Mycorrhizae and Soil Quality

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Abstract

Q1 Soil is a dynamic and complex natural system, which is interactively regulated by physical, chemical, and biological properties and processes to provide ecosystem services including crop production. The soil quality as the critical component of the ecosystems is associated with soil's usefulness or performance to environmental quality as well as food quality. Soil quality is related to the development of many soil properties such as providing soil health, reflecting the fitness of a soil body, supporting water quality, sustaining plant productivity, and promoting human health. Soil is a sink for soil organic carbon (SOC). SOC, infiltration, aggregation, pH, microbial biomass, nitrogen forms, topsoil depth, conductivity or salinity, and available nutrients are the important indicators for soil quality. Mycorrhizal fungi also have an effect on soil quality in terms of increase in SOC, aggregation, nutrient uptake, and also increase in soil capacity for better health. The strength of the mycorrhizal association and its relationship with soil structure depends on root morphology and mycorrhizal hyphae. Arbuscular mycorrhizal fungi inoculation often increases the success of the ecological restoration as well. Mycorrhizal fungi are also effect on the soil function and capacity to increase productivity, resilience, and health functions. Also mycorrhizae increase SOC content, rhizosphere fertility, aggregation, porosity, and bulk density and reduce the stress factors that are all increase the soil quality.

WHAT IS SOIL QUALITY?

Soil is a dynamic and complex natural system, which is interactively regulated by physical, chemical, and biological properties and processes to provide ecosystem services including crop production. Soil as part of natural systems is a basis for life and habitat for soil organisms, i.e., plants. Soil's ability and functions in ecosystem to sustain plant and animal productivity and to maintain or enhance water and soil quality are critically important for human health and habitation. The soil quality as the critical component of the ecosystems is associated with soil's usefulness or performance to environmental quality as well as food quality. Soil has a significant contribution on filter of water and nutrient cycles and buffer of the soil reactions. Karlen et al.[1] indicated that organic matter, infiltration, aggregation, pH, microbial biomass, N forms, topsoil depth, conductivity or salinity, and available nutrients are the important indicators for soil quality. Moreover, biological activity, enzymes, total organic carbon (C) and nitrogen (N), cation exchange capacity, aggregation, bulk density, and water retention and release capacity are very sensitive and important indicators of soil quality.[2] Although there is not a complete consensus that has yet reached on the definition of soil quality, soil quality is usually related to soil organic matter (SOM) content, number and diversity of organisms, microbial by-products, hydrologic characteristics, aggregate stability, etc.

Aggregation Is a Very Important Parameter of Soil Quality

The dynamics of soil aggregate characteristics are often associated with changes in management practices and environment. Generally, soils in harsh environment are characterized by poor and compacted soil structures, low water-holding capacity and SOM content, and widespread nutrient deficiency. For a successful crop production or vegetation, it is necessary to improve soil quality and the ability of the plant's adaptation.[3]

Management of SOM is important to maintain soil quality including soil physical characteristics. Soils, in general, have varied C storage capacity and aggregate size distribution. Soil organic carbon (SOC), as the main component of SOM, is an important determinant of the soil physical quality influencing water-holding capacity, porosity, aggregation, and fertility.[4] The SOC content with other essential nutrients directly affects the production of biomass by improving soil quality.[5] Kavdir and Smucker[6] reported that soil structure influences several important soil functions such as soil productivity, biological activity, root growth, soil stability, and nutrient cycling as well. Borie et al.[7] reported that soil structure stability is strongly influenced by the nature and content of SOM. Moreover, land use and management practices influencing SOM content are determinant of soil aggregation. Soil aggregates especially both macro- and

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microaggregates exhibited a significant positive relationship with SOC and particulate organic matter.[8]

WHAT IS THE ROLE OF MYCORRHIZAE IN SOIL?

Arbuscular mycorrhizal fungi (AMF) are the largest symbiotic associations between plants and fungi, which make significant contribution on physical, chemical, and biological aspects of soil quality through AMF hyphae extending into the rhizosphere and thereby improving the absorption of nutrients especially phosphorus (P) and micronutrients.[9–11] The establishment of mycorrhiza causes changes in the physiology of the host plants. Like other soil microorganisms, AMF act as ecosystem engineers on roots and root surface of the plants. The AMF as soil microorganisms play a contributory effect on soil aggregate formation because of the symbiosis that significantly changes the root functioning.[12] Thus, mycorrhiza has a significant impact on soil resilience, which is also an important component of soil quality.

Several studies have reported that soil biology especially mycorrhizal fungi significantly influences soil fertility and soil quality. However, the study on applied mycorrhizae is very new avenue in the field of soil quality research. The AMF also influence other soil functions, such as C, N, and P cycling to support plant growth and nutrition in the agroecosystems. Mycorrhizal inoculated plants are effective competitors in P-limited soil conditions. Several studies reported that mycorrhizal associations improve soil structures and increase uptake of nutrients and water through the extension of AMF hyphae distribution within the rhizosphere.[9–11] Medina and Azcon[3] suggested that soil amended with mycorrhizal fungi inoculation can be used as a successful biostrategy to improve plant performance in P-deficient soils under Mediterranean conditions. As shown in Table 1, mycorrhizal inoculation under field conditions increased the N, P, and K contents of sweet corn.

Table 1 The effect of P application and mycorrhizal inoculation on N, P, and K concentration (%) in shoots of sweet corn at silking.

Treatments	N	P	K
−Mycorrhizae			
P0	2.31 ± 0.01	0.16 ± 0.01	0.80 ± 0.28
P1	2.44 ± 0.02	0.20 ± 0.00	0.90 ± 0.14
P2	2.44 ± 0.12	0.22 ± 0.01	0.60 ± 0.03
+Mycorrhizae			
P0	2.60 ± 0.00	0.22 ± 0.01	1.20 ± 0.28
P1	2.84 ± 0.12	0.23 ± 0.01	1.30 ± 0.14
P2	2.58 ± 0.11	0.24 ± 0.03	1.00 ± 0.28

Source: Ortas & Sari.[13] ©2003.

Mycorrhizal inoculation has been found to decrease the concentrations of salts and electrical conductivity of the soil.[14] The AMF colonization can also improve plant tolerance to stress conditions caused by drought and salt. Cekic, Unyayar, and Ortas[15] showed that under different salt level applications, mycorrhizal inoculation increased relative water content, P, total chlorophyll, and carotenoid content of pepper plants.

Mycorrhizae and Roots Effect on Soil Quality

Soil quality is also related to the rhizosphere beneficial microorganisms, such as AMF and bacteria. The AMF are an active and major component of the soil microbial community and have an important role on soil quality. Barea et al.[16] indicated that symbiotic mycorrhizal associations are fundamental in optimizing plant fitness and soil quality. The AMF symbiosis has been proposed as one of the most effective mechanisms of plant heavy metal tolerance and water stress avoidance due to their effect on rhizosphere physical, chemical, and biological activities.[10] The AMF are expected to have a synergistic effect on crops by improving the soil quality. The potential role of AMF in soil quality is related to improved soil physical properties.[17] The contribution of mycorrhizal inoculation to the SOC content and aggregate formation depends on roots and hyphae productivity, roots and hyphae turnover rates, and their exudation. They improve soil quality by binding microaggregates and primary soil particles together and consequently resulting in: 1) improved soil structure; 2) increased water infiltration and retention; and 3) reduced soil erosion by minimizing leaching and runoff, while making them available to plants. As expected, plant roots are different and have significant effect on soil aggregation. Plant roots and AMF have direct and indirect binding effects on soil aggregate formation and stability. Jastrow, Miller, and Lussenhop[18] have provided the evidence related to the direct effects of mycorrhizal hyphae on soil aggregation. Soil aggregates play an important role in sequestering and stabilizing SOC.[19] Other soil properties are also affected by plant roots and rhizosphere by significantly changing the soil physical, chemical, and biological properties.[20]

Nadian, Hashemi, and Herbert[21] demonstrated that colonized Berseem clover (*Trifolium alexandrinum* L.) root length was improved by 20%, as soil aggregate diameter increased. Six et al.[22] indicated that plant roots influence soil structure in diverse ways such as through root exudation, which includes polysaccharides that help to bind microaggregates and clay particles, and also through root pressure and penetration, which help to increase the proportion of stable aggregates through root entanglement. Mycorrhizae inoculated root also has mycorrhizosphere, which expanded rhizosphere volume and improved soil aggregate formation. The adherence of soil particles and sand grains on the root via AMF

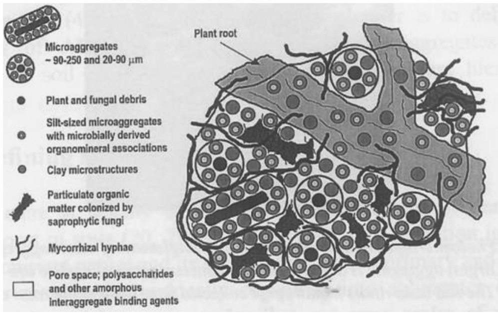

Fig. 1 Aggregate formation by the plant roots and AM mycelium.
Source: Ortas, unpublished data.

mycelia was pictured by Ortaş in field grown sorghum plant (Fig. 1).

The strength of the mycorrhizal association and its relationship with soil structure depend on root morphology[23] and mycorrhizal hyphae. AMF inoculation often increases the success of the ecological restoration.[24] Rillig[12] indicated that AMF are one of the important factors of soil quality through their effects on soil ecological interactions and their contributions to maintaining soil structure. However, AMF contributions on soil physical development depend on several factors and have a significant effect on ecosystem services. The ecosystem services provided by AMF are based on the modification of the root morphology and development of a complex ramified mycelia network in soil. These interactions improve plant–soil adherence and soil stability (binding action and improvement of soil structure), which in turn increase mineral nutrient and water uptake contributions by plants. It has been demonstrated that the mycorrhizal mycelial network can have a binding action on the soil and improve soil structure.[25–27]

A major contribution of AMF in soils is their role on the maintenance of soil structure and plays a significant role in maintaining soil quality. The elongation of AMF from the mycorrhizal root to soil is a complex and ramifying network into the surrounding soil that can reach up to 30 m of fungal hyphae per gram of soil.[28,29] Fig. 2 shows the adherence of soil particles and sand grains on the roots via AM mycelia in soil aggregation conceptual diagram.[30]

Organic amendment and mycorrhizae are the well-known aggregate building agents.[17] Extensive soil-based mycelium of fungus around roots can help soil aggregation processes (Fig. 3).

Mycorrhizal Hyphae, Glomalin, and Soil Quality

AMF enhance soil aggregate stability due to the production of extraradical hyphae and a protein known as glomalin. Glomalin, a brown to red–brown colored glycoprotein

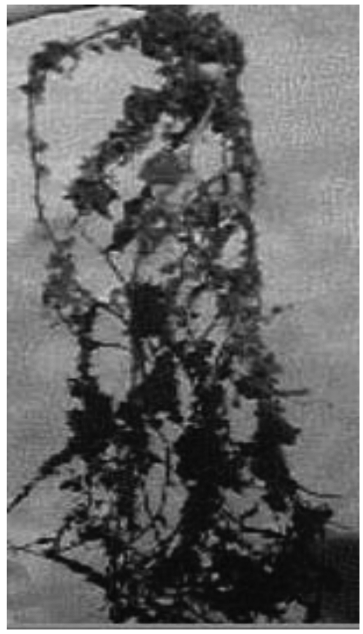

Fig. 2 Aggregate formation by the AM mycelia.
Source: Miller & Jastrow.[30] ©2000 Kluwer Academic Publishers.

produced by AMF, is a major component of SOM that is defined operationally by the extraction method.[31] The AMF, fed on C, found living on plant roots and appear to be the only producer of glomalin. A laboratory procedure reveals glomalin accumulation on soil aggregates as the green material (Fig. 4). Wright and Upadhyaya[33] have shown a strong non-linear relationship of the AMF hyphae product “glomalin” with water-stable aggregates across several soil types.

Glomalin was reported to be a non-water soluble, highly persistent glycoproteinaceous substance[33] produced in mycorrhizal fungal cell walls, and it remains in soil after hyphae died.[34] A strong correlation has been found between glomalin and water-stable aggregates in a wide

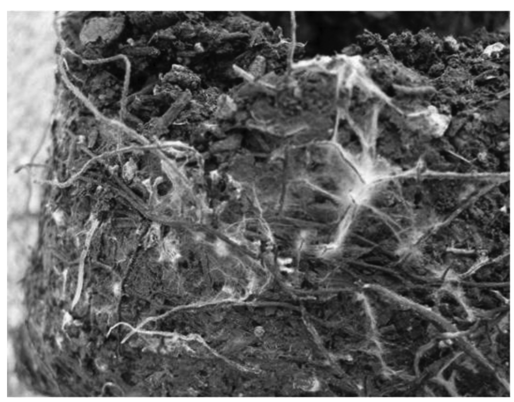

Fig. 3 Mycorrhizal hyphae through soil profile.
Source: Photo by Ortas, unpublished data.

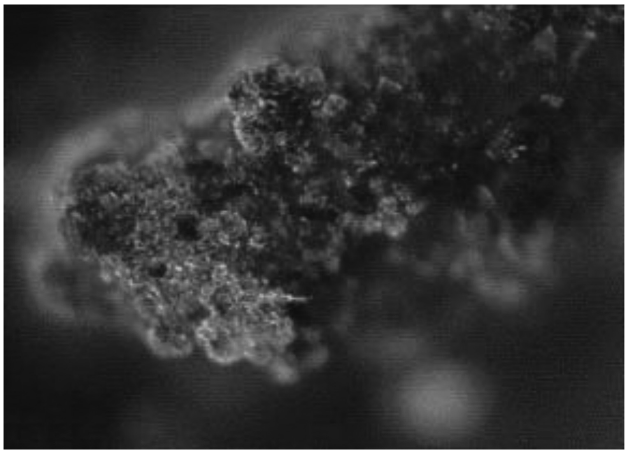

Fig. 4 Glomalin under microscope.
Source: Nichols.[32] ©2010.

variety of soils where organic material is the main binding agent.[12,35] Wright and Upadhyaya[36] indicated that increased aggregate stability, which leads to better soil structure, in turn, leads to control soil erosion for better plant production.

Bedini et al.[37] showed that the secretion by AMF glomalin contributes to soil stability and water retention. Furthermore, it has been indicated that higher levels of glomalin increase water infiltration, improve porosity and air permeability, better root development, improve microbial efficiency, and increase resistance to surface sealing and erosion. Driver, Holben, and Rillig[34] indicated that glomalin is thought to be deposited in soil by the degradation of extraradical hyphae of AMF. Bedini et al.[37] indicated that (AM) fungi are key organisms of the soil–plant system, influencing and contributing to soil aggregation and soil structural stability by the combined action of extraradical hyphae and of a hydrophobic proteinaceous substance named glomalin. Rillig, Wright, and Eviner[38] shown that AMF hyphae and their glomalin products had significant contribution on water-stable aggregates of soil.

Treseder and Turner[39] postulated that the role of glomalin in the ecosystem is not very clear and should be studied thoroughly under long-term and diverse management systems. Glomalin as a strong cementing agent is produced by a beneficial fungus that grows on plant roots. When hyphae stop transporting water, their protective glomalin sloughs off into the soil, where it helps soil build defenses against degradation and erosion and boosts its productivity.

As mycorrhizae produce enzymes (such as alkaline phosphatase), the activity of phosphatase can increase plant nutrient uptake as well.[40] Phosphatase enzymes are developed by plants for an effective P acquisition and possibly for N and less mobile micronutrients.

EFFECT OF MYCORRHIZA INOCULATIONS ON SOIL QUALITY UNDER LONG-TERM FIELD CONDITIONS

Long-term effects of mycorrhizal inoculation (after 14 years) on soil quality were presented in Table 2. Water-stable aggregation (WSA) had significantly affected by the organic (mycorrhiza + compost 10 ton ha^{-1}) and inorganic fertilizer treatments after 14 years' long-term experiment and ranged from 71.1% to 87.6%. The highest WSA was observed in compost + mycorrhizae treatment (87.6%), whereas the lowest WSA was found in control treatment (71.13%); mineral fertilizer has 74.6% of WSA. Mean weight diameter (MWD) of aggregates increased by 44% under the mycorrhizae + compost treatment as compared with the control.

Bedini et al.[37] showed that MWD values of soil aggregates were positively correlated with the values of total hyphae length and hyphae density of the AMF. They also showed that the MWD of macroaggregates was significantly higher in mycorrhizal inoculated soils as compared to the non-mycorrhizal soils. Ortas et al.[17] showed that the high values of MWD were associated with mycorrhizal inoculation rather than with application of organic fertilizer and that the MWD depended more on mycorrhizae application than on SOC content. Wilson et al.[29] also reported that AMF abundance was a dominant factor affecting variability in soil WSA and MWD. The development of soil structure and the dynamics of WSA in many soils are closely related to the SOM cycling and the magnitude of root growth and mycorrhizal hyphae.[41,42] Smith and Read[10] concluded that the contribution of mycorrhizal root plus hyphae on aggregation is more than those of the

Table 2 Effect of mineral fertilizer and mycorrhizae + compost application on soil properties after 14 years' long-term field experiment.

	SOM (%)	Bulk density (ρb; g cm^{-3})	Total porosity (St; %)	Soil-available water (cm^{-3})	WSA (%)	MWD
Treatments						
Control	1.50	1.46	45	8.69	71.13	1.47
Mineral fertilizer	2.01	1.47	48	9.45	74.72	1.43
Mycorrhizal + compost	2.31	1.31	53	11.48	87.60	2.12

Source: Ortas, unpublished data.

hyphae alone, and that under pasture, the contribution of root and hyphae to WSA increases with increase in SOC content.

There were also significant differences in SOM content among the treatments (Table 2). The SOM content was 2.01% and 2.31% for chemical fertilizer and compost +mycorrhizae treatments, respectively, as compared with the SOM content in control (1.50%). Increasing SOM increases aggregate stability, infiltration, nutrient mineralization and availability, and cation exchange capacity. It suggests that mycorrhizal inoculation increased SOM content, which is directly related to soil quality. According to Harris, Karlen, and Mulla's[43] soil quality assessment scorecard, SOC has high score range. Soil bulk density, porosity, and soil water availability were significantly affected by mycorrhizal inoculation compared with the chemical fertilizer treatment.

There were also significant differences in total porosity among the treatments. As discussed earlier, Ortas et al.[17] showed that soils treated with the compost + mycorrhizae organic fertilizers have the highest total porosity (St). The porosity was 45%, 48%, and 53% for control, chemical fertilizer, and compost + mycorrhizae treatments, respectively (Table 2).

Soil quality is related to the development of many soil properties such as providing soil health, reflecting the fitness of a soil body, supporting water quality, sus-
Q2 taining plant productivity, and promoting human health. Mycorrhizal fungi are also effect on the soil function and capacity to increase productivity, resilience, and health functions. Also mycorrhizae increase SOC content, rhizosphere fertility, aggregation, porosity, and bulk density and reduce the stress factors that are all increase the soil quality. Accordingly, it seems that mycorrhizal fungi have significant contribution on soil quality development. Usually, soil physical and chemical components were used for soil quality assessment; it may be possible to use mycorrhizae as a biological component as well. Usually, healthy soils have a rich diversity of soil useful microorganisms including mycorrhizal fungi. Mycorrhizal infection and spore germination can also be used as a soil quality indicator.

REFERENCES

1. Karlen, D.L.; Mausbach, M.J.; Doran, J.W.; Cline, R.G.; Harris, R.F.; Schuman, G.E. Soil quality: A concept, definition, and framework for evaluation (A Guest Editorial). Soil Sci. Soc. Am. J. **1997**, *61*, 4–10.
2. Askari, M.S.; Holden, N.M. Indices for quantitative evaluation of soil quality under grassland management. Geoderma **2014**, *230*, 131–142.
3. Medina, A.; Azcon, R. Effectiveness of the application of arbuscular mycorrhiza fungi and organic amendments to improve soil quality and plant performance under stress conditions. J. Soil Sci. Plant Nutr. **2010**, *10*, 354–372.
4. Tisdall, J.M.; Oades, J.M. Organic matter and water-stable aggregates in soils. J. Soil Sci. **1982**, *33*, 141–163.
5. Lal, R. Soil quality impacts of residue removal for bioethanol production. Soil Till. Res. **2009**, *102*, 233–241.
6. Kavdir, Y.; Smucker, A.J.M. Soil aggregate sequestration of cover crop root and shoot-derived nitrogen. Plant Soil **2005**, *272*, 263–276.
7. Borie, F.; Rubio, R.; Morales, A. Arbuscular mycorrhizal fungi and soil aggregation. Rev. Cienc. Suelo Nutr. **2008**, *8*, 9–18.
8. Mikha, M.M.; Benjamin, J.G.; Vigil, M.F.; Nielson, D.C. Cropping intensity impacts on soil aggregation and carbon sequestration in the Central Great Plains. Soil Sci. Soc. Am. J. **2010**, *74*, 1712–1719.
9. Karandashov, V.; Bucher, M. Symbiotic phosphate transport in arbuscular mycorrhizas. Trends Plant Sci. **2005**, *10*, 22–29.
10. Smith, S.E.; Read, D.J. *Mycorrhizal Symbiosis*; Academic Press: San Diego, 2008.
11. Ortas, I. Effect of selected mycorrhizal inoculation on phosphorus sustainability in sterile and non-sterile soils in the Harran Plain in South Anatolia. J. Plant Nutr. **2003**, *26*, 1–17.
12. Rillig, M.C. Arbuscular mycorrhizae, glomalin, and soil aggregation. Can. J. Soil Sci. **2004**, *84*, 355–363.
13. Ortas, I.; Sari, N. Enhanced yield and nutrient content of sweet corn with mycorrhizal inoculation under field conditions. Agricoltura Mediterranea **2003**, *133* (3–4), 188–195.
14. Li, Y.; Chen, Y.L.; Li, M.; Lin, X.-G.; Liu, R.-J. Effects of arbuscular mycorrhizal fungal communities on soil quality and the growth of cucumber seedlings in a greenhouse soil of continuously planted to cucumber in North China. Pedosphere **2012**, *22*, 79–87. Q3
15. Cekic, F.O.; Unyayar, S.; Ortas, I. Effects of arbuscular mycorrhizal inoculation on biochemical parameters in *Capsicum annuum* grown under long term salt stress. Turk. J. Bot. **2012**, *36*, 63–72.
16. Barea, J.M.; Palenzuela, J.; Cornejo, P.; Sánchez-Castro, I.; Navarro-Fernández, C.; Lopéz-García, A.; Estrada, B.; Azcón, R.; Ferrol, N.; Azcón-Aguilar, C. Ecological and functional roles of mycorrhizas in semi-arid ecosystems of Southeast Spain. J. Arid. Environ. **2011**, *75*, 1292–1301.
17. Ortas, I.; Akpinar, C.; Lal, R. Long-term impacts of organic and inorganic fertilizers on carbon sequestration in aggregates of an entisol in Mediterranean Turkey. Soil Sci. **2013**, *178*, 12–23.
18. Jastrow, J.D.; Miller, R.M.; Lussenhop, J. Contributions of interacting biological mechanisms to soil aggregate stabilization in restored prairie. Soil Biol. Biochem. **1998**, *30*, 905–916.
19. Sundermeier, A.P.; Islam, K.R.; Raut, Y.; Reeder, R.C.; Dick, W.A. Continuous no-till impacts on soil biophysical carbon sequestration. Soil Sci. Soc. Am. J. **2011**, *75*, 1779–1788.
20. Ortas, I. Determination of the extent of rhizosphere soil. Commun. Soil Sci. Plan. **1997**, *28*, 1767–1776.
21. Nadian, H.; Hashemi, M.; Herbert, S.J. Soil aggregate size and mycorrhizal colonization effect on root growth and phosphorus accumulation by berseem clover. Commun. Soil Sci. Plan. **2009**, *40*, 2413–2425.

22. Six, J.; Bossuyt, H.; Degryze, S.; Denef, K. A history of research on the link between (micro)aggregates, soil biota, and soil organic matter dynamics. Soil Till. Res. **2004**, *79*, 7–31.
23. Miller, R.M.; Jastrow, J.D. Hierarchy of root and mycorrhizal fungal interactions with soil aggregation. Soil Biol. Biochem. **1990**, *22*, 579–584.
24. Jeffries, P.; Gianinazzi, S.; Perotto, S.; Turnau, K.; Barea, J.-M. The contribution of arbuscular mycorrhizal fungi in sustainable maintenance of plant health and soil fertility. Biol. Fert. Soils **2003**, *37*, 1–16.
25. Tisdall, J.M.; Smith, S.E.; Rengasamy, P. Aggregation of soil by fungal hyphae. Aust. J. Soil Res. **1997**, *35*, 55–60.
26. Rillig, M.C.; Wagner, M.; Salem, M.; Antunes, P.M.; George, C.; Ramke, H.-G.; Titirici, M.-M.; Antonietti, M. Material derived from hydrothermal carbonization: Effects on plant growth and arbuscular mycorrhiza. Appl. Soil Ecol. **2010**, *45*, 238–242.
27. Caravaca, F.; Alguacil, M.M.; Azcón, R.; Roldán, A. Formation of stable aggregates in rhizosphere soil of *Juniperus oxycedrus*: Effects of AM fungi and organic amendments. Appl. Soil Ecol. **2006**, *33*, 30–38.
28. Cavagnaro, T.R.; Smith, F.A.; Smith, S.E.; Jakobsen, I. Functional diversity in arbuscular mycorrhizas: Exploitation of soil patches with different phosphate enrichment differs among fungal species. Plant Cell Environ. **2005**, *28*, 642–650.
29. Wilson, G.W.T.; Rice, C.W.; Rillig, M.C.; Springer, A.; Hartnett, D.C. Soil aggregation and carbon sequestration are tightly correlated with the abundance of arbuscular mycorrhizal fungi: Results from long-term field experiments. Ecol. Lett. **2009**, *12*, 452–461.
30. Miller, R.M.; Jastrow, J.D. Mycorrhizal fungi influence soil structure. In *Arbuscular Mycorrhizas: Physiology and Function*; Kapulnik, Y., Douds, D.D., Eds.; Kluwer Academic Publishers: Dordrecht, 2000; 3–18.
31. Nichols, K.A.; Wright, S.F. Comparison of glomalin and humic acid in eight native U.S. soils. Soil Sci. **2005**, *170*, 985–997.
32. Nichols, K.A. Glomalin production and accumulation in soilless pot cultures. Can. J. Soil Sci. **2010**, *90*, 567–570.
33. Wright, S.F.; Upadhyaya, A. A survey of soils for aggregate stability and glomalin, a glycoprotein produced by hyphae of arbuscular mycorrhizal fungi. Plant Soil **1998**, *198*, 97–107.
34. Driver, J.D.; Holben, W.E.; Rillig, M.C. Characterization of glomalin as a hyphal wall component of arbuscular mycorrhizal fungi. Soil Biol. Biochem. **2005**, *37*, 101–106.
35. Rillig, M.C.; Ramsey, P.W.; Morris, S.; Paul, E.A. Glomalin, an arbuscular-mycorrhizal fungal soil protein, responds to land-use change. Plant Soil **2003**, *253*, 293–299.
36. Wright, S.F.; Upadhyaya, A. Extraction of an abundant and unusual protein from soil and comparison with hyphal protein of arbuscular mycorrhizal fungi. Soil Sci. **1996**, *161*, 575–586.
37. Bedini, S.; Pellegrino, E.; Avio, L.; Pellegrini, S.; Bazzoffi, P.; Argese, E.; Giovannetti, M. Changes in soil aggregation and glomalin-related soil protein content as affected by the arbuscular mycorrhizal fungal species *Glomus mosseae* and *Glomus intraradices*. Soil Biol. Biochem. **2009**, *41*, 1491–1496.
38. Rillig, M.C.; Wright, S.F.; Eviner, V.T. The role of arbuscular mycorrhizal fungi and glomalin in soil aggregation: Comparing effects of five plant species. Plant Soil **2002**, *238*, 325–333.
39. Treseder, K.K.; Turner, K.M. Glomalin in ecosystems. Soil Sci. Soc. Am. J. **2007**, *71*, 1257–1266.
40. Tarafdar, J.C.; Marschner, H. Phosphatase-activity in the rhizosphere and hyphosphere of VA mycorrhizal wheat supplied with inorganic and organic phosphorus. Soil Biol. Biochem. **1994**, *26*, 387–395.
41. Rillig, M.C.; Mardatin, N.F.; Leifheit, E.F.; Antunes, P.M. Mycelium of arbuscular mycorrhizal fungi increases soil water repellency and is sufficient to maintain water-stable soil aggregates. Soil Biol. Biochem. **2010**, *42*, 1189–1191.
42. Hallett, P.D.; Feeney, D.S.; Bengough, A.G.; Rillig, M.C.; Scrimgeour, C.M.; Young, I.M. Disentangling the impact of AM fungi versus roots on soil structure and water transport. Plant Soil **2009**, *314*, 183–196.
43. Harris, R.F.; Karlen, D.L.; Mulla, D.J. A conceptual framework for assessment and management of soil quality and health. In *Methods for Assessing Soil Quality*; Doran, J.W., Jones, A.J., Eds.; SSSA: Madison, 1996; 61–82.

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