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# Toward An Understanding of Arbuscular Mycorrhizal Symbioses within a Creation Model of Ecology: Implications for Godly Stewardship and Sustainable Agriculture

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## Abstract

Building a creation model of ecology is a worthwhile endeavor. An important ecological relationship is the understanding of arbuscular mycorrhizae (AM) which are complex symbioses between plants and fungi. Understanding these relationships have implications in origins issues, taxonomy, post-flood diversification, and land stewardship. A working knowledge of the plant/fungus system has potential for how God's people can exercise a biblical ethic of environment because as we unravel their intricacies they demonstrate incredible design. As we seek to discover the intent of the Designer, we can enhance our stewardship of the land by using this symbiosis to re-establish polluted and disturbed landscapes and grow sustainable crops.

**Keywords**: Arbuscles, Arbuscular mycorrhiza, Bioremediation, Ecology, Endomycorrhiza, Glomeromycota, Hyphae

## Introduction

*A Christian-based science and technology should consciously try to see nature substantially healed, while waiting for the future complete healing at Christ's return* (Schaeffer and Middelmann 1970, p. 81).

Historically Christians have often forfeited a biblical worldview of environment which has allowed a naturalistic philosophy to be established in its place. A biblical perspective of ecology is not anti-environment but critical to a proper understanding of our place in the world, both with our Creator and fellow creatures. Ecology is the study of complex relationships between organisms and their surroundings. Encompassed within these studies, are environmental issues which include human population, "global warming", and preserving earth's biodiversity. For these reasons, pursuing the development of a creation model of ecology is a worthwhile endeavor because as we understand the complex ecosystems of the planet, we can better manage earth resources for the benefit of all and fulfill our God-given roles as planetary stewards (Hennigan 2009).

One important area of ecological research is the study of complex mycorrhizal symbioses. Mycorrhiza literally means "fungus root" and refers to the relationship that many plant species have with fungi. There are several types of mycorrhizal associations and they include ectomycorrhizae and endomycorrhizae. Classified according to fungal type, whether or not they penetrate cortical cells, and/or their host relationships, distributional patterns between the major mycorrhizal associations have been made according to the biomes they inhabit (Smith and Read 1997, p 451).

As the mysteries of these relationships are brought to light, the infinite design of the Creator is clearly observed by those who have eyes to see. Furthermore, an understanding of these systems has promise in managing essential forest services, reclaiming damaged ecosystems, and growing sustainable crops. This paper will focus on the design, life history, and ecological importance of arbuscular mycorrhizae (AM). It is hoped that the study of these intricate relationships will direct our praise and attention to the Creator and with the knowledge gained, build creation models of ecology that enable us to better manage the land for the glory of God and the benefit of all.

## What are Arbuscular Mycorrhizae?

Arbuscular mycorrhizae (AM) are obligate fungal symbionts of an estimated 80–90% of vascular plants and some nonvascular plants such as mosses (Smith and Read 1997, p. 11). Compared to the diversity of mycorrhizal associations, this symbiosis is the most prevalent and is a type of endomycorrhiza in which the fungus penetrates cortical cell walls. They are characterized by specialized intercellular hyphae and unique branching hyphal arbuscles which form inside the cells. The fungi responsible are classified in the phylum Glomeromycota, order Glomales. They are assumed to be mostly unculturable and, except for germination, wholly dependent on photosynthetic plants. AM used to be classified as Vesicular Arbuscular Mycorrhizae (VAM) but research uncovered that a major suborder did not form thin-walled, lipid filled vesicles so they are referred to as AM associations today.

There is no evidence for specificity between plants and fungi in AM (Smith and Read 1997, p. 27). However, it is important to distinguish between *specificity* (the ability to colonize), *effectiveness* (plant response to colonization) and *infectiveness* (the amount of colonization) because AM are widely different in these abilities depending on the environment. They do have wide host ranges, however, and are capable of long term relationships with many different plants. In order for these partnerships to work at least four elements must be in place: appropriate root morphology, fungal structures able to penetrate the plant cell, extraradical mycelia, which are root-like vegetative fungal structures growing in the soil, and soil conditions. The details of these elements and their amazing choreography will be discussed later.

### Fossil History and Origins of AM Associations

Scotland's Rhynie chert is one of the most famous paleobotanical treasures in the world. Chert is a dense, fine-grained sedimentary rock thought to be formed from silica-based precipitates of marine micro-organisms. Though the fossils in these strata are found in various stages of preservation, the Rhynie chert's treasure is the numerous superb plant preservations, including AM arbuscles. Unicellular and multicellular plants, including whole organisms, pollen, germinating spores, and freshly released sperm abound. Because of this, silicification is thought to have been rapid, and using evolutionary assumptions, is associated with hot spring deposits at least 400 million years old (Palaeobotanical Research Group 2000). The well preserved AM arbuscles are found in an early Devonian terrestrial plant known as *Aglaophyton major* and are morphologically identical to those known today (Remy et al. 1994). This suggests remarkable stasis for a highly complex and difficult to understand symbiosis.

### An Amazingly Sophisticated Choreography

Fungal colonization starts from source inocula that include spores, infected root fragments and hyphae. The fungal spores tend to be thick walled and contain several thousand nuclei. Both hyphae and spores can survive harsh conditions including plant dormancy, plant death and seasonally severe environmental circumstances (Smith and Read 1997, p. 44). Spores can also persist in the brutal environment of the guts of various soil invertebrates, birds, and burrowing mammals. Interestingly, not only can spore germination be increased in the presence of soil microorganisms, but also, burrowing animal behavior may be very important for the dispersal and arrangement of AM colonization. The task of unraveling these complex relationships is difficult and implies fascinatingly designed systems working together for the good of the ecosystem.

As obligate biotrophs, fungal spores will germinate on agar and produce small amounts of mycelia in the lab, but will not develop unless they penetrate a plant and obtain its nutrients (Smith and Read 1997, p. 37). Plants can chemically communicate with fungi to initiate the relationship. For example, *Glomus mossae* produces hyphae that respond to phenol based chemical compounds secreted by plant roots by growing toward them (Sbrana and Giovannetti 2005). There is evidence that non host plants do not produce these chemical signals and therefore fungal hyphae are not stimulated to form AM symbioses.

Other evidence for genuine communication and coordination between plant and fungus are seen at the hyphal/root interface (Smith and Read 1997, p. 82). Once the hypha makes contact, a flattened hyphal pressing organ, or appresorium, narrows into an infection peg and punches through the epidermis of the outer root using turgor pressure (Smith and Read 1997, p. 50). Once inside, hyphae grow intercellularly and some develop across the outer cells of the cortex. Though they may breech the first part of the cell wall, they do not penetrate the plasma membrane. Instead, the plant plasma membrane grows around the hypha and it becomes the periarbuscular membrane. This compartment keeps the fungus cytoplasm from mixing with plant cytoplasm as hyphae branch into short-lived, tree-shaped arbuscles. Arbuscular growth requires further genetic coordination as evidenced in the major cell modifications taking place such as vacuole shrinkage, increased number of cell organelles, and cytoskeleton reorganization. Nuclei increase in size and it is hypothesized that this may indicate genome reduplication and/or increased rates of gene transcription. It is thought that many genes must be involved with both organisms and what the fungus lacks at a metabolic level can be supplemented by plant genes enabling them to work in tandem. This speculation has yet to be demonstrated (Smith and Read 1997, p. 103). I hypothesize that continued research will show this type of system coordination and will fulfill the criteria of irreducible interdependence (Zuill and Standish 2007). Proposed after Behe's (1996) model of irreducible complexity, irreducible interdependence is the idea that there are a series of biochemical reactions or "ecochemical pathways" across multiple species, where each step of the reaction is mediated by one or several species. An irreducibly interdependent system is consistent with fully functional and rapid design (Zuill 2000) and has the following testable characteristics:

1. Potential gaps in the system cannot be reasonably bypassed by inorganic nature alone.
2. It must have a degree of specificity that in all

probability could not have been produced by chance.
3. A given function or step in the system may be found in several different unrelated organisms.
4. The removal of any one of some individual biological steps will result in a functional loss to the system.

Elsewhere, as intercellular hyphae penetrate the epidermis, extra radical hyphae grow at rapid rates in the soil and appear to differentiate into various functions. Some hyphal networks seem to be involved with nutrient absorption while others may enable the plant to survive by protecting it from parasites (Gianinazzi-Pearson 1996; Smith and Read 1997, p. 64). The choreography between the two may explain the increased mychorrizal efficiency of obtaining important soil nutrients, especially phosphorus (P). As both organisms need P for the synthesis of crucial compounds such as ATP and nucleic acids, it is hypothesized that the arbuscles are the sites of P transfer from fungus to plant. The fungus requires 4–20 % of the photosynthate produced by the plants and carbon transfer is thought to be between the intercellular hyphae, cortical cells and arbuscles (Muchovej 2001). Pfeffer et al. (1999) suggest that hexose is taken up by the interior (intraradical) hyphae and converted to trehalose, a carbon compound thought to prevent cell damage and injury from prolonged desiccation. Lipids are synthesized by intraradical mycelia and may be exported and stored as the major carbon compound in extraradical mycelia. Carbon is used by the fungus to produce vegetative and reproductive structures and respiration for the energy needed in nutrient uptake. At this stage, the plant has increased capabilities for absorbing elements like Zn, C, Ni, and P, and is more efficient at nutrient gathering than non-mychorrizal roots (Smith and Read 1997, p. 114). The efficiency of P and other crucial nutrient absorption is dependent on many ecological variables including the ability of extraradical hyphae to explore more soil volume, smaller diameter hyphae having greater surface area than plant roots, carbon availability, bacterial community, and various fungal chemicals needed for the process (Büching and Shachar-Hill 2005).

### Importance of AM in Ecosystems

The ecosystem is a natural unit where the intricate relationships between a community of organisms and their physical environment occur. Large ecosystems are biomes and include; deserts, boreal forests, grasslands, and taiga. Patterns of mycorrhizal symbioses have been observed according to biome. For example, though AM are common in deciduous forests, tropical rain forests, and arid/semi arid grasslands they are ubiquitous (Smith and Read 1997, p. 451). Their responses in ecosystems are extremely difficult to measure because the complexities require a consideration of many variables including climate, soil type, seasonal plant requirements, stage of plant growth, and other community members. However, based on the current data, arbuscular mycorrhizas are the most important microbial symbioses under conditions of P-limitation because they influence the development of plant communities, increase nutrient uptake and above ground productivity, improve water relations and act as bioprotectants against plant pathogens (Jeffries et al. 2003).

AM seem to play important roles in competition and redistribution of nutrients in ecosystems. They are more frequent in plants growing on mineral soils and less frequent in nutrient rich soils. There is some speculation that they store excess P in roots, leaves, and seeds when demand is low. There is also evidence that AM provides seedlings with nutrients from hyphal networks connected to established plants. These relationships may minimize competition with other plants, allow seedlings to experience considerable energy savings, and give them a greater chance of establishment (Smith and Read 1997, pp. 122–123).

AM relationships with other community members are continuing to be revealed. Animals can act as vectors of AM inocula which affects plant succession. Allen and Allen (1988) report that animals transported AM propagules over several miles of sterile pumice near Mt. St. Helens, facilitating succession in that devastated area. There is interesting evidence that AM can work synergistically with organisms such as P solubilizing bacteria and fungi to further increase available P in the rhizosphere. This has been especially highlighted in sterile soils where plants did noticeably better when AM inoculation worked synergistically with the phosphate solubilizing fungus *Penicillium balaji* (Smith and Read 1997, p. 141). There is also growing evidence that AM, in conjunction with nitrogen fixing bacteria, improves soil quality by providing nitrogen nutrition. Hamel (2004) suggests that AM produce genes that establish symbioses with nitrogen fixing bacteria resulting in increased legume nodulation with a corresponding increase in nitrogen fixation and utilization by the symbionts. For example, in Samphire Hoe, UK, the above AM abilities were observed when organisms infiltrated virgin soils and contributed to the rapid development of plant communities.

### AM in Phytoremediation and Land Reclamation

Bioremediation is the biochemical technology that uses organisms to alter polluted environments back to their healthy conditions. Phytoremediation is a form of bioremediation where plants are used to detoxify soil and AM has great promise in this area

(Khade and Adholeya 2007). Because of the nutrient absorption capability of AM and resistance to heavy metals in certain fungal species, interest in using AM to detoxify polluted soils is growing. Because of their ability to sequester toxic metals on degraded soil, bioremediation is also being done on degraded and desertified landscapes (Jeffries et al. 2003). Though the ability to absorb heavy metals depends on fungal species, soil microbes, and plant/fungus interactions, toxics sequestered include; zinc and cadmium (Giasson et al. 2005). Gaur and Adholeya (2004) conclude that AM can play important roles in plant survival on metal contaminated soils by serving as filtration barriers to the transfer of heavy metals to shoots. They suggest that it will be important to use only indigenous heavy metal tolerant fungi with appropriate plant species in order to get the best results which require a basic understanding of the local ecology.

### AM in Agriculture

Improper agricultural practices can cause harm to ecosystems and healthy crops by destroying soil structure and overloading them with chemicals such as fertilizer and pesticides. These practices have far reaching effects on the surrounding ecosystems and the health of crops that include soil erosion, soil degradation, and chemical pollution of the water supply. For example, we know that AM forms direct links to crop plants and builds organic matter, rather than depletes it. This alone has the indirect result of growing healthier crops (Smith and Read 1997, p.468). AM also affects soil structure by binding soil aggregates that increases soil stability and decreases soil loss and nutrition from the effects of erosion. This can result in improved water management and increased plant productivity.

Benefits of AM are the greatest in P-deficient soils and colonization tends to be minimized with high P concentrations. Because of its nutrient absorption abilities, it is possible that in certain environments and with the proper AM management there would be a substantial reduction of fertilizer which could translate into significant monetary savings and prevent a pollutant overload to the system.

### AM Understanding Within a Bible-Based Model of Creation Ecology

Genesis 1 says that in the beginning there was an all powerful Creator that made the heavens, the earth, and all that is in them. In his satisfaction God declared it very good. With man's desire for independence from the Creator, sin entered the world and today we must tease the data in order to determine that which may have been part of the original design and that which is a result of the Fall. For example, though the intricacies of AM symbiotic systems are consistent with complex engineering by Christ, some of these systems appear to have deteriorated over time suggesting possible effects of the curse due to broken, distorted and displaced relationships. Parasitism, for example, is usually deleterious to agricultural plants and affects traits such as yield. A parasitic relationship of this type seems unlikely to have existed in the world before man's fall and seems to be a product of system deterioration or organism relationship malfunction (Wood and Francis 2008).

The Hebrew word for the scriptural life that God brought forth applies to humans and certain animals and refers to a moving, holistic living experience that does not include plants (Kennard 2008). Human death is a result of sin and the curse, but plants, created on Day 3, are never described as having scriptural life but were created, among other things, to be food for animals. Fungi would be classified in the non-living category as well. Fungi are ubiquitous and fill many niches. Some are parasitic and are probable results of the Curse. Others are fundamentally intertwined with numerous species such as the obligate orchid/fungus symbiosis (Hennigan 2009). Orchids rely solely on special fungi for their existence and persistence. This has led to a proposal by Gillen (2008) that some microbes such as certain fungi and bacteria were created as biological systems within plant and animal baramins on multiple days of Creation Week.

It has been demonstrated that the plants in AM symbiosis are not obligate with fungi but are often enhanced when they are in relationship. The plants can be classified in their own baramins based on their originally created kinds. In contrast, AM fungi are obligate symbiotes with plants for their development and persistence. The fossil evidence suggests that this relationship is an original creation and may not be affected by the fall in certain circumstances. How then are we to understand the origin, baraminology, and purpose of AM symbioses?

At least two neo-Darwinian hypotheses have been suggested to account for their origin (Remy et al. 1994). The first is that fungi became parasitic on plants, changing over time to a mutualistic relationship. A second proposal is that the fungus started as a saprobe, able to obtain its nutrition from dead or non-living organic matter, and slowly evolved into an endosymbiont that obtains its nutrition from a plant host. From a creation perspective, these hypotheses are possible and would not automatically be ruled out. Neo-Darwinists believe random beneficial mutations and natural selection provide the mechanisms that produced mycorrhizal systems. They refer to biochemical processes, often highlighted in bacteria, which include abilities to genetically adapt to environmental stresses and metabolize new materials by random processes. This evidence is then extrapolated to show that such systems need not be designed. However, though random processes may be involved in certain situations, randomness is still an unproven naturalistic assumption. New insight has suggested that when beneficial changes in nucleotide sequences occur in organisms like bacteria, there may either be a loss of pre-existing activities in the original (wild-type) biochemical system (Anderson and Purdom 2008) or a designed mechanism for adaptation (Batten 2003).

Research continues to suggest that neo-Darwinian mechanisms can not account for the origin of complex systems (see also Purdom and Anderson 2008). Anderson and Purdom (2008) describe bacterial biochemical machinery getting "knocked out" which tends to change the enzymatic, regulatory or transport systems that confer temporary survival value to the bacterium in that new environment. This mutation does not add complexity to the already existing system and, therefore, does not explain the origin of complex, interconnected systems such as AM. In the case of nylon eating bacteria, Batten (2003) observes that these mutations do not show signs of randomness, but instead, act as if they are responding to environmental cues by unknown designed mechanisms, a prediction of the creation model. Though random mutations are possible in a fallen world, creationists predict that as the mysteries of the AM coordination of the plant/fungal systems are unveiled evidence of programmed, mediated design will become more apparent.

Francis (2003) has proposed that God created some microbes as a link between macro-organisms and the chemical environment, calling them an organosubstrate or biomatrix. He hypothesizes that if these are designed for this purpose they should be abundant, ubiquitous, involved in complex and crucial symbiotic relationships involving macro-organisms, able to form symbiotic microbial communities, mine and provide chemical elements from the lithosphere, and cycle elements in the biosphere. Add to the above the ability to survive harsh environments such as animal guts, freezing and extreme heat and AM fungi seem to fit these parameters. Rather than trying to trace their evolution as a species or attempt to place them in a baramin, creationist research may be more fruitful if they are viewed as a created organosubstrate designed to help restore disturbed ecosystems. In other words a designed and robust mechanism meant to remediate areas affected by catastrophic disturbance.

Creationists presume that the Creator desires to see his creatures persist knowing that the curse, brought on by the Fall, would drastically change environments. This would have been especially important during and after the Flood. The current research on AM relationships is in its infancy but has implications for post flood diversification. Fungal inocula are very resistant to environmental extremes and can be dispersed by wind and tide. They are able to short circuit nutrient cycles in mineral and sterile soils, regulate nutrient transfer, protect against soil parasites and rapidly modify plant colonization. In God's love for His creation and desire to see His creatures persist, AM may have been an important factor in post-Flood soil improvement and facilitation of plant succession and biodiversity.

The Fall brought sin into the world. Sin has been the basis for the greed, selfishness and sorrow that is so prevalent. These symptoms are a product of broken relationships, first with the Creator and then with our fellow man. The results of these dysfunctional relationships often result in suffering, death, and the spoiling of the land and its creatures. The prevailing humanistic view of environment interprets this wonton destruction by man a tragedy and views mankind as an evolutionary newcomer to the world scene (Hölldobler and Wilson 1994). Others have a more extreme view and see man as a dangerous plague needing to be drastically eliminated (Pianka 2006).

From a creation ecology perspective man needs Christ in order for the proper relationships to be restored. Our relationship with him will manifest itself in our care of each other and our fellow creatures. An understanding of AM symbiosis means that we recognize their function and use the gifts God has given us to restore ecosystems that man has destroyed in his uncaring selfishness. To understand these systems is to allow us to better steward the land in a sustainable way for generations to come. If sustainable agriculture is the goal it will require us to avoid activities that degrade the soil and overwhelm ecological systems. One method of doing this is an ecosystem approach where we manage crop growth with an understanding of the system components. The idea is to work in conjunction with the system and not against it. The more we understand the various components, the more we can manage the land the way it was created to work and take the knowledge learned to impoverished countries where the potential of land improvement will produce enough food for those who are suffering.

## Conclusion

When God commanded us to have dominion and subdue creation, many have misunderstood the intent of the command. This misunderstanding has caused some to interpret it as a justification for wonton environmental harm. However, biblical stewardship has the idea of managing something for someone else. It involves taking control of the land in a benevolent dominion that balances economic needs while maintaining optimum habitat and preserving beneficial ecosystem services for years to come (Hennigan 2009). In order to manage ecosystems in this manner, AM symbioses must be understood and incorporated accordingly. As creation ecologists, resource managers, and farmers understand and use this complex system in their attempt to unravel God's intent, the potential for soil health improvement, the remediation of polluted landscapes, optimum nutrient transport and transfer, and parasite control may allow more efficient and economical ways to grow sustainable crops, especially in impoverished countries. The symbiosis is consistent with God's care and desire to see His handiwork persist without having to step in and recreate the system. Participating in these activities give glory to God and fulfill our stewardship mandate so that all may enjoy and benefit from God's provisions.

## Glossary of Terms

Appresorium—the tip of fungal structures used to penetrate plant cells

Arbuscles—branching fungal structures that form inside plant cortical tissue, where nutrient exchange probably takes place between plant and fungus

Arbuscular Mycorrhiza—endomycorrhizal fungi from the phylum Glomeromycota that are dependent on plants for their survival by entering their cells and obtaining nutrition, in return, the fungi provide the plant with important soil nutrients

Bioremediation—a biochemical technology that uses organisms to restore polluted ecosystems

Biome—large ecosystems such as the desert, rain forest, taiga, and eastern deciduous forest

Biotrophic—an organism completely dependent on nutrients from another organism

Cortex (Cortical)—tissue made of unspecialized cells in the roots and stems of plants, lying between the outer cells of the epidermis and the conducting tissues

Ectomycorrhiza—fungi that do not penetrate the plant cell wall

Endomycorrhiza—fungi enter the plant by penetrating the cell in such a way that the cell membrane is not breached and fungus and plant cytoplasms never mix

Endosymbiont—an organism living inside another where both benefit from the relationship

Extraradical Mycelia—mycelium growing outside the plant, in the soil media

Glomeromycota—fungal phylum referring to the fungi that make up arbuscular mycorrhiza

Hypha—a long, filamentous fungal structure, plural hyphae

Inoculum(a)—the fungal sources of plant colonization that are the basis for starting symbioses with plants

Intraradical Mycelia—mycelium growing inside the plant

Mycelium—the vegetative part of the fungus made up of large numbers of hyphae

Mycorrhiza—literally "fungus root" which are symbiotic associations between fungi and plant roots

Obligate Symbiont—an organism that depends on another (host) and cannot live without it

Periarbuscular Membrane—derived from the plants plasma membrane, it surrounds the colonizing arbuscles in a compartment between the cell wall and plasma membrane

Phytoremediation—a type of bioremediation where terrestrial plants are used to restore polluted ecosystems

Rhizosphere—the area that surrounds the roots of plants

Saprobe (saprobic)—an organism capable of obtaining nutrients from dead or inorganic matter

Turgor Pressure—Pressure against a cell wall created by the contents of a cell and determined by the water content of the vacuole

Vesicles—thin walled, lipid filled structures that sometimes grow between cortical cells from some arbuscular mycorrhizae

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