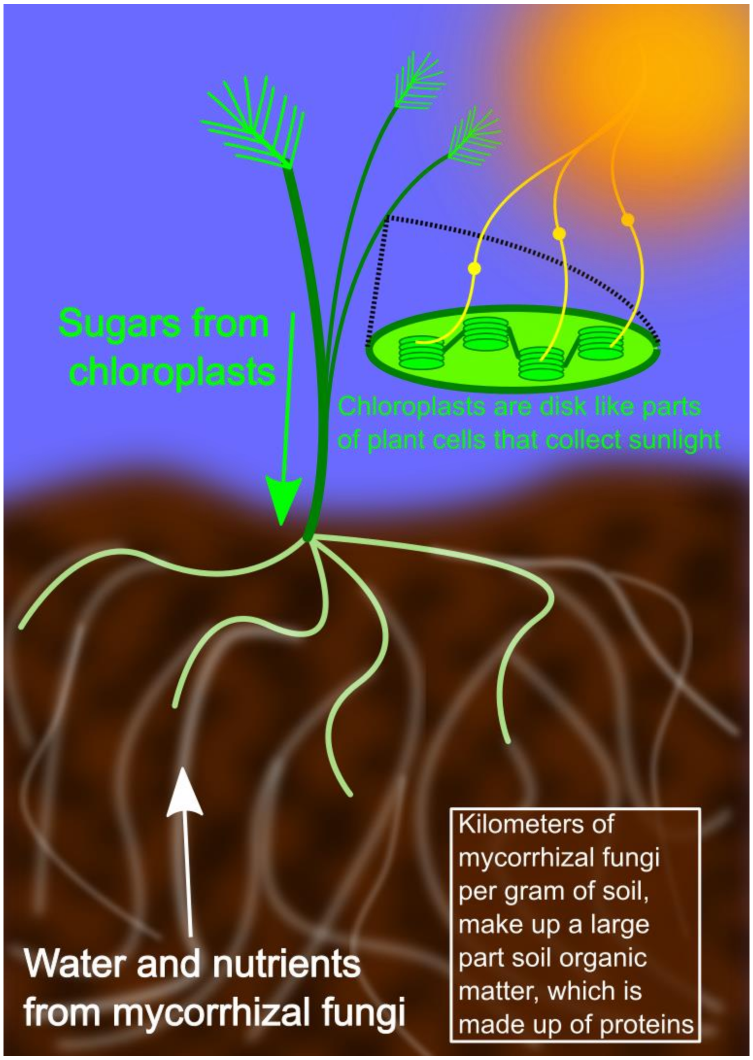
Can mycorrhizal fungi harvest water and nutrients, in the way that chloroplasts harvest sunlight?

Commissioned by Soil Secrets LLC
Written by Aurora Fabry-Wood, B.S., Biology, M.S., Biomedical Engineering

ABSTRACT

Urban and rural landscapes across the globe are being impacted by water shortages that are having grave economic consequences. Drought significantly decreases crop yield, and agricultural practices that use water more efficiently are greatly needed. Thankfully, naturally occurring alliances between mycorrhizal fungi and nearly all crops provide much needed solutions. In exchange for sugars produced by photosynthesis, mycorrhizal fungi improve drought tolerance, increase water uptake, provide nitrogen, and increase phosphorus uptake; thereby significantly increasing crop yields. In the way that chloroplasts, once free-living bacteria, harvest sunlight, mycorrhizal fungi harvest water and nutrients. Mycorrhizal fungi are as important as chloroplasts for plant health and productivity. Mycorrhizal fungi improve drought tolerance in crops by increasing photosynthesis, improving a plants immune system, and improving the plants ability to



uptake water and nutrients in dry soils. Mycorrhizal fungi, ranging from 2-10 micrometers in diameter, can penetrate pores, which are too small even for root hairs to grow into, and solubilize rock. In addition, mycorrhizal fungi improve a plants ability to cope with naturally occurring toxins, poor soil types, and pollutants. Mycorrhizal fungi increase yields of various crops and improve the establishment of landscape plants, including: maize, wheat, tomatoes, citrus, poplars, olives, turf and flowers. When inoculating it is incredibly important to ensure that the appropriate species of mycorrhizal fungi is being used and that a high enough spore count per pound is provided. Bioidentical supramolecular humic molecules will greatly improve mycorrhizal fungi ability to penetrate the soil. The number of scientific publications on mycorrhizal fungi has increased exponentially over the last 25 years.

Introduction

Urban and rural landscapes across the globe are being impacted by water shortages that are having grave economic consequences. Drought greatly decreases crop yield, and agricultural practices that use water more efficiently are greatly needed (Bodner et al. 2015). Thankfully, naturally occurring alliances between mycorrhizal fungi and nearly all crops provide much needed solutions. In exchange for sugars produced by photosynthesis, mycorrhizal fungi improve water and nutrient uptake; thereby significantly increasing crop yields (Allen 2007).

Plants rely on chloroplasts found in their cells to convert sunlight into energy. Endosymbiotic theory describes the process that allowed larger host cells to develop a mutualistic relationship with free-living bacteria that resembled blue-green algae (Margulis 1970; Whatley et al. 1979). Over time, the bacteria became what are now known as chloroplasts, which provided a huge benefit to the host cell - photosynthesis. As the host cells diversified into the thousands of plants found on earth today, as a result of photosynthesis, the chloroplast became fully dependent on the host and could no longer survive as a free-living organism.

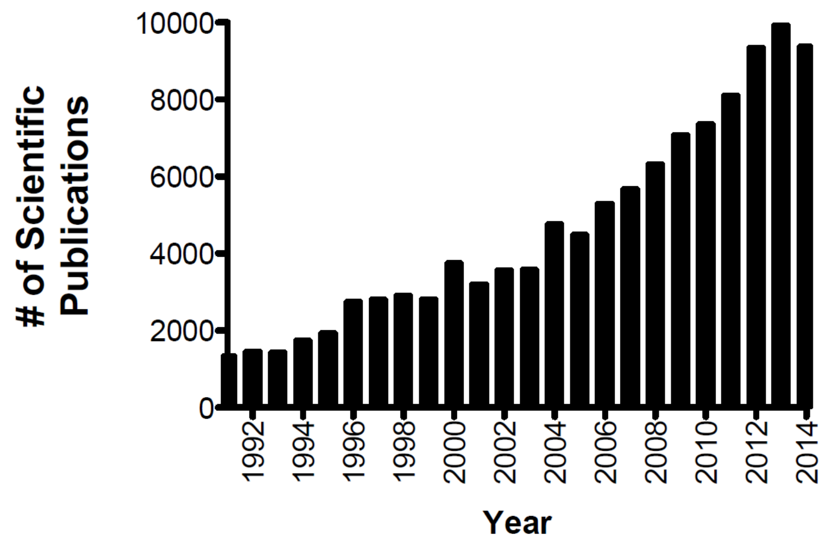


Figure 1. The number of publications associated with the term "mycorrhizal fungi", according to Google Scholar, increased exponentially from 1991-2014.

Mycorrhizal fungi are equally necessary for plant health and productivity. Unlike chloroplast however, mycorrhizal fungi are not automatically reproduced when a seed germinates. In addition, conventional agricultural practices (i.e. tillage and fertilizers) negatively impact the survival of mycorrhizal fungi (Gai et al. 2015), meaning that many farmland soils are not functioning at optimum capacity. The number of scientific publications on mycorrhizal fungi has increased exponentially over the last 25 years, Figure 1. Mycorrhizal fungi associate with the root system of plants either extracellularly (outside cells), these mycorrhizae are called ectomycorrhizae, or intracellularly (within cells) in which case they are termed arbuscular mycorrhizal fungi. Both types represent a beneficial mutualistic fungus, and form mycelium that extends beyond the host plant's root system as a network of branched hyphae. Mycorrhizal fungi associate with roots and increase the uptake of water and mineral nutrients from the soil, particularly during times of drought or when soil pH decreases mineral availability. This paper will highlight some of the current literature on mycorrhizal fungi, showing how mycorrhizal fungi increase drought tolerance and nutrient uptake, improve the immune system of plants and increase plant tolerance to abiotic stresses.

Improved water and mineral uptake

Mycorrhizal fungi improve drought tolerance in crops by increasing photosynthesis, improving a plants immune system and improving a plants ability to uptake water and nutrients. Abiotic stresses, such as drought, inhibit crop growth by decreasing photosynthesis, or the conversion of sunlight light into carbon-based sugars by chloroplasts. Mycorrhizal fungi have been shown to increase photosynthesis in drought stressed crops (Zhou et al. 2014). Drought also causes plants to accumulate

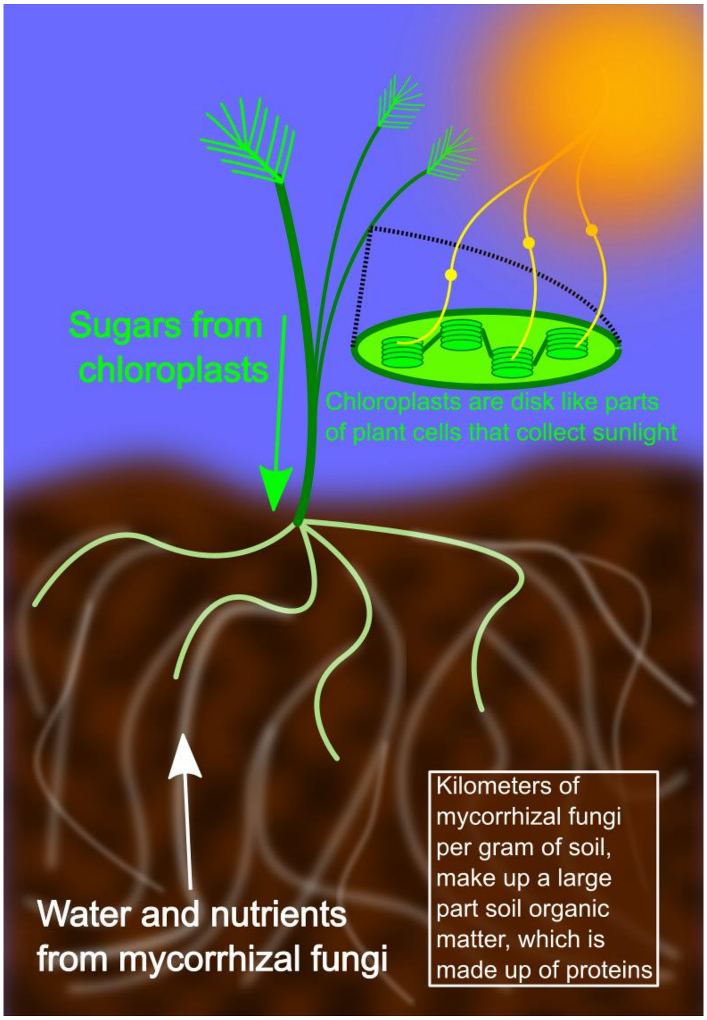


Figure 2. Chloroplasts, once free-living bacteria, provide mechanisms for harvesting sunlight and converting it to energy in for form of sugars. In exchange for a percentage of those sugars mycorrhizal fungi provide water and nutrients that the plant would otherwise be unable to access. Studies have shown that within a gram of soil kilometers of fungi hyphae exists. This network of cells significantly increases the root mass of the host plant and makes up a large percentage of soil organic matter.

reactive oxygen species, which inhibit metabolism and cause permanent damage to proteins and nucleic acids. Mycorrhizal fungi help to eliminate reactive oxygen species by increasing antioxidant production (Benhiba et al. 2015), and by promoting vitamin B6 synthesis (Benabdellah et al. 2009). Dry soils decrease the ability of roots to uptake water, due to decreased water potential, meaning that as the water in a soil decreases it becomes more difficult for a plant to absorb the water. Aquaporins are proteins involved in water uptake, especially as soils dry. It has been shown, that aquaporin expression is increased by mycorrhizal fungi (Bárzana et al. 2014). This increase in photosynthetic capacity, immune response and water absorption greatly increases yield in drought stressed crops, tied closely to these benefits is the ability for a plant to uptake nutrients.

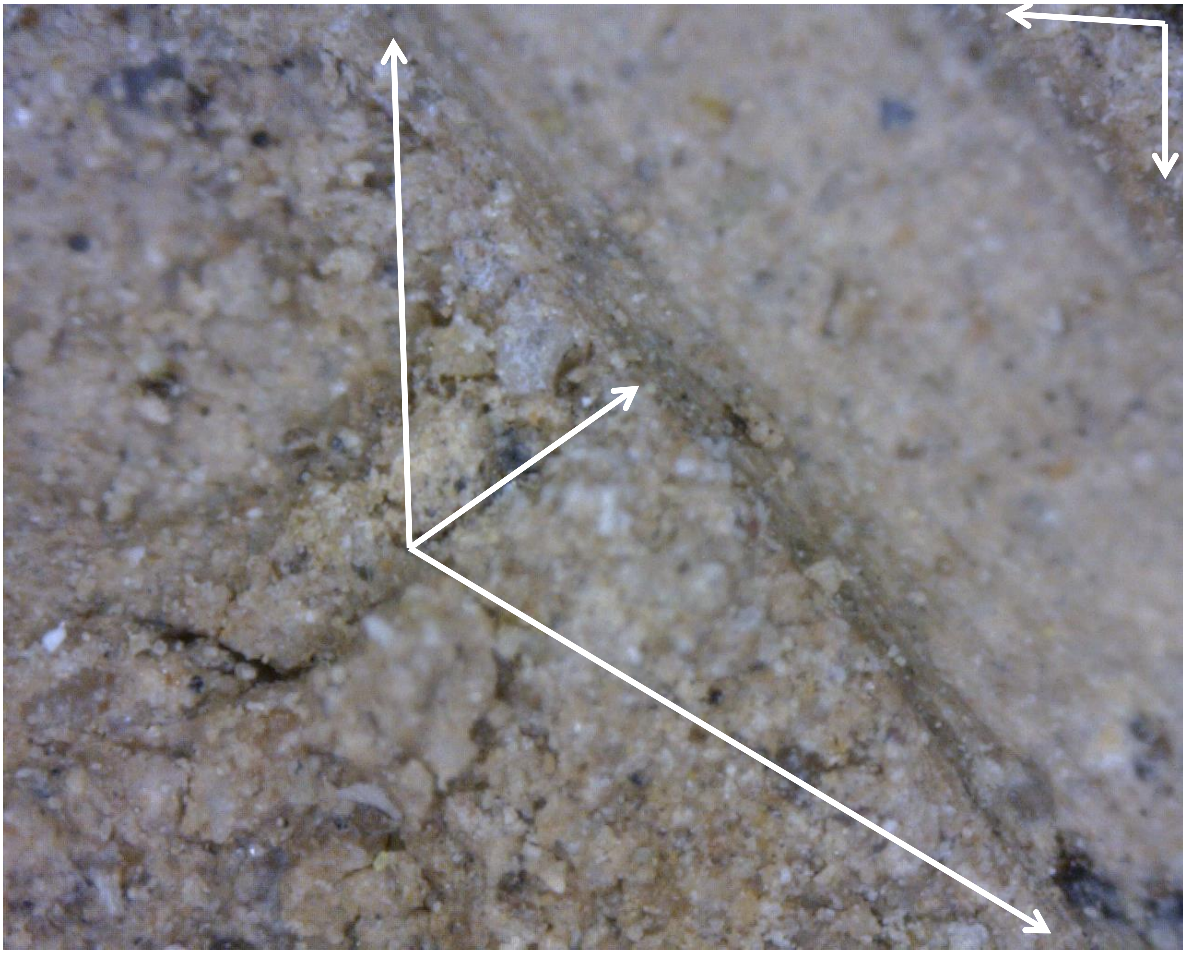


Figure 3. This image is of a tunnel drilled by the hyphae of mycorrhizal fungi through solid granite, the borders of the tunnel are indicated by the arrows,. Showing how mycorrhizal fungi solubilize rock to create a water-nutrient solution of mineral elements easily transported back to the host plant.

Conventional agricultural practices also negatively impact soil structure, and often times cause soils to collapse. Meaning that the pore size decreases significantly, preventing water, air and roots from penetrating. Mycorrhizal fungi, ranging from 2-10 micrometers (μm) in diameter, can penetrate pores, which are too small even for root hairs to grow into, and solubilize rock (Allen 2007), see Figure 3. This ability to reach smaller regions greatly increases the availability of not only water but nutrients, such as phosphorus (P). Studies have proved that mycorrhizal fungi increase P concentrations, while root hairs alone do not (Li et al. 2014). Organic phosphate is only usable by plants after being hydrolyzed by phosphatases. Phosphatase activity is strongly affected by soil pH, and various other soil components (Ca^{+}, aluminum oxides) can make phosphatases inactive. However, increasing the pH of the hyphosphere, or the soil directly adjacent to the hyphae, can greatly increase phosphatase activity. Mycorrhizal fungi bring in acidic chemical compounds, increasing phosphatase activity and thereby solubilizing the otherwise unavailable organic phosphate (Wang et al. 2013).

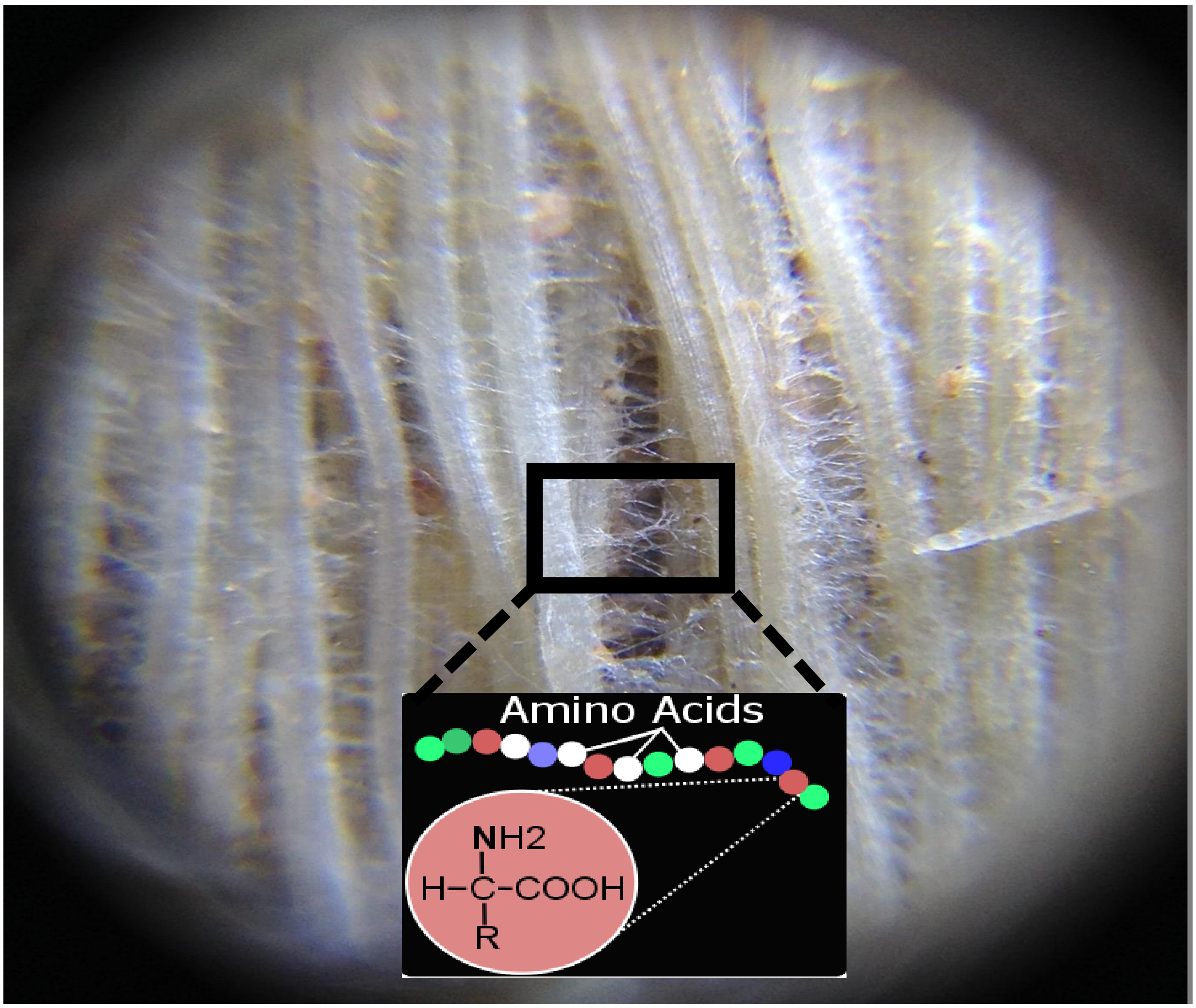


Figure 4. This image was taken with a microscope and shows mycorrhizal hyphae associated with plant roots. Mycorrhizal fungi are made up of proteins and proteins are made up of amino acids. Amino acids have 4 groups (NH_2, H, COOH and R) attached to a carbon. As proteins are broken down in the soil the nitrogen from the NH_2 group is released.

The hyphae of mycorrhizal fungi are composed primarily of proteins, which are made up of amino acids, Figure 4. Amino acids are composed of amino and carboxyl groups, as well as a side chain that varies with the amino acid. The amino group contains a nitrogen, while the carboxyl group contains carbon and oxygen. As hyphae dye, the lifespan of individual hyphae is relatively short, they are converted into soil organic matter. The organic matter generated from hyphae is rich is proteins and as it begins to decay the nitrogen, from the amino group is released and plant are then able to use it.

Finally, mycorrhizal fungi improve a plants ability to cope with naturally occurring toxins, poor soil types, and pollutants. Arsenic is naturally occurring in sedimentary rocks, and is found in soils as a result of human activities. High level of arsenic will

Figure 5. These pictures were taken 3 days after planting. The seeds on the left were not inoculated with mycorrhizal fungi, while those on the right were.

cause death in plants, and negatively impact food safety. Mycorrhizal fungi have been shown to decrease arsenic concentrations by diluting the element, decrease plant uptake and improving plant tolerance to arsenic (Spagnoletti & Lavado 2015). Alongside naturally occurring elements such as arsenic, poor soil types also negatively affect crop yields. For instance gypsum can greatly reduce crop productivity, as a result of hard soil crusts, mechanical instability, compaction, and low nutrient levels. Interestingly, mycorrhizal fungi improve plant success in gypsum rich soils as much as in soils with high salt content (Khabou et al. 2014). Crude oil hydrocarbons contaminate a significant percentage of soils, and removing these contaminates is very costly. Mycorrhizal fungi bioremediation of oil contaminated soils significantly increases the effectiveness of various other techniques (Gao et al. 2014).

Benefits to a wide range of crops and landscape plants

Table 1. Benefits provided by mycorrhizal fungi to a wide variety of crops.

Crop/Landscape Plant	**Benefit**	**Citation(s)**
Maize (*Zea mays L.*)	Improved plant nutrition and growth in drought stressed plants[1]; Improved P uptake, by increasing the pH in the hyphosphere[2]; Increased aquaporin expression[3]	1. Subramanian & Charest 1997 2. Wang et al. 2013 3. Bárzana et al. 2014
Wheat (*Triticum aestivum L.*)	Increased photosynthesis[1]; Improved drought tolerance[2]	1. Zhou et al. 2014 2. Al-Karaki & Al-Raddad 1997
Tomatoes	Increased terpenoid production and thereby improved defense against insect pests	Shrivastava et al. 2015
Oranges (*Poncirus trifoliate*)	Improved phosphatase activity, thereby increasing P uptake and drought tolerance	Wu et al. 2011
Poplar (*Populus* spp.)	Improved growth, water uptake and photosynthesis	Liu et al. 2015
Olives	Improved plant success in gypsum soils, by increasing nutrient uptake	Khabou et al. 2014
Marigolds (*Tagetes erecta*)	Stimulated photosynthetic pigment production and flower quality	Asrar & Elhindi 2011
Soybeans (*Glycine max L.*)	Decreased arsenic concentrations	Spagnoletti and Lavado 2015

Mycorrhizal fungi increase yields of various crops and improve the establishment of landscape plants, including: maize, wheat, tomatoes, citrus, poplars, olives, turf and flowers. Table 1 explains the various benefits, and associated citations, for these crops. Figure 5, shows 2 sets of seeds three days after planting, the seeds on the left were not treated with mycorrhizal fungi. The seeds on the left were inoculated with arbuscular mycorrhizal fungi.

What to look for when selecting mycorrhizal fungi spores

A common inoculant species of arbuscular mycorrhizal fungi, *Glomus intraradices*, has recently been reclassified as *Rhizophagus intraradices* (Krüger et al. 2011). When inoculating it is incredibly important to ensure that the appropriate species of mycorrhizal fungi is being used and that a high enough spore count per pound is provided. A spore count of >50,000 $\frac{\text{spores}}{\text{g}}$, which equates to 22 million $\frac{\text{spores}}{\text{lb}}$ is preferred. A significant number of suppliers do not provide spore counts above 54,000 $\frac{\text{spores}}{\text{lb}}$. Additionally, it is vital that the product contains 100% spores, otherwise planting machines, such as vacuum planters, will become clogged by debris.

It is important to recognize that mycorrhizal fungi alone will not solve all agricultural maladies. Bioidentical supramolecular humic molecules will greatly improve mycorrhizal fungi ability to penetrate the soil. These supramolecular molecules are highly hygroscopic, meaning that they attract water molecules from the surrounding environment and hold it. Don DeBoer with Mid Valley Agricultural Services in California has shown a dramatic reduction in soil compaction as a result of these molecules. On a pistachio orchard, DeBoer probed the soils with an instrument calibrated to measure the pounds per square inch (psi) of the soil. In this study, the soil psi dropped from 300 to

75 six months after applying the bioidentical supramolecular humic molecules. Initially the probe could only penetrate 1 inch, with 300 pounds of pressure applied, after the six month period the probe penetrate to 3 feet with only 75 pounds of pressure applied. Bioidentical supramolecular humic molecules and mycorrhizal fungi together form top soil and remediate damaged soils, with results surpassing most other techniques.

Conclusion

It is becoming evident that mycorrhizal fungi are extremely important to plant health and production. These beneficial fungi improve drought tolerance by increasing photosynthesis, improving plant immunity, and stimulating aquaporin expression. Nutrient uptake is also improved by mycorrhizal fungi ability to sequester important chemical compounds necessary for the hydrolysis of organic phosphorus. Finally, mycorrhizal fungi improve soil structure resulting in higher moisture content and improved mineral availability. In the way that chloroplasts, which were once free-living bacteria, provide mechanisms for harvesting sunlight, mycorrhizal fungi provide mechanisms for harvesting water and nutrients.

References:

Al-Karaki, G. N., & Al-Raddad, A. (1997). Effects of arbuscular mycorrhizal fungi and drought stress on growth and nutrient uptake of two wheat genotypes differing in drought resistance. *Mycorrhiza*, *7*(2), 83-88.

Allen, M.F., 2007. Mycorrhizal fungi: Highways for water and nutrients in arid soils. *Vadose Zone Journal*, 6(2), pp.291–297.

Asrar, A.-W.A. & Elhindi, K.M., 2011. Alleviation of drought stress of marigold (Tagetes erecta) plants by using arbuscular mycorrhizal fungi. *Saudi Journal of Biological Sciences*, 18(1), pp.93–98.

Bárzana, G. et al., 2014. New Insights into the Regulation of Aquaporins by the Arbuscular Mycorrhizal Symbiosis in Maize Plants Under Drought Stress and Possible Implications for Plant Performance. *Molecular Plant-Microbe Interactions*, 27(4), pp.349–363.

Benhiba, L. et al., 2015. Arbuscular mycorrhizal symbiosis enhanced growth and antioxidant metabolism in date palm subjected to long-term drought. *Trees*, pp.1–9.

Bodner, G., Nakhforoosh, A. & Kaul, H.-P., 2015. Management of crop water under drought: a review. *Agronomy for Sustainable Development*, 35(2), pp.401–442.

Gai, J. et al., 2015. Infectivity and community composition of arbuscular mycorrhizal fungi from different soil depths in intensively managed agricultural ecosystems. *Journal of Soils and Sediments*, 15(5), pp.1200–1211.

Gao, Y.-C. et al., 2014. Effects of different remediation treatments on crude oil contaminated saline soil. *Chemosphere*, 117(C), pp.486–493.

Khabou, W. et al., 2014. Arbuscular mycorrhizal fungi improve growth and mineral uptake of olive tree under gypsum substrate. *Ecological Engineering*, 73, pp.290–296.

Krüger, M. et al., 2011. Phylogenetic reference data for systematics and phylotaxonomy of arbuscular mycorrhizal fungi from phylum to species level. *New Phytologist*, 193(4), pp.970–984.

Li, T. et al., 2014. Relative importance of an arbuscular mycorrhizal fungus (Rhizophagus intraradices) and root hairs in plant drought tolerance. *Mycorrhiza*, 24(8), pp.595–602.

Liu, T. et al., 2015. Impact of arbuscular mycorrhizal fungi on the growth, water status, and photosynthesis of hybrid poplar under drought stress and recovery. *Photosynthetica*, 53(2), pp.250–258.

Margulis, L. (1970). *Origin of eukaryotic cells: evidence and research implications for a theory of the origin and evolution of microbial, plant, and animal cells on the Precambrian earth*. New Haven: Yale University Press.

Shrivastava, G. et al., 2015. Colonization by arbuscular mycorrhizal and endophytic fungi enhanced terpene production in tomato plants and their defense against a herbivorous insect. *Symbiosis*, 65(2), pp.65–74.

Spagnoletti, F. & Lavado, R., 2015. The Arbuscular Mycorrhiza Rhizophagus intraradices Reduces the Negative Effects of Arsenic on Soybean Plants. *Agronomy*, 5(2), pp.188–199.

Subramanian, K.S. & Charest, C., 1997. Nutritional, growth, and reproductive responses of maize (Zea mays L.) to arbuscular mycorrhizal inoculation during and after drought stress at tasselling. *Mycorrhiza*, 7, pp.25–32.

Wang, F. et al., 2013. Arbuscular mycorrhizal fungal hyphae mediating acidification can promote phytate mineralization in the hyphosphere of maize (Zea mays L.). *Soil Biology and Biochemistry*, 65, pp.69–74.

Whatley, J. M., John, P., & Whatley, F. R. (1979). From extracellular to intracellular: the establishment of mitochondria and chloroplasts. *Proceedings of the Royal Society of London B: Biological Sciences*, *204*(1155), 165-187.

Wu, Q.-S., Zou, Y.-N. & He, X.-H., 2011. Differences of hyphal and soil phosphatase activities in drought-stressed mycorrhizal trifoliate orange (Poncirus trifoliata) seedlings. *Scientia Horticulturae*, 129(2), pp.294–298.

Zhou, Q. et al., 2014. Changes in carbon and nitrogen allocation, growth and grain yield induced by arbuscular mycorrhizal fungi in wheat (Triticum aestivum L.) subjected to a period of water deficit. *Plant Growth Regulation*, 75(3), pp.751–760.

Glossary of Terms

Amino acids – are the building blocks of proteins, they contain an amino group, a carboxyl group, a proton and a side chain that determines the type of amino acid (i.e. phenyl alanine, serine, cytosine). The amino group contains a nitrogen, which can be used by plants as the protein breaks down.

Aquaporin – proteins involved in the passive uptake of water, found in cell membranes. Mycorrhizal fungi increase aquaporin expression, which improves water uptake during times of drought.

Arbuscular mycorrhizae – associate intracellularly with plants.

Chloroplast – an organelle (essential part) found in plant cells, that was at one time a free-living bacteria, and now harvests and converts sunlight into sugars.

Ectomycorrhizae – associate extracellularly with plants.

Hygroscopy – a molecule that attracts and holds water.

Hyphosphere – the area directly adjacent to mycorrhizal hyphae.

Rhizosphere – the area directly adjacent to plant roots.

The Author

Aurora Fabry-Wood
M.S., Biomedical Engineering
B.S., Biology

Aurora served as a Forestry Extension Officer, with the United States Peace Corps, in Zambia from 2008-2010. In Eastern Province, Zambia Aurora coordinated with community leaders to develop sustainable agricultural practices and to diversify income generation, with the aim of decreasing deforestation rates. After several months of travel Aurora returned stateside and began working as the Staff Biologist for Soil Secrets LLC (2011-2013). Currently Aurora is working towards a Ph.D. in Biomedical Engineering at the University of New Mexico's Center for Biomedical Engineering. Her research focus is on biomimetic nanoscale design.