MYCORRHIZA IS NOT ROCKET SCIENCE

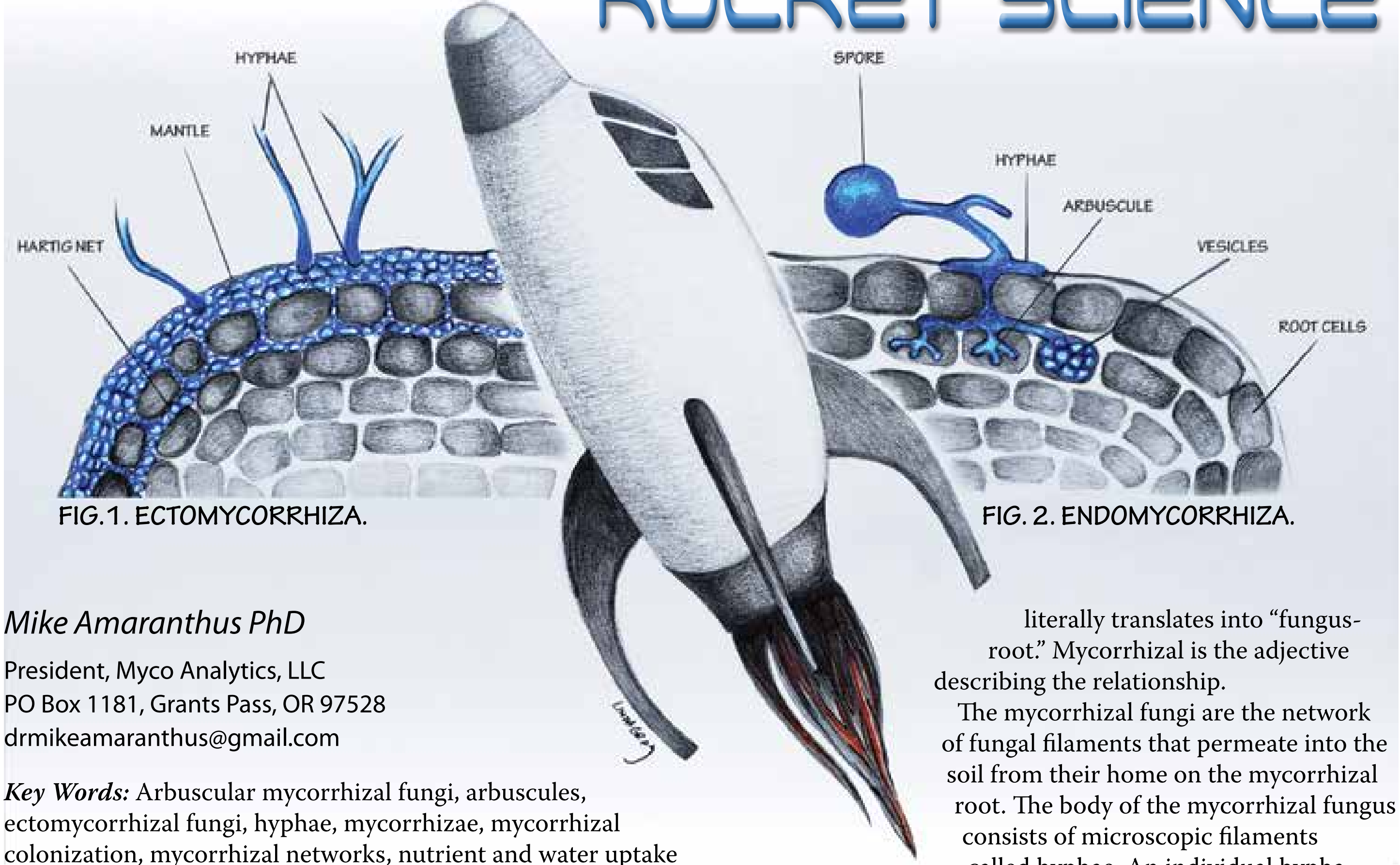

FIG.1. ECTOMYCORRHIZA.

FIG. 2. ENDOMYCORRHIZA.

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We live on top of a hidden world. Beneath the soil surface is a fascinating combination of life forms interacting in an abundance of ways. But life in the soil does not have to be a mystery. It does not have to be so technical, so full of jargon and gobbledygook that we cringe at the sound of certain terms. Mycorrhiza (myco-what?) is probably the best-studied plant-microbial relationship. There are over 100,000 peer-reviewed scientific studies in the technical literature. The problem is the scientific literature is difficult to read, especially without expertise in technical papers. In addition, access to the mycorrhizal literature is buried in journals that are obscure to the general public. The purpose of this article is to explain the basic workings and benefits of this remarkable group of fungi. Mycorrhiza is not rocket science.

Myco-what?

Let’s start with some basics. Not all species need to compete with each other to survive and evolve. The vast majority of plant species form a beneficial (“mutualistic”) living relationship with fungi. It’s generally a 1+1=3 association. Even in a mutualistic relationship there are lots of checks and balances. It is not a given that both partners always benefit all of the time. The roots of an estimated 85% of the world’s plant species are colonized by symbiotic fungi. We call a root/fungus combination a mycorrhiza (plural is mycorrhizae). Mycor-rhiza literally translates into “fungus-root.” Mycorrhizal is the adjective describing the relationship.

The mycorrhizal fungi are the network of fungal filaments that permeate into the soil from their home on the mycorrhizal root. The body of the mycorrhizal fungus consists of microscopic filaments called hyphae. An individual hypha is approximately 1/25th the diameter of a human hair and can grow up to 15 to 25 inches in length. Hyphal strands grow from within and around the root cells of the host plant, spreading out into the surrounding soil, increasing the effective surface area of the root system several hundred to several thousand times. Mycorrhizae are so common and fundamental to plant nutrition that most plant species could not survive without the mycorrhizal relationship in the absence of artificial inputs. Mycorrhizae are as common to the roots of plants as chloroplasts—the photosynthetic factories—are to the leaves of plants. We all need to know more about them because they play key roles in the health and productivity of our planet earth.

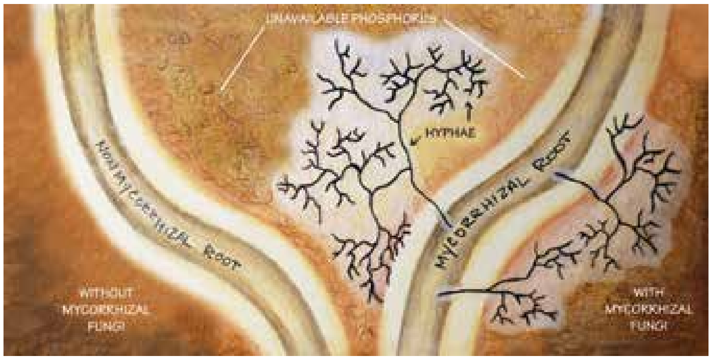

Fig. 3. Uptake of pools of soil nutrients.

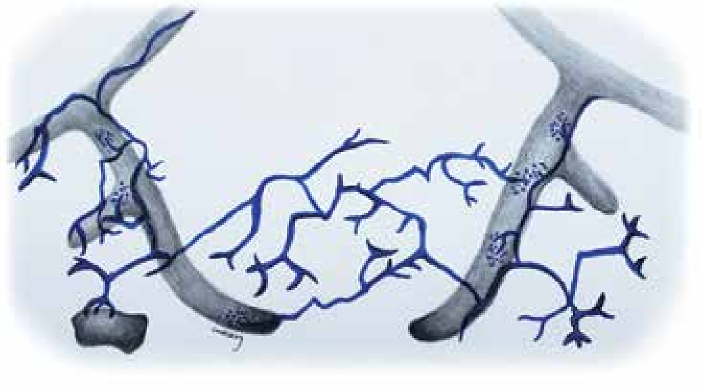

Fig. 4. Dialing into the network to become colonized.

The fossil evidence indicates that the specialized mycorrhizal plant relationship dates back over 460 million years and actually played a key role in allowing aquatic plants to invade and utilize land habitats. Aquatic plants did not have the ability to survive in the harsh soil conditions on land until the fortuitous marriage of plant and mycorrhizal fungus. The trading of soil water and nutrients captured by the mycorrizal fungus for sugars produced by plant photosynthesis was the foundation for this ancient relationship.

Mycorrhiza in nature is the rule not the exception. You don't need to be a rocket scientist to understand the significance of the relationship. There are two basic mycorrhizal types to know.

Ectos

The ectomycorrhiza group of mycorrhizae are associated with conifers in the pine family, oaks, pecan, hazelnut, beeches, eucalyptus, alders, cottonwoods, poplars, birches, some tropical hardwoods that are dipterocarps and members of the Fabaceae (Figure 1). The ectomycorrhizal fungi do not enter the root cells but grow around the outer cortical cells of the root forming what is call the Hartig net. (Robert Hartig is pictured on page 8.)

Ectomycorrhizae (plural; or simply "ectos") exist most often as a "mantle" or covering of interwoven fungal hyphae on the surface of the fine roots of trees. The mantle makes the roots look swollen and can be visible to the unaided eye or viewed closely with a low-power dissecting microscope. Well over 4,000 species of ectomycorrhizal fungi occur in our forests across the globe. When you walk through a forest and see a mushroom or puffball, you may be seeing the fruiting body of an ectomycorrhizal fungus. Above ground, mushrooms and puffballs actively disperse their spores into the air. Below ground and hidden from view, truffles (known as hypogeous fungi) use mammals or other animals to disperse their spores. Once dispersed, spores can colonize the sites of new tree roots. Some of these species, including boletes, chanterelles, and several types of morels, are prized by mushroom hunters. Some truffle species can be an epicurean delicacy; but not all truffles are tasty. However, they do contain millions to billions of spores waiting for a tree root to colonize.

Endos

Endomycorrhizae (plural; or simply "endos") (Figure 2) form a symbiotic relationship with a much broader array of plants. Like ectomycorrhizal fungi, the filaments of endomycorrhizal fungi expand into the soil forming a feeding network that provide soil nutrients and water to the plant and in exchange for energy and other compounds provided by the plant. But unlike the ectos, endos penetrate into the plant root cells. They also lack the thick mantle over the surface of the root common to ectos. They also reproduce very differently by not producing fruiting bodies like mushrooms, puffballs, or truffles; but forming spores individually within the roots or in clusters in the soil.

There are several types of endomycorrhizae. By far the largest endo group is the arbuscular mycorrhizae fungi (AMF), which also claims the most mycorrhizal host species in the plant kingdom. As the name implies, arbuscular mycorrhizae produce arbuscules, the location of fungus and plant nutrient exchange. Arbuscules are shaped like "little trees" inside the plant root system (Figure 2). Many AMF also contain vesicles which are oil storage organs in the root cell. Other specialized and less common types of endomycorrhizae form with orchids; with rhododendron, azalea, blueberries, and cranberries; and a few other plant groups.

Most, but not all, plants, including grains, vegetables, orchard trees, vines, turf grasses and horticulturally important plants evolved with, and achieve optimum growth and vigor by forming arbuscular fungal relationships. There are approximately 200 known AMF species (with many more undiscovered) forming symbioses with more than 300,000 plant species. Nearly all of the AMF species are generalists that associate with a wide variety of plants, in a broad assortment of soil types, geologies, topographies and climates. In this arbuscular mycorrhizal fungal symbiosis, the plant is provided better access and uptake of nutrients, especially phosphorus, and water from the soil. In return, the fungus, which cannot synthesize its own nourishment, receives its energy source in the form of carbohydrates donated by the plant.

Fig. 5. Linking one plant root system to the next.

Although the arbuscular mycorrhizae cannot be seen with the naked eye, your rocket science degree will not be necessary to observe their occurrence. A dissecting microscope of 30x power will do the trick. Fine plant roots are soaked in potassium hydroxide solution to clear out the root tannins then rinsed and placed in an ink solution. The ink turns the hyphae, arbuscules, vesicles and spores blue inside the roots for easy viewing.

What mycorrhizae do

The effect of mycorrhizae on the root system of a colonized plant is mind boggling. What we typically think of as a plant root system is in most cases a web of fungal hyphae doing most of the work feeding the plant. Just a teaspoon of healthy soil can contain several miles of hyphae! This is because hyphae are far thinner than roots or root hairs and are able to penetrate the tiniest pores and fissures in the soil. The mycorrhizal fungi can be viewed as the "stomach" of the plant, producing enzymes that digest and absorb food in the soil. And like the bacteria and fungi in our gut, mycorrhizal fungi increase the availability of the pools of nutrients that may otherwise be limited or not available. Mycorrhizal fungi are particularly important in accessing phosphorus, nitrogen, zinc, iron, calcium, magnesium, manganese, sulfur and other important soil nutrients by enzymatic release from tightly held soil chemical bonds and transporting them back to the plant (Figure 3). Plant uptake and utilization of fertilizer likewise can become far more efficient, often leading to significant savings in fertilizer costs in a mycorrhizal-plant system.

Fig. 6a. The propagule germinates and grows to the root.

Fig. 6b. The endomycorrhiza filament branches and forms arbuscules in the root.

Mycorrhizal benefits do not stop there. These fungi also play a definitive role in a plant's natural defense against widespread fungal root diseases which include *Phytophthora*, *Fusarium*, *Pythium* and *Rhizoctonia* (St-Arnaoud et al., 2007). Mycorrhizal fungi release suppressive exudates, such as antibiotics, that inhibit infection by these and other fungal root pathogens. Studies have documented that mycorrhizae also defend root systems by forming a physical barrier to deter invasion by soil pathogens. This barrier is made of chitin (the same tough material that is in mammal claws and insect shells) and forms a tough, protective layer protecting root cells.

Drought tolerance

Anyone who grows plants recognizes the need for fresh water is not always in sync with Nature's inclination to provide it. We often see abundant, lush vegetation in natural and wild plant habitats without the benefit of irrigation. How do natural areas provide for such luxuriant plant growth without irrigation? One key factor is the mycorrhizal fungi attached to plant roots thoroughly scour the soil for available water resources (Auge, 2004). They absorb water during periods of adequate soil moisture, then retain and slowly release it to the plant during periods of drought. Plant systems in natural areas generally achieve levels of drought tolerance far exceeding those found in agriculture or horticulture partly due to the enormous web of mycorrhizal hyphae which act like a giant sponge to protect the plant communities from extreme soil moisture deficits.

The mycorrhizal filaments can penetrate into the smallest of soil pores and fissures to access microscopic sources of water that are unavailable to the thicker roots. An extensive body of research documents the importance of the mycorrhizal relationship for efficient water use and drought protection among a wide array of important plant species (Al Karaki, 1998). The declining availability of water and its ever-increasing cost are formidable issues facing today's growers. Mycorrhizal fungi can be a powerful tool to enhance water-use efficiencies.

Climate change

In the last 50 years, atmospheric carbon dioxide (CO_2) levels have risen from 320 ppm to 415 ppm (Lindsey, 2018). Usually these kinds of changes in the atmosphere occur over geologic time scales. The effects on the climate are indisputable. Added CO_2 has contributed to higher temperatures and extreme changes in weather, the environment, and is threatening the health and safety of human generations to come. With regard to stabilizing our increasingly unruly climate, arbuscular mycorrhizal fungi have been busy taking CO_2 out of the atmosphere and carbon into soil with the sticky compound glomalin for hundreds of millions of years. Glomalin may be the most important soil component you have never heard of. This sticky soil "superglue" is 40% carbon and binds soil together in stable aggregates. The mycorrhizal fungi produce the sticky compound in their vast webs of root-like hyphal threads. Glued together by glomalin soil aggregates shelter organic matter rich in carbon and nutrients.

Mycorrhizal fungal activity has help create a huge pool of carbon in our soils. Glomalin may account for as much as one-third of the world's soil carbon and the soil contains more carbon than all plants and the atmosphere combined! Scientists are discovering the activity of mycorrhizal fungi to deposit carbon in the soil is a valuable tool to mitigate global warming. Mycorrhizal connections may also allow for the successful transition from one plant community to another in responses to a changing climate (Perry and Amaranthus, 1990). Fire, heat, and drought, as a result of climate change, are causing plant communities to migrate. Rapid mycorrhizal colonization allows plants to survive and adapt to new growing conditions. Keeping mycorrhizal populations healthy during periods of transition will help plant communities establish. Mycorrhizal plant communities can prevent dominance of a site by non-mycorrhizal weeds which, over time, can reduce the productive capacity of soils.

How do host plants become colonized?

Most plant roots become readily colonized by indigenous mycorrhizal fungi through spores and hyphae in natural and undisturbed settings. Before the 1970s scientific papers used the term "infected" to describe the mycorrhizal relationship. Infected sounded so pathological to describe the relationship especially since both the plant and fungus benefitted. Scientists now use the word "colonized" to describe the mycorrhizal root. Host plants can differ in the degree in which they depend on the mycorrhizal relations. A few plant families such as the Amaranthaceae, Chenopodiaceae, and Brassicaceae are not known to form mycorrhizae at all. Many weed species gain little from the relationship even though they are capable of forming mycorrhiza. The vast majority of plants, however, benefit and will not grow well without their fungal partners unless heavily watered and fertilized.

Dialing into the network to become colonized

Plants that germinate or are planted in soil with an existing mycorrhizal presence can quickly become mycorrhizal (Figure 4). They plug into the existing mycorrhizal network of hyphae and mycelium. When a mycorrhizal hypha supported by an adjacent plant comes in contact with a non-mycorrhizal root it penetrates into the root forming the mycorrhiza. The fungal hyphae effectively link one plant root system to the next (Figure 5). This is possible because the mycorrhizal fungi, especially the arbuscular mycorrhizal fungi, can colonize most plant species. The network spreads using energy gained from previously colonized roots linking to nearby plants. Plants that germinate or are planted in soil without a mycorrhizal network become colonized much more slowly and sometimes not at all.

Much like the internet, mycorrhizae can link all plant species together into an underground network known as the "common mycelial network." New scientific evidence indicates that this network does more than just transport water and nutrients—it can act as a communication system by sharing chemical information between plants. Communication between plants via linked mycelium has demonstrated benefits to the plant recipients. For example, signals between plants can stimulate a common defense against soil pathogens, inhibit the growth of neighboring plants, and warn of insect attacks.

Investigators demonstrated the transfer of defensive molecules between tomato plants linked by mycorrhizal fungi to protect against the root pathogen *Alternaria solani* (Song et al., 2010). These shared chemicals allowed the recipient plants to be more resistant to the pathogen. Researchers have found that marigolds inhibit the growth of neighboring plants by producing phytotoxic chemicals delivered through their mycorrhizal network (Barto et al., 2006). In a more recent study, beans that were attacked by aphids sent chemical messages, via the common mycelial network, alerting neighboring bean plants of the threat and activating a defense system that protected them from attack (Babikova et al. 2013). Interplant communication via the common mycelial network is now well established in the scientific community.

Inoculating to become colonized

Where soils are low in mycorrhizae due to disturbance or poor management, colonization can occur by reintroducing the appropriate mycorrhizal fungi through a commercial product (Amaranthus et al. 2003). These products contain mycorrhizal propagules used to create new mycorrhizae. Mycorrhizal propagules are commonly the spores or mycorrhizal colonized root fragments containing spores, arbuscules, or vesicles within the fragment. Colonized root fragments as inoculum have been shown to be as effective and, in many cases, more effective than spores themselves.

The inoculum is often a powder or clay granule with spores or colonized root fragments attached. As a plant root grows into the soil and encounters a propagule of a mycorrhizal fungus, it sends a signal to the propagule to germinate and grow into the root itself (Figure 6a). This starts a symbiotic process where the germinating mycorrhizal propagule grows a hypha to the root and upon contact, penetrates the root surface with specialized cells, called appressorium. These flattened cells press through the infection site and enter the root.

Once inside, the hypha branches and forms arbuscules within the cells of the root cortex (Figure 6b). Inoculation is most successful and the relationship happens more quickly when propagules are adjacent to the growing plant root system. Once the connections have formed inside the root, the external portion of the fungus starts to grow and branch. At this point the plant begins to feed the mycorrhiza and mycorrhizal fungus with carbohydrates obtained through photosynthesis. This fuels the fungus to grow external mycelium that expand into the soil absorbing nutrients, water and contacting new roots.

Conclusions

Mycorrhizal fungi, both ecto and AMF are critically important to the function and well being of our forests and agricultural systems. Mycorrhizae connect plant species together into an underground network, the common mycelial network. New scientific evidence indicates that this network does more than just transport water and nutrients—it can also act as a communication system between plants. Modern plant science has begun to understand that in natural habitats plant roots are a complex interaction between fungus and plant and fundamental to life on our planet. Reintroducing the mycorrhizal relationship on disturbed lands is a "growing" opportunity.

It took a long time for people to recognize the importance of mycorrhizal fungi because of jargon and complicated presentations. Learning the basics of the living soil, like mycorrhiza, can be a rewarding undertaking and leave one with a vast respect for this hidden world. This includes a greater inclination to treat soil with thoughtful consideration. It's time to get the message out regarding mycorrhiza. The mycorrhizal interactions of the soil are don't have to be presented as rocket science.

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Mike Amaranthus is a retired research soil scientist for the USDA and associate adjunct professor at Oregon State University. He was the recipient of the USDA Highest Honors award for scientific achievement and has several mushrooms and truffles named in his honor. He was the founder of Mycorrrhizal Applications, Inc. He is president of Myco Analytics, LLC in Grants Pass, Oregon.