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Arbuscular mycorrhizal fungi and common mycorrhizal networks benefit plants through morphological, physiological and productive traits and soil quality

Los hongos micorrícicos arbusculares y las redes micorrízicas comunes benefician a las plantas a través de caracteres morfológicos, fisiológicos y productivos y la calidad del suelo

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ABSTRACT

The extraradical hyphae of arbuscular mycorrhizal fungi (AMF) of one plant root system forage for the soil nutrients and induce the root colonization of the nearby plants, which leads to the formation of common mycorrhizal networks (CMNs) that interconnect roots. Inoculation with AMF can increase the root length, surface area and volume of seedlings in nutrient-limited karstic soils. Mycorrhizal symbioses can secrete glomalin to help promoting soil aggregates for water and nutrients storage, through an extended hyphae to absorb water and nutrients from long distances. AMF can boost rhizosphere soil enzyme activities, and may help to drive carbon sequestration. AMF also improve plant growth by advancing soil quality through influencing its structure and texture. As a result, AMF and CMNs benefit plants through improving soil quality and enhancing morphological (e.g., hyphal length, tillering, number of stolons per individual), physiological (e.g., water use efficiency) and productive (e.g., fresh and dry shoot and root weights) traits.

Keywords — Common mycorrhizal networks; morphological, physiological and productive traits; soil quality.

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RESUMEN

Las hifas extraradicales de los hongos micorrízicos arbusculares (HMA) de un sistema radical vegetal se proveen de nutrientes del suelo e inducen la colonización de las raíces de las plantas cercanas. Esto conduce a la formación de redes micorrízicas comunes (RMCs) que interconectan los sistemas radicales. La inoculación con los HMA puede incrementar la longitud radical, el área superficial y el volumen de las plántulas en suelos kársticos limitados en nutrientes. La simbiosis micorrízica es capaz de secretar glomalina que incrementa el almacenaje de agua y nutrientes en los agregados del suelo, a través de una extensión de las hifas que permite absorber agua y nutrientes desde largas distancias. Los HMA pueden enriquecer la actividad de las enzimas que están en la rizosfera del suelo, y pueden ayudar a incrementar el secuestro de carbono. Los HMA también benefician el crecimiento de las plantas mejorando la estructura y textura del suelo. Como resultado, los HMA y las RMCs benefician a las plantas modificando el suelo y mejorando caracteres morfológicos (ej., longitud de hifas, macollaje, número de estolones por individuo), fisiológicos (ej. eficiencia de uso del agua) y productivos (ej. pesos frescos y secos del tallo y de las raíces).

Palabras clave — Redes micorrízicas comunes; caracteres morfológicos, fisiológicos y productivos; calidad de suelo.

INTRODUCTION

Nearly 90% of plant species including flowering plants, bryophytes and ferns can develop interdependent connections with arbuscular mycorrhizal fungi (AMF) (Ahanger *et al.*, 2014). Formation of hyphal network by the AMF with plant roots significantly enhance the access of roots to a large soil surface area, causing an improved nutrient uptake and improvement in plant growth (Bowles *et al.*, 2016). AMF form vesicles, arbuscules, and hyphae in roots, and also spores and hyphae in the rhizosphere. Fungal hyphae can expedite the decomposition process of soil organic matter (Paterson *et al.*, 2016). Furthermore, mycorrhizal fungi may affect atmospheric CO_2 fixation by host plants, by increasing sink effect and movement of photo-assimilates from the shoots to the roots.

The symbiosis of AMF with plants had been reported 400 million years ago (Selosse *et al.*, 2015). Such types of links are established as a succession of biological processes, which lead to a variety of useful effects in both natural ecosystem and agricultural biotas (Van Der Heijden *et al.*, 2015). The symbiotic association of AMF is a classic example of mutualistic relationship, which can regulate the growth and development of plants. The mycelial network of fungi extends under the roots of the plant and promotes nutrient uptake that is otherwise not available. The fungal mycelium colonizes roots of many plants even if they belong to different species, resulting into a common mycorrhizal network (CMN). This CMN is considered a primary component of the terrestrial ecosystem with its significant effects on different plant communities, particularly on invasive plants (Pringle *et al.*, 2009) and the fungal-mediated transport of phosphorus (P) and nitrogen (N) to plants (Smith& Read, 2008). AMF have the ability to improve characteristics of soil and consequently encourage plant development in normal as well as in stressful circumstances (Navarro *et al*., 2014). AMF are used as bio-inoculants, and researches encourage their use as prominent bio-fertilizers in sustainable crop productivity (Barrow, 2012). Glomalin-related soil protein (GRSP) is believed to maintain water content in soils exposed to different abiotic stresses (Wu *et al*., 2014), which later on regulates water frequencies between soils and plants, triggering plant development. Glomalin contains 30-40% C and its related compounds that safeguard soil from desiccation by enhancing the soil water holding capacity (Sharma *et al*., 2017). Exploitation of AMF for plant growth in various biological ecosystems can contribute greatly to organic culturing for growth promotion and yield maximization.

Bio-fertilizer is a substance containing live microorganisms which exhibit beneficial properties toward plant growth and development (Pandey & Chandra, 2016). These fertilizers are useful for soil health and plant growth and development (Sadhana, 2014). Different research studies conducted on AMF during the past two decades have highlighted their countless benefits on soil health and crop productivity. Therefore, it is widely believed that AMF can effectively reduce the quantitative use of chemical fertilizer. This is because mycorrhizal application can effectively reduce the quantitative use of chemical fertilizer input especially of phosphorus (Ortas, 2012). Continuous use of organic fertilizers, herbicides, and fungicides has caused serious problems to soil, plant, and human health, through their damaging impact on the quality of food products, soil health, and air and water systems (Yang *et al.*, 2004). It is believed that AMF can possibly lower down the use of chemical fertilizers up to 50% for best agricultural production, but this estimate depends on the type of plant species and the prevalent stressful regimes as was reported by Begum *et al*. (2019).

The distribution of limiting nutrients (e.g., N) among the interconnected plants is influenced by the formation of common mycorrhizal networks (CMNs) between the roots of conspecific and heterospecific plant individuals (Hogh-Jensen, 2006). The extraradical hyphae of AMF (AMF) of one plant root system forage for the soil nutrients and induce the root colonization of the nearby plants, which leads to the formation of CMNs that interconnect roots. Because of this, N transfer from one plant (donor) to another (receiver) is not restricted to mass flow and diffusion through soil pathways. The agricultural and ecological importance of CMNs might be clarified by understanding the directions and magnitude of nutrient transfer between plants through CMNs (Hogh-Jensen, 2006). The indefinite host range of arbuscular mycorrhiza fungi is what allows them to interconnect plants of the same or different species (Smith & Read 2008). CMNs are very important for the mineral nutrient distribution among the interconnected plant species, especially in N-limited habitats (Nara, 2006). Because of this, plant morphology and production and soil quality are improved (Begum *et al*., 2019; Muneer *et al*. 2020; Duan *et al*., 2021).

SOME BENEFITS OBTAINED BY PLANTS FROM ROOT COLONIZATION BY MYCORRHIZAE AND COMMON MYCORRHIZAL NETWORKS

Morphological, physiological and productive traits

A significant decrease in AMF colonization rates of wheat roots was caused by increasing plant densities (Duan *et al*., 2021). These authors also reported the same trend as the root colonization rate for the hyphal length of soil. However, plant density did not have a significant effect on the AMF colonization rate in the non-irrigated treatment (Duan *et al*., 2021). The results of these authors disagree with those of Eissenstat & Newman (1990), who found that AMF colonization rate increased as plant density also increased. Duan *et al*. (2021) suggested that this may be related to differences in the experimental conditions such as the plant species and the AMF fungal species. They indicated that the intraspecific competition increased as plant density also increased, but the dry matter production of wheat decreased. As a result, they concluded that as plant density increased, the photosynthetic product transport from the plant to the mycorrhizal fungi was reduced, which eventually determined a reduction in the mycelial growth of mycorrhizal fungi. Even more, the root colonization rate increased in the non-irrigated treatment in comparison to well-irrigated conditions, especially at high densities. These results agree with those reported by Rahimzadeh & Pirzad (2017) but disagree with results of Kohler *et al.*, (2009). These later authors found that AMF colonization was significantly decreased by unirrigated conditions in other plant species. Duan *et al*. (2021) attributed this difference in the obtained results to the experimental conditions under which the studies were conducted (e.g., AM fungal species, wheat variety, level of fertilization, etc.).

Furthermore, root colonization rate by AMF in the inoculated wheat plants was greater under drought stress than under all remaining treatments, and it was positively correlated to shoot biomass, grain yield, harvest index and water use efficiency (Duan *et al*., 2021). These authors also demonstrated that wheat grain yield, shoot biomass, shoot biomass water use efficiency and grain yield water use efficiency showed an increased trend when the studied plant densities increased from 50 to 800 plants m^{-2}, and then declined up to the studied plant densities reached 3200 plants m^{-2} in all studied treatments during the two studied growing seasons. Duan *et al.* (2021) showed that the AMF symbiosis with plants provided benefits for dryland wheat production, which agrees with studies of Zhang *et al*. (2016) and Sui *et al*. (2019). Under well irrigated conditions, however, AMF inoculation had different, although not significant effects. For example, at low plant densities, AMF inoculation increased grain yields and aboveground biomass, but at high plant densities, grain yields and aboveground biomass were reduced in the irrigated and AMF inoculated treatment in comparison to the irrigated treatment. These results may be due to that the role of mycorrhizae is reduced under high soil moisture conditions (Trejo *et al*., 2016). This is, plants do not need to absorb water and nutrients through mycorrhizas under sufficient water conditions.

In general, harvest index tended to decrease with the increase in plant density over two growing seasons (Duan *et al*., 2021). Lack of irrigation greatly reduced the wheat harvest index but increased it when inoculated with AMF (Duan *et al*., 2021). This suggests that the mycorrhizal symbiont helps the host to absorb deeper water and nutrients, reducing intraspecific competition as a result and ultimately promoting higher yields under dryland conditions. In the study of Duan *et al*. (2021), shoot biomass water use efficiency was lower at low than high plant densities. This is, high plant densities greatly improved water use efficiency. Even more, wheat water use efficiency was greater in the irrigated than in the non-irrigated treatment in both years. This was because the increment of water consumption was lower than the increment of production in the irrigated treatment.

Shoot and grain yields water use efficiencies were greater when inoculated with AMF under non-irrigated than under irrigated conditions (Duan *et al*., 2021). Zhang *et al*. (2016) reported that the symbiosis of AMF with wheat improved water uptake, water use efficiency, and phosphorus uptake of the wheat by the external hyphae of AMF. However, in the study of Duan *et al*. (2021) mycorrhizal inoculation had no significant effect in most cases on the shoot weight, grain yield, or harvest index at high plant densities in the well-irrigated treatment compared with non-mycorrhizal inoculation treatments, except at some low plant densities which agrees with the results of Trejo *et al.* (2016). This may be attributed to the AMF forming a mycelium network structure among plants that enhance the intraspecific competition and reduce the amount of carbon available for growth in host plants unable to adjust their carbon assimilation rate to match the increased demand created by the AMF sink, especially with the increasing plant density (Duan *et al*., 2021). These results show that under not enough water conditions, AMF inoculation enhances crop drought tolerance, increases the water use efficiency and harvest index, and finally improves crop productivity. The different effects of AMF at different plant densities can be attributed to the increase of light competition between plants and the decrease in photosynthetic capacity as plant density increases. This suggests that photosynthetic products were a more important limiting factor for hosts plants than soil water and nutrients especially in well-irrigated conditions, so that the mycorrhizae became less important for host plants and their effects decreases as the plant density increases (Duan *et al*., 2021).

Zhu *et al.* (2017) reported that AMF inoculation significantly further improved grain yield over plastic film mulching (PFM), showing an amplifying effect on the PFM system. Plastic film mulching is an agricultural management practice that is mostly used to inhibit weed growth (Cuello *et al*., 2015). Increased field productivity resulted from improved soil hydrothermal conditions under PFM or coupled PFM with AMF. It was noted that the warming effects of PFM were produced early in the growth stages, which benefit seedling growth and biomass accumulation at the cool early spring (Cuello *et al*., 2015). Additionally, plastic mulching suppressed soil water evaporation (Chai *et al*., 2014) and in the meantime impelled water movement from deep to shallow soil layers, leading to substantial increases in topsoil moisture (Gao *et al*., 2014), which affected AM fungal spores and diversity in the wheat rhizosphere soil (Liu *et al*., 2015).

In a recent experiment of Xia *et al*. (2020), the AM fungus *Glomus etunicatum* differentially increased the dry weight, length, surface area, volume, tips, branching points and N and P contents in the roots of the invasive *Eupatorium adenophorum* and the native *Artemisia annua*. Previous studies have shown that AM mycelia can complement plant roots to expand the uptake range from soil to improve plant nutrients (Nottingham *et al*., 2013). For instance, AM fungi could obtain N from organic matter and transfer it to host plants (Hodge *et al*., 2004), and could enhance P uptake for the invasive plant *Microstegium vimineum* (Lee *et al*., 2014). Lee *et al*. (2014) reported that invasive plant species can interact with native soil microbes in ways that change how they use nutrients and allocate biomass. These authors showed for the first time that the invasive plant *Microstegium vimineum* was mycorrhizal, with greater colonization rates in its native than the invaded range. *Microstegium vimineum* biomass accumulation (both fresh and dry weight of shoots and roots) was significantly promoted by the addition of an AMF inoculum mixture in both field and sterilized soils. More interestingly, AMF altered plant morphology by increasing the number of stolons and aerial roots per individual, aerial roots per gram aboveground biomass and aerial roots per stolon. Their results suggested that mycorrhizal enhancement of plant growth by stimulating tillering may serve as another mechanism by which *M. vimineum* can quickly take over new territory.

Arbuscular mycorrhizal fungi promoted the root growth of *E. adenophorum* and *A. annua* consisting of root morphology changes and root biomass enhancement of seedlings that promoted growth and development via AM fungi (Xia *et al*., 2020). Root morphological plasticity, when associated with AM fungi, may be more substantial in karst habitats with limited nutrients. For example, Yang *et al*. (2017) discovered that inoculation with AM fungi markedly increased the root length, surface area and volume of *Cinnamomum camphora* seedlings in karst soil. Zhang *et al* (2015) showed that AM fungi significantly enhanced the total root length, surface area and volume of *Cyclobalanopsis glauca* in karst rocky desertification areas. Root morphology can reveal a plant´s ability to absorb nutrients (Hodge, 2004), and different plant species vary in the plasticity of their root morphology when in association with microorganisms or in response to other factors (Osmont, 2007). The results of Xia *et al.* (2020) indicated that invasive plants overall exhibited better performance of root traits and nutrients than a co-ocurring common native plant in a karst region. This agrees with findings of previous studies comparing invasive and native plants (Wang *et al*., 2019). Xia *et al*. (2020) found that root traits and nutrient utilization of an invasive plant were greater than those on a native plant in a mycorrhizal fungus treatment inoculated with *G. etunicatum* than on that without the fungus. Zhang *et al.* (2018) also showed that AM fungi rendered invasive species presenting superior plant traits compared with native species. Together, these results indicated that invasive plant is competitively superior over the co-occurring native plant when with AM fungi.

He & Zhong (2012) showed that root average diameter and number of tips are parameters reflecting root absorption efficiency. However, Fitter *et al*. (1994) suggested that fine roots have low input, large surface area and short life, while thicker roots grow fast and have a long life, but have a relatively small surface area, so fine roots have more robust uptake capacity. In the study of Xia *et al.* (2020) AM fungi decreased the root average diameter, and significantly increased the number of root tips of *E. adenophorum* and *A. annua* seedlings. This indicated that AM fungi can enhance the root absorption area and efficiency of invasive and native plants in nutrient-deficient karst soil. The greater the specific root length and area, the greater the ability of fine roots to absorb nutrients and water (Pregitzer *et al*., 2002). Wang *et al.* (2016) determined that AM fungi had a significant effect on the specific root length and area of *Sinocalyanthus chinensis*. In the study of Xia *et al*. (2020) the AM fungus differentially improved the specific root length of invasive *E. adenophorum* and native *A. annua*, and enhanced the specific root area of *E. adenophorum*. This study also showed that the increases were greater in the invasive *E. adenophorum* as compared to the native *A. annua*.

Arbuscular mycorrhizal fungi affected plant competition on nutrient uptake (Zabinski *et al*., 2002) and enhanced the invasiveness of alien plants competing with native plants (Yu *et al*., 2014), which likely is mediated by mycorrhizal networks among plant species (Weremijewicz & Janos, 2013). AM fungi regulate competition among host plants by reallocating soil resources through mycorrhizal networks (Van Der Heijden *et al*., 2008; Van Der Heijden *et al*., 2015). Weremijewicz *et al*. (2016) found that common mycorrhizal networks can amplify competition by preferential mineral nutrient allocation to large host plants, and Awaydul *et al*. (2019) showed that common mycorrhizal networks preferentially transferred mineral nutrients to the invasive species, but inhibited the nutrient uptake of native species.

Additionally, AM fungi will inevitably cause changes in plant phenotype while improving plant nutrients (Lin *et al*., 2013). Plants will maximize resources use to adapt to competition by regulating productivity and root morphology (Rubio *et al*., 2001). Research showed that increasing the number of root tips can enhance the ability of plants to use soil resources *in situ* (Campbell *et al*., 1991). Also, the growth and extension of lateral roots can increase the root length and expand the spatial area where plants can utilize soil resources (Henke *et al*., 2014). Root surface area and root length can be used to represent to root competitiveness (Casper & Jackson, 1997; Mommer *et al*., 2011). Root diameter size determines the utilization efficiency of plant roots for belowground resources, and the uptake capacity of nutrients and water by the smaller diameter roots higher than that the thicker diameter roots (De Kroon & Visser, 2013). Meanwhile, the smaller the root diameter, the larger the specific root length, indicating that the plant root system has greater uptake ability (Hodge, 2004).

Soil quality

In order to cope with the negative effects of climate change on agricultural production, environment-friendly agronomic measures have been explored in recent years (Mowery *et al*., 2010). Beneficial soil microorganisms like AMF have shown great potential as part of organic agriculture (Hodge *et al*., 2004). Organic agriculture (OA) as a model for agricultural sustainable development has received increasing attention worldwide (Youngberg & DeMuth, 2013). Organic agriculture aims to reduce or stop the application of pesticides and chemical fertilizers, and instead increase nutrient recycling as much as possible, in order to realize the aim of a green environment while improving agricultural output (Oelofse *et al*., 2010). AMF inoculation is extensively recognized as an environment-friendly agronomic measure in the practice of organic agriculture. Mycorrhizal symbioses can secrete glomalin to help improving soil aggregates for water and nutrients storage (Driver *et al*., 2005), through extended hyphae to absorb water and nutrients from long distance (Ruth *et al*., 2011). Ensuring long-term sustainable use of soil resources while promoting agricultural development is mandatory to find a scientific and rational way to steadily increase crop yields (Mo *et al*., 2020).

Over the last two decades, plastic film mulching (PFM) as an efficient farming technology has been extensively used in drought-prone, relatively-cool areas, which helps to improve agricultural provision and sustainability (Zhou *et al*., 2009). Plastic film mulching can substantially increase topsoil water content by reducing soil evaporation and increasing water movement from deep to shallow soil (Gao *et al*., 2014). In addition, it can also increase topsoil temperature in cool early stage of growing season, and improve seed germination and seedling growth (Zhao *et al*., 2012; Cuello *et al*., 2015). Previous studies showed that topsoil (0-20 cm) temperature was increased by 2-7 ^{o}C in initial growth stage of wheat or maize under PFM in the Loess Plateau of northwest China (Li *et al*., 2013). In recent years, PFM has become one of the major farming technologies to improve wheat productivity in rainfed agricultural regions of China.

One major component which determines the function and sustainability of the ecosystem is soil organic matter (Koch *et al*., 2004). A decrease in field productivity may be further accelerated by soil degradation, which is mainly determined by a decrease in soil organic carbon. Thus, a greater attention has been put in soil organic carbon and total soil N. The functioning of soil microorganisms is essential for the maintenance of soil quality and crop yields. This is because of the importance of soil microorganisms for soil organic matter decomposition, residue degradation, nutrient transformations and determination of the nutrient pool available to plants in the soil (Ren *et al*., 2021). The soil layer affected by plant roots and microorganisms is the rhizosphere, which plays a major role in plant growth and soil quality.

Arbuscular mycorrhizal fungi (AMF) are beneficial to crop growth and productivity; they are considered as ‘‘microbial fertilizers’’ (Sui *et al*., 2019). Soil organic matter decomposition and nutrient cycling (e.g., N), which is a major determinant of a sustainable agriculture (Wezel *et al*., 2014), can be significantly influenced by mycorrhizal fungi (Bedini *et al*., 2009). In spite of intensive agricultural management practices are often considered to reduce mycorrhizal function, AMF generally have positive effects on plant growth and soil quality (Thirkell *et al*., 2017). The role of mycorrhizas may be reduced to neutral symbionts when they are exposed to high nutrient availability, high soil moisture, and disturbances (Trejo *et al*., 2016). This may make farmers doubtful on the application of AMF inoculation in agriculture. Thereafter, more research is necessary to determine the effects of environmental stresses on plant production and soil organic matter decomposition with AMF inoculation. For evaluating the usage of AMF on soil quality and agricultural sustainability are necessary studies which evaluate the AMF inoculation on the soil carbon and N pools.

AMF symbiont with plants exerted a variety of benefits for crop production in dryland agricultural systems (Wu & Xia, 2006). On the one hand, the symbiosis between plants and AMF can improve soil aggregation that enables the storage of more water and nutrients by secreting glomalin (Driver *et al*., 2005). On the other hand, most of root AMF hyphae was also able to enlarge the region and availability of water and nutrients uptake, which enables the host plant to take in more water and mineral elements (Ruth *et al*., 2011). It was demonstrated by molecular techniques that AMF exogenous *Funnelliformis mosseae* acted effectively on soil quality (Zhu *et al*., 2017).

Currently, to increase soil organic matter and its decomposition has become a hot issue in dryland agriculture as a result of climate change. Existing studies suggested that total soil organic carbon (SOC) level was frequently affected by soil temperature and soil enzyme activity, both of which are responsible for the rate of soil organic decomposition (Qi *et al*., 2016). Wang *et al*. (2016a, b) found that while maize productivity was massively improved under plastic film mulching (PFM), total soil organic carbon content in 0-0.15 m topsoil remained almost constant on the Loess Plateau of China. This result was not consistent with the observations of Zhu *et al*. (2017). These authors suggested that it was likely that maize as a crop of large individuals tended to consume more soil organic carbon so as to sustain a higher quantity of metabolic substrates (e.g., water and nutrient uptake and transportation, photosynthetic product transfer and reallocation) in comparison with small individuals of a wheat crop. In their study with wheat, improved soil hydrothermal conditions under PFM led to increases in SOC, which was closely related to the mineralization of soil organic matter. In the treatments with PFM or further with AMF, total rhizosphere SOC was significantly decreased in the period of vigorous development during vegetative growth of wheat (i.e., from jointing to flowering). However, during reproductive growth (from flowering to maturity), total rhizosphere SOC began to recover gradually to a higher level relative to the level before sowing. Therefore, total rhizosphere SOC was increased at maturity in PFM and integrated PFM-AMF treatments (Zhu *et al*., 2017). Actually, there existed a dynamic balance between soil organic matter mineralization and SOC consumption in rainfed farms (Wang *et al*., 2016b). In most cases, the consumption of SOC frequently offset the newly fixed SOC in the soil system if subjected to continuous cropping. Only when the amount of carbon sequestration exceeded the amount of carbon consumption can the final SOC level increase depending on stimuli such as vegetation and climate (Torn *et al*., 1997). Differing from the C_4 maize plant, wheat is a C_3 plant and has a relatively low carbon assimilation rate (Wynn & Bird, 2007). Accordingly, the C_3 wheat plant consumed relatively less SOC than the C_4 maize plant, particularly in semiarid rainfed agricultural areas where soil carbon fixation remained at a relatively low level. In the rainfed wheat field, there was a dynamic balance between carbon consumption and fixation in the soil of root zone. Plastic film mulching application accelerated soil carbon turnover and fertility recovery owing to improved soil hydrothermal conditions, and this trend was further enhanced under AMF inoculation. AMF can improve rhizosphere soil enzyme activities, and may help to drive carbon sequestration (Li *et al*., 2012).

Zhu *et al*. (2017) showed that the net income was significantly elevated under PFM relative to no PFM. Importantly, AMF application further resulted in a significant increase in net income across the two studied growing seasons. The output to input ratio was significantly increased under exotic AMF application in the wet year, and remained at a relatively stable level in the dry year. In this case, Zhu *et al*. (2017) argued that the economic ratio was affected by the absolute level of grain yield as achieved in the wet environment. A dry environment brought a relatively low level of absolute yield, and did not increase the economic ratio significantly. Their findings demonstrated that an integrated AMF-PFM farming system would be a promising farming strategy to increase the provision of agroecosystem services by buffering environment changes and uncertainty. Also, AMF increase plant health by improving soil quality by influencing its structure and texture (Thirkell *et al*., 2017).

CONCLUSIONS

The extraradical hyphae of AMF of one plant root system forage for the soil nutrients and induce the root colonization of the nearby plants, which leads to the formation of common mycorrhizal networks (CMNs) that interconnect roots of the same or different species. Because of this, nutrient transfer from one plant (donor) to another (receiver) is not restricted to mass flow and diffusion through soil pathways. In karst habitats with limited nutrients, root morphological plasticity may be more substantial when associated with AMF. Inoculation with AMF can markedly increase various morphological traits of seedlings in karst soil. Water and nutrients storage of soil aggregates might be improved by glomalin, which is secreted by the mycorrhizal symbiosis, through extended hyphae to absorb water and nutrients from long distance. Because of an improvement in soil hydrothermal conditions, and suppression of soil evaporation, plastic film mulching (PFM) application can accelerate soil carbon turnover and fertility recovery, and this trend can be further enhanced under AMF inoculation. Several studies have shown that AMF inoculation significantly further improved morphological characteristics and production over PFM, showing an amplifying effect on the PFM system. Carbon sequestration may be improved by AMF through an increase of the rhizosphere soil enzyme activities. By influencing soil texture and structure, AMF also increase plant health by improving soil quality. Since different research studies conducted on AMF during the past two decades have highlighted their countless benefits on soil health and crop productivity, it is widely believed that AMF could be considered as a replacement of inorganic fertilizers in the near future.

When mycorrhizas are exposed to high nutrient availability, high soil moisture, and disturbances, their role may be reduced to neutral symbionts. This may make farmers doubtful on the application of AMF inoculation in agriculture. Thereafter, more research is necessary to determine the effects of environmental stresses on plant production and soil organic matter decomposition with AMF inoculation. Studies that evaluate the AMF inoculation on the soil carbon and N pools are needed for determining the usage of AMF on soil quality and agricultural sustainability.

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