chambers of murky water - reservoirs of life for gigantic tree roots penetrating, circulating and searching for sustenance. Battlegrounds of ant colonies warring. Aeons of bacteria and archaea living, fermenting in the walls. Yet in the great dark distances, stretch highways of light. Flashing pulses of nutrients and information twist, wind and turn around rocks and roots. Plants whisper to each other through the medium, trading, negotiating with others and supporting those in need. Who is the hidden agent of this biological mastery? The mycorrhizal fungus.

It might seem like fiction - distant from science, but I'm here to tell you it isn't. This organism exists to connect plant life through the soil and to construct massive interconnected networks in forest ecosystems. Without it - life on Earth would be completely unrecognisable. With it - we could harness the powers of hundreds of millions of years of evolution and accomplish the unimaginable. Today, I want to share the biochemical wonder of plant-fungal symbiosis.

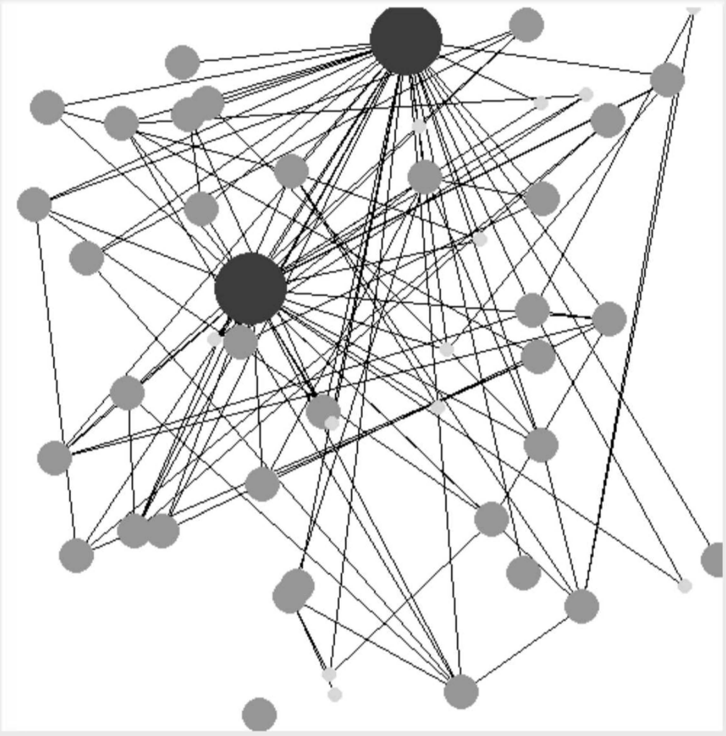
Symbionts

We've all heard of the term fungus before - a filamentous organism that moves by growing its strand-like cells called hyphae - but 'mycorrhizal': not so much. Mycorrhizal fungi are a sub-group of fungi that can form symbiotic trade relationships with plants by colonising their roots and exchanging key biological molecules. The plant allocates the fungus between 5-30% of its photosynthetic product in exchange for an expanded root system, access to phosphates, ammonium, and protection from other pathogenic fungi and bacteria. Interesting, right? What most people cannot quite grasp, however, is the sheer scale and expanse of these fungi in natural ecosystems. Approximately 95% of all plants on earth, from hundred-metre-tall redwood trees to tiny blueberry bushes *fundamentally rely* on this symbiosis for their survival and well-being. This symbiosis is in fact *so* fundamental for plants, that it's likely that these mycorrhizal fungi were responsible for the very evolution of plants as we know them ~500 million years ago

The strands of a white fungus growing through the soil.

Networks

That's not all - there is good evidence alluding to the existence of ancient, expansive, interconnected networks of dozens of different fungal species in the soils of every single forest on this planet. These networks, similar to the internet today, connect trees not with underground optic fibre cables, but with fungal hyphae. What is the name of this system? The Wood-Wide-Web (WWB). The Wood-Wide-Web is considered to function in a source-sink fashion. Trees that produce more carbon through photosynthesis than they need, can allocate some of their produce to the mycorrhizal network. As a result, juvenile trees that have high metabolic demands, or germinating seeds that are covered by shade are able to absorb and utilise this carbon. This mechanism has been proposed to massively strengthen the regenerative ability of forest ecosystems.



The above is a graphical representation of a Wood Wide Web. Large green nodes are mother trees (well established, old trees with many connections). Medium green nodes are adult trees and small nodes are young juvenile trees.

In fact, a famous study performed by Suzane Simard at the University of British Columbia in Canada proved that mycorrhizal networks can connect hundreds of different trees. In this specific study, Suzane found an immense diversity of underground forest connections: one single fungus linked 19 different trees, and one tree was linked to 47 others via a dozen fungal networks (some completely different species).

Theories

The idea of the Wood-Wide-Web is fascinating. But, since its creation, it has been host to various criticisms. A recent article in the *New Scientist* magazine questioned the experimental legitimacy of some studies done on the Source-Sink capabilities of Common Mycorrhizal Networks (CMN). The experiments were conducted by covering root networks of trees with a fine mesh - allowing for the flow of nutrients and water, but preventing the growth of fungus. The studies showed that trees prospered from connection to the CMN. However, by restricting fungal growth, the studies didn't just prevent connection to a CMN - they prevented *any* fungal connection, impairing the tree's ability to take up water and nutrients. Some studies even showed negative growth results when connected to a CMN; there seems to be a slight inconsistency in the research done into mycorrhizal networks.

Not all hope should be lost, however. Every great scientific theory has once come under scrutiny, and this one isn't the exception. There is an alternate highly promising hypothesis for mycorrhizal network function: the Biological Market theory (BMT). This theory postulates that mycorrhizal networks don't only function as simply as Source-Sink, but on a basis of reciprocity. What does that mean? A study conducted in 2013 found that clipping the roots of large plants (hence preventing fungi from establishing connections to them) actually benefited the growth of neighbouring, smaller plants. The novel idea suggests that plants compete via resource production to be selectively 'plugged in' to the network by the fungus. As we will see in a moment, this likely runs in reverse too, with plants showing selective behaviour.

Negotiation

To truly bring our understanding of plant-fungal mycorrhizal interactions full circle, we need to know what happens between the two organisms on a biochemical, and even genetic level: how does a fungus enter, colonise a plant's roots and convince the plant to structurally change them, allowing for nutrient exchange without initiating an aggressive immune response? It all has to do with the symbiosis signalling pathway.

The arbuscular mycorrhizal fungus, originating from the Glomeromycota family creeps gingerly towards the roots of the young blueberry bush. It extends a welcoming hand in the form of signalling chemicals, revealing its intention for partnership.

The first event that occurs when a fungus approaches a plant root epidermis (the outer layer of root cells) is the production and release of chitooligosaccharides and lipo-chitooligosaccharides - so-called 'Myc factors'. These are fungal signalling chemicals produced within the hyphae that stimulate the plant to begin its own signalling and structural changes.

The chemicals streak through the soil like messengers on horseback and reach the giant, fortified trojan walls of the plant root. Waving a white flag, they are let in through the gates and questioned by the plant cells who stand guard.

As the Myc factors come into contact with the plant root epidermis, they bind to specialised oligosaccharide-binding receptors on the plant root cells, causing oscillations of calcium ions travelling continuously in and out of the nucleus.

Waves of calcium ions flow through the nuclear membrane in the plant epidermis cells, signalling to the plant to allow the fungus to enter the cell. The first message has been received.

While this is happening, the nucleus (as a result of recognising the Myc factor signalling chemicals) is moving to the area of the cell membrane where the fungus is/ entering before immediately migrating to the opposite side of the cell. Slightly random, right? This process is very important because it allows for the formation of the pre-penetration apparatus (PPA). This structure can be thought of as a path being cleared through a forest to allow hikers easier travel. When it is formed, the fungal hyphae grow into the cell following the PPA, forming the arbuscule - a sac of hyphae that acts as the nutrient-trade interface between the fungus and the plant.

As the hyphae slowly ooze into the cell, twisting, turning and forming the arbuscule, oscillating calcium ions at the cell nucleus wake a certain protein from its deep slumber.

The protein CCaMK snaps into action. It recognises the calcium oscillations and turns on a gene called CYCLOPS, which activates and turns on the protein called RAM1. RAM1 itself controls a few other pathways that lead to the construction of a special membrane around the fungal hyphae. This membrane is host to a whole myriad of nutrient transporters - ones which allow the plant to give sugars and receive ammonium, nitrates and phosphorus in return. The most interesting thing about this entire process is that it's been shown that plants are able to detect the levels of nutrients entering their roots - and using this information they dictate how long the arbuscule structures last. Effectively, if a fungus doesn't give the plant enough, the plant will simply evict the arbuscules from its roots and look for another fungal partner! This is highly supportive of the Biological Market Theory, showing that there truly is more than we think to the workings of underground mycorrhizal networks.

Futures

What we know today is a tiny fraction of the truth behind these massive underground ecosystems. Once we truly understand their capabilities, what stops us from using them to artificially protect the environment? We could apply them to our own crop fields, completely removing the need for any pesticides or fertiliser, or use them to regenerate destroyed forests. We could even go as far as decoding signals sent by trees through WWB allowing us to communicate with them! *The limits are endless.*

Further reading

1. Lekberg, Y., Hammer, E.C. and Olsson, P.A. (2010). Plants as resource islands and storage units - adopting the mycocentric view of arbuscular mycorrhizal networks. *FEMS Microbiology Ecology*, 74(2), pp.336–345. doi:https://doi.org/10.1111/j.1574-6941.2010.00956.x.
2. Teste, F.P., Simard, S.W., Durall, D.M., Guy, R.D., Jones, M.D. and Schoonmaker, A.L. (2009). Access to mycorrhizal networks and roots of trees: importance for seedling survival and resource transfer. *Ecology*, 90(10), pp.2808–2822. doi:https://doi.org/10.1890/08-1884.1.
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4. Merrild, M.P., Ambus, P., Rosendahl, S. and Jakobsen, I. (2013). Common arbuscular mycorrhizal networks amplify competition for phosphorus between seedlings and established plants. *New Phytologist*, 200(1), pp.229–240. doi:https://doi.org/10.1111/nph.12351.