Chapter 17
Mycorrhizas in South American Anthropic Environments

Marcela C. Pagano, Newton Falcão, Olmar B. Weber, Eduardo A. Correa, Valeria S. Faggioli, Gabriel Grilli, Fernanda Covacevich, and Marta N. Cabello

17.1 Introduction

The agricultural expansion has leaded to increase the irrigated cropland area and the use of fertilizers, resulting in water degradation, increased energy use, and common pollution (Foley et al. 2011). Of particular concern is the increased interest to reduce the environmental impacts of high quantities of water dedicated to irrigation by agricultural activities (Foley et al. 2011).
We are now truly recognizing the importance of sustainable measures in agriculture such as conservation of the vegetation cover and management approach to understand surface and deep soil responses to global change (Chaparro et al. 2012). For example, promising plant species can be tested to engineer the cultivable soil microbiome (Ellouze et al. 2013). The new alternatives for the agro-ecosystem management, such as inter-cropping, tillage and organic amendments, affect soils physical and chemical properties, modifying the abundance, diversity and activity of the mycorrhizal communities (Cardoso and Kuyper 2006; Pagano et al. 2011). Thus, the agroecology management based on key processes from natural ecosystems can help to solve some agricultural difficulties. For example, cultural practices (rotation, intercropping and fungal inoculation) that mimic the natural processes can reinforce the mycorrhizal potential in degraded ecosystems (Wahbi et al. 2016).

Increasing studies on the Arbuscular mycorrhizal fungi (AMF) has showed their importance for soil ecology (Bradford 2014) and studies on their biodiversity have spread in some agro-ecosystems such as corn and soybean monocultures (Carrenho et al. 2001; Gomes et al. 2015; Pontes et al. 2017) and coffee plantations (Cogo et al. 2017). Therefore, it is needed to deeply study the mycorrhizal functions under global change. In this chapter, we examine the major developments and advances on mycorrhizal fungi based on recent research from South American countries. New reports on the occurrence of mycorrhizas in Amazonian dark earth, as well as the inoculum production of arbuscular mycorrhizal fungi native of soils under native forest covers (dos Santos et al. 2017), have resulted in a more detailed understanding of the soil biology from South America.

Reports from Amazonian dark earth or “Terra preta do índio” soil has stimulated the use of biochar worldwide as a soil conditioner (Glaser 2007) that can add value to non-harvested agricultural products (Major et al. 2005) and promote plant growth. Few reports from Brazil showed that the addition of inorganic fertilizer, compost and chicken manure resulted in increases in plant cover and plant species richness (Major et al. 2005). In this sense, the biochar/mycorrhizae interactions also can be prioritized for sequestration of carbon in soils to contribute to climate change mitigation (Warnock et al. 2007).

17.2 The Mycorrhizal Symbioses in Agro-Ecosystems

Microorganisms are intensively investigated for novel compounds from saprophytic terrestrial fungi to marine habitats and living plants with their endophytes (Schueffler and Anke 2014). A growing worldwide attention on fungi is noticed, as of 100,000 known fungal species more than one million are predictable to exist (Schueffler and Anke 2014). Among soil fungi, AMF are of special interest for agriculture and increasing investigation from South America is continuously reported (Stürmer and Siqueira 2006; Pagano and Covacevich 2011; Castillo et al. 2016).

More information on indigenous AMF occurrence in agro-ecosystems as well as enough understanding of inoculum persistence, and cover crops that favor the
indigenous arbuscular mycorrhizal fungi (AMF) by means of active roots (Douds et al. 2005) is needed. In general, compared to grasslands, conventionally managed fields can present low AMF diversity and low sporulation capacity (Thougnon Islas et al. 2016). Moreover, fruit plants (pineapple, Sapota trees) under organic management systems can also reduce the AMF species richness and abundance in relation to natural vegetation areas (Dantas et al. 2015).

Increasing interest in plant species for forest use as commercial plantations in Brazil has led to studies of response to inoculation of seedlings with AMF at different doses of P, such as for the Australian red cedar (*Toona ciliata* M. Roem var. *australis*) which presented high mycorrhizal root colonization, and thus, high quality seedlings (da Silva et al. 2017). Moreover, other researchers investigated the diversity of mycorrhizal fungi in planted forest in Northeast Brazil (Weber et al. unpublished) providing indication of Brazilian trees for reforestation in the tropical region.

AMF density and distribution vary both spatially and temporally with soil types and with host plant species diversity. Important economic plant species worldwide are being examined for AMF symbioses. Some agroecosystems have high economic interest such as coffee, vineyards and olive plantations, which are in the focus of interest from new technologies for their cultivation including their associated microbiota. Olive trees are mycotrophic species (Roldan-Fajardo and Barea 1986) associated with a high number of AMF species in the rhizosphere of plants growing in Morocco (Chliyeh et al. 2016) and Spain (Porras Soriano et al. 2002). The AMF diversity was studied for sustainable management of vineyards, showing low values in France (Bouffaud et al. 2016) and high values in vineyards from Germany under permanent vegetation cover or not (Oehl and Koch 2018). In Brazil, few studies such as from Rosa et al. (2016) investigated the application of AMF to reduce copper toxicity in young rootstock grapevines, pointing out some fungal species as promoters of great benefit. In the wine-growing regions of Southern Brazil a high humidity increases the susceptibility to foliar pathogens and thus, successive applications of copper fungicides are commonly used.

Much interest is nowadays dedicated in the preparation of inocula suitable for use in nurseries as this symbiosis improve plant performance and resistance to pathogens and water stress after transplantation. In Argentina, robust plants for field cultivation were obtained under greenhouse and nursery conditions by the coinoculation of two AMF strains at the beginning of plant propagation (Bompadre et al. 2014). It is known that the addition of organic amendments to the substrate can improve sporulation avoiding the replacing of nutrient solutions, vermicompost being commonly utilized. In Brazil, inoculated corn presented high number of infective propagules and biomass when inoculated with AMF and amended with vermicompost (Coelho et al. 2014). Peanut also responds positively when inoculated with different AMF species; however, the dependence on phosphorus (P) modified the plant responses (Hippler and Moreira 2013).

With regard to biochar, most reports are from Europe and the USA, and few reports from south American researchers, most from International Conferences, mention its interaction with AMF. One of them showed that biochar from *Eucalyptus*
at high temperatures (700 °C) improved plant growth and AMF root colonization of sorghum, besides a higher spore germination (Dela Piccola et al. 2016). Reports from Chile showed the early effect of the application on wheat in an Andisol and Ultisol improving root colonization by native AMF and glomalin content besides soil properties, thus encouraging implementation of sustainable systems. Biochar also improved sustainable barley grain production in field trials in the Araucanía Region of southern Chile (Curaqueo et al. 2014a, b).

In Brazil, investigating field samples in economic tree plantations and cassava in crop rotation, Pereira et al. (2014) found higher AMF species richness (30 taxa) in rhizospheric soil samples. However, Oehl et al. (2005) stressed that deep soil layers should be included in studies to better know the AMF diversity, especially in agro-ecosystems, where soil stirring is frequent. At present, research on crops, especially corn (Gomes et al. 2015), have increased and new reports compiled new information on AMF (Table 17.1). Weber (2014) also compiled the importance of biofertilizers and AMF in agriculture (Fig. 17.1).

In Chile, reports compiled during the last 10 years form the Southern-Central zone showed a total of 21 genera (represented by 57 species of AMF) that have been recognized, equivalent to 21% of all AMF species described worldwide (Castillo et al. 2016). Twenty-four AMF species were associated with different cultivars of Triticum aestivum and, differently, Acaulospora and Scutellospora predominate. In that study, AM fungal community structure differed along wheat cultivars: ‘Porfiado’ and ‘Invento’, with 19 species in relation to ‘Otto’ cultivar (15 species) (Aguilera et al. 2014). Castillo et al. (2006) studied the effects of tillage on AMF propagules. They found little differences in spore numbers, however a high root colonization in no-tillage treatments. Moreover, Scutellospora was common under no-tillage.

In Argentina, earlier studies have found less management of AMF to increase plant productivity (Covacevich and Echeverría 2009). It is known that soils of the Pampas region present high native AMF that colonize crop plants under different management systems (Covacevich et al. 2006, 2007; Schalamuk et al. 2006; Covacevich and Echeverría 2008); however, they are not yet manipulated. To avoid decreases in the grassland productivity, which leads to decline livestock production, new studies including AMF ecology and on the impact of agricultural practices on AMF symbiosis pointed to a selective decrease of viable spore number with glyphosate applications in native grasslands (in the Flooding Pampa), resulting in altered AMF community structure. However, the use of sublethal doses of the herbicide was more useful contributing to project more sustainable land management agro-ecosystems (Druille et al. 2015). In this regard, undisturbed (pristine) soils could be considered a reserve pool of diversity of native AMF, showing that spore and large number of propagules (hyphae) can be the main source of inoculum. Thus, low or no relationship between spore number with the root colonization and/or glomalin content can be found (Thougnon Islas et al. 2016).

Investigating the richness of AMF in soybean fields in Argentina (Fig. 17.2), Faggioioli et al. (2019) found 95 AMF virtual taxa (VT) belonging to 8 families: Acaulosporaceae, Archaeosporaceae, Claroideoglomeraceae, Diversisporaceae, Gigasporaceae, Glomeraceae (57), Pacisporaceae, and Paraglomeraceae. Among
| Country/state          | Biome/region                          | Crops/ Vegetation type                                                                 | AMF species/ genera          | Indicator/dominant species | Root colonization by AMF/ECM | Reference                  |
|-----------------------|---------------------------------------|----------------------------------------------------------------------------------------|----------------------------|---------------------------|------------------------------|----------------------------|
| Brazil                | Amazonia                              | Cowpea                                                                                 | Inoculation (13 isolates)   | ND                        | 1–82%                       | Silva et al. (2018)         |
| Brazil                | Amazonia                              | Secondary vegetation                                                                   | 12                         | ND                        | NE                          | Pagano et al. (2016)        |
| Brazil                | Amazonia                              | Secondary vegetation                                                                   | 24                         | ND                        | NE                          | Leal et al. (2009)          |
| Brazil                | Amazonia                              | Babassu palm                                                                          | 16                         | ND                        | NE                          | Nobre et al. (2018)         |
| Brazil, Pernambuco    | Atlantic rain forest                  | Sapodilla, rubber tree, mahogany, eucalyptus plantation and cassava                     | 24–30                      | Detected                  | NE                          | Pereira et al. (2014)       |
| Brazil                | Atlantic rain forest/ Caatinga ecotone| Forest trees                                                                           | 15–20                      | Detected                  | 15–57% AMF / 12–29% ECM     | Weber et al. (unpublished)  |
| Brazil                | Cerrado (14 sites)                    | Coffee                                                                                 | 70                         | ND                        | 13–40%                      | Cogo et al. (2017)†         |
| Brazil                | Cerrado                               | Maize                                                                                  | 10 genera                  | ND                        | NE                          | Gomes et al. 2015           |
| Brazil                | Cerrado                               | Grassland (Brachiaria brizantha)                                                      | 11                         | ND                        | 40–62%                      | Ferreira et al. (2012)      |
| Brazil                | Atlantic rain forest/ Cerrado ecotone | Native and exotic trees                                                                | 16                         | D                        | NE                          | Correa et al. (unpublished) |
| Brazil                | Cerrado                               | Soybean                                                                                | 15–18                      | D                         | NE                          | Pontes et al. (2017)        |
| Brazil / Sao Paulo    | Sugarcane cropping region             | Sugarcane                                                                              | 22                         | ND                        | 30–52%                      | Azevedo et al. (2014)       |

(continued)
| Country/state        | Biome/region | Crops/ Vegetation type                                      | AMF species/ genera | Indicator/dominant species | Root colonization by AMF/ECM | Reference                  |
|---------------------|--------------|------------------------------------------------------------|---------------------|----------------------------|-------------------------------|-----------------------------|
| Brazil / Sao Paulo  |              | Leguminous green manure and sunflower in rotation with sugarcane | NE                  | ND                         | 49–74%                      | Ambrosano et al. (2010)     |
| Brazil / Londrina, Paraná |            | Soybean and cotton                                          | *Rhizophagus clarus* inoculation | ~20–70%                  |                               | Cely et al. (2016)          |
| Brazil              | Pampa        | Various species                                             | NM                  | NM                         | Presence                     | König et al. (2014)*        |
| Brazil              | Santa Catarina state/ Experimental Station | Cassava                                                      | *Rhizophagus clarus* inoculation | 4–9                       | 13–20%                      | Heberle et al. (2015)       |
| Chile               |              | Horticultural, wheat managed grasslands, wheat rotation, other crops | 5–24                | *Glomus spp.*              | NM                           | Castillo et al. (2016)*     |
| Argentina           | Pampa        | Wheat                                                       | NE                  | ND                         | NM                           | Schalamuk et al. (2013)     |
| Argentina           | Pampa        | Wheat                                                       | Inoculation of *Glomus mosseae* | ND                        | ~40%                        | Schalamuk et al. (2011)     |
| Argentina           | Pampa (126 sites) | Soybean                                                   | 37 species          | *Glomus fuegianum* (long term agriculture) |                               | Faggioli (2016)             |
| Argentina           | Rainforest of Misiones | *Ilex paraguariensis* (traditional / high technology fertilized crops) | NE                  | ND                         | 25–50%                      | Velázquez et al. (2018)     |

AMF (spores): species (N° min – N° max); Indicator species (the most characteristic of a site): D (detected) or ND (not detected); NE (not evaluated); NM (not mentioned); *†Checklist or review
them, Diversisporaceae was the most sensitive to long term Agricultural practices (Fig. 17.3). VT richness per sample did not differ between historical land uses and it could be attributed to the widespread use of no-tillage practices associated with soybean cultivation. This conservative soil management has been well documented as positive in the maintenance of AMF richness (Colombo et al. 2014). Soil textural components (i.e. clay and sand content) appeared as significant determiners of AMF richness (Fig. 17.4). Coarser soils were related to high VT richness in soil but low VT richness in roots. This probably was consequence of different textural preferences of AMF species (Lekberg et al. 2007). However, it is worth to highlight here that sandy soils were located in the driest area. Hence, the effect of drought on plant growth could also negatively affect key stages of AMF colonization resulting in the diminution of VT richness in roots of Livestock sites.

Among crop variables, only plant density was significantly correlated with VT richness (Fig. 17.5). Larger density of plant roots might improve resource availability for AMF because more carbohydrates would be available to support the symbiosis (Lekberg et al. 2010). In addition, roots and the associated fungal network might explore higher soil volume and contact propagules of rare and infrequent AMF species which may result in increases of VT richness. Therefore, our results reveal that appropriate plant density is a promising agronomical parameter for the maintenance of AMF species in agroecosystems.

Fig. 17.1  Some AMF spores from cultivated areas in Brazil. Clockwise, from upper left: AMF spores of *Acaulospora* spp., *Glomus* and *Gigasporales* representant isolated from Northeast region (Photo-credit: M. Pagano)
Fig. 17.2 Historical land uses (HLU) currently cultivated with soybean in Pampas Region (Cordoba, Argentina): (a) agricultural, (b) Livestock-Agricultural, (c) Agricultural after recent deforestation of shrub land area. Each location was approximately 100 km from another one. Ten sampling sites were selected in each situation (Faggioli et al. 2019) (Photo-credit: V Faggioli)
In South America, the impact of different agricultural practices on AMF in arable fields is still poorly understood. Wheat phenology improved AMF biodiversity during grain filling; however, tilling and fertilization did not decrease spore biodiversity (Schalamuk et al. 2006). Spore populations of AMF communities in arable fields of wheat crop can vary between from just one to 4 spores g⁻¹ soil in conventional tillage, from 3 to 5 in no-tillage (Schalamuk et al. 2013) but it also depends on plant phenological stages. Rarely more than 26 AMF species were reported in field studies (Schalamuk and Cabello 2010a, b). Pioneer studies on propagules in soils (propagule bank) from Argentina showed that different environmental

Fig. 17.3  Glomeromycota phylogenetic tree with virtual taxa (VT) recorded in different historical land use (HLU). The tree contains type SSU rRNA gene sequences of VT from the MaarjAM database (Öpik et al. 2010). Coloured lines indicate the presence of VT in HLU: Agricultural (Agr., black lines), Forest (For., red lines) and Livestock (Liv., green lines). Molecular study performed by 454 pyrosequencing and taxonomic assignment of sequences against MaarjAM database according to Faggioli et al. (2019)
**Fig. 17.4** Correlations between soil particles (%) and AMF Virtual Taxa (VT) richness from soybean fields with contrasting HLU: Agricultural (squares), Forest (circles) and Livestock (triangles); solid or empty symbols represent soil or root samples, respectively. Correlations are statistically significant (Spearman Test $p < 0.001$). Molecular study performed by 454 pyrosequencing and taxonomic assignment of sequences against MaarjAM database according to Faggioli et al. (2019).

**Fig. 17.5** Correlation between plant density (number or plant per square meter) and VT richness in soil samples in soybean fields with contrasting HLU (p-value < 0.01, Spearman coefficient 0.47). Molecular study performed by 454 pyrosequencing and taxonomic assignment of sequences against MaarjAM database according to Faggioli et al. (2019).
conditions and the effects of tillage and no-tillage modify both the composition of the AMF soil propagule bank and the diversity (Schalamuk and Cabello 2010a, b). Generally, Acaulosporaceae, Gigasporaceae, Glomeraceae can be found in agricultural fields; however, *Glomus* predominate (Schalamuk and Cabello 2010a, b). This can lead to think in different types of AMF inocula based on the proportions of their AMF families (Acaulosporaceae, Gigasporaceae, Glomeraceae) between field and trap cultures. For instance, in the forest garden, Czerniak and Stürmer (2015) tested two AMF species of different families, such as Gigasporaceae and Glomeraceae (*Dentiscutata heterogama* and *Claroideoglomus etunicatum*, respectively) in on farm production of inoculum against residues from the forestry industry (pine bark and pulp sludge).

In the trap cultures from agro-ecosystems more than 90% of AM species belong to Glomeraceae (Schalamuk and Cabello 2010a, b). *Glomus* spp. (Glomeraceae) present more extensive root colonization than other families and lower soil colonization by extraradical hyphae besides rapid colonization of new plants also from colonized roots fragment (Hart and Reader 2002). Thus, in the trap cultures prepared from crop systems generally *Glomus* or *Acaulospora* species are recovered.

In Southern Brazil, increasing studies of AMF in experimental farms and fruit plant orchards have extended the panorama of investigation with this type of soil fungi. Reports on AMF diversity in fruit orchards of Blueberries cultivars showed the prevalence of species of *Glomus* and *Acaulospora* and the potential benefit from inoculated AMF such as *Gigaspora margarita* and *Glomus etunicatum* (Farias 2012). In the semiarid region, Dantas et al. (2015) investigated the AMF occurrence in the establishment of fruits plants (pineapple, Sapota trees) under organic management, detecting *Glomus* spores in all the areas, and corroborated the fact that soil management in organic cropping systems reduce the AMF species richness and abundance in relation to natural vegetation areas.

The AMF occurrence was investigated in an experimental farm in Minas Gerais State (Correa et al. unpublished) under different plant covers. High diversity and abundance were related to adjacent native forest, with 16 AMF species; however, grassland and maize field presented lower values.

Lastly, another anthropic environment is the man-made anthrosols conformed by Amazonian Dark earth, also called Terra preta do índio (TPI), a highly fertile soil whose processes of formation has not yet been resolved (Hofwegen et al. 2009). In this regard, more recent reports (Tsai et al. 2009; Pagano et al. 2016) on the microbial communities of TPI have pointed to the presence of AMF of varied families/order unlike trends for cultivated field soils, with dominance of Glomeraceae. Black carbon prevalence and its unique physical and chemical characteristics, point it as the chief component conforming recalcitrant biochar with unique microbial communities (Tsai et al. 2009). For example, in TPI samples at different depths: from 0–20 to 100 cm, from Amazonas State, Brazil, Pagano et al. (2016) identified 12 AMF species (*Acaulospora bireticulata, A. mellea, A. rhemii, A. scrobiculata, A. spinosa, Ambispora appendicula, Claroideoglomus etunicatum, Scutellospora calospora, Racocetra castanea, Funneliformes geosporus, Glomus tortuosum, Pacispora franciscana*) and 6 were *Glomus* like species. Glomeromycota were dominated by Diversisporales, followed by Glomerales and Gigasporales.
As seen in previous observations in other soil types most of the AMF species richness and diversity (Shannon index) were concentrated in the topmost soil horizons. The *Scutellospora* species was found only in the deeper strata, in agreement with some previous reports (Oehl et al. 2005). *Scutellospora calospora* was also found in the control soil only at subsurface layer (0–20 cm) in contrast to its occurrence at 60–100 m in TPI soil samples.

With regard to the control adjacent soil samples (oxisol and ultisols), similar AMF species were detected, with 8 species identified and 3 unidentified. *Racocetra castanea* found only in the control soil at subsurface layer (0–20 cm) together with *Glomus tortuosum* (20–40 cm depth) occurred exclusively in adjacent soils and most species (11) were in common between the TPI and adjacent soils. This microbiological analysis showed that the abundance of AMF was greater in TPI than in control soils. AMF richness decreases only at great depth; however, diversity remained similar.

### 17.3 The Soil Conditioners in Agro-Ecosystems

Similar to methods to potentialize the mycorrhizal fungal inoculation of roots using soil amendments (Smith and Read 2008), no-tillage methods used to apply biochar into the root zone of crop soils and the mycorrhizal responses to biochar addition were amongst the pioneering works in biochar research. Another anthropic environment originated from South America is the ancient man-made anthrosoils conformed by Amazonian Dark earth, also called *Terra preta do índio* (TPI) (Fig. 17.5), a highly fertile soil whose processes of formation has not yet been resolved (Hofwegen et al. 2009). In Brazil, the Amazonian Dark Earth “Terra Preta” is dated about 7000 years being common at the Amazon basin (Falcão et al. 2003; Glaser 2007) and it is a promising subject to help sustainable agriculture, soil C sequestration and thus, climatic change mitigation. The climate at these areas is Köppen’s Af tropical rainforest with an annual average temperature between 25 °C and 35 °C. At the time of sampling the vegetation cover is usually secondary forest. In this regard, more recent reports (Tsai et al. 2009; Pagano et al. 2016) on the microbial communities of TPI have pointed to the presence of AMF of varied families/order unlike trends for cultivated field soils, with dominance of Glomeraceae. Black carbon prevalence and its unique physical and chemical characteristics, point it as the chief component conforming recalcitrant biochar with unique microbial communities (Tsai et al. 2009). For example, in TPI samples at different depths: from 0–20 to 100 cm, from Amazonas State, Brazil, Pagano et al. (2016) identified 11 AMF species (*Acaulospora bireticulata*, *A. mellea*, *A. rhemii*, *A. scrobiculata*, *A. spinosa*, *Ambispora appendicula*, *Claroideoglomus etunicatum*, *Scutellospora calospora*, *Racocetra castanea*, *Funneliformes geosporus*, *Glomus tortuosum*, *Pacispora franciscana*) and 6 were *Glomus* like species. Glomeromycota were dominated by Diversisporales, followed by Glomerales and Gigasporales.
As seen in previous observations in other soil types most of the AMF species richness and diversity (Shannon index) were concentrated in the topmost soil horizons. The *Scutellospora* species was found only in the deeper strata, in agreement with some previous reports (Oehl et al. 2005). *Scutellospora calospora* was found in the control soil only at subsurface layer (0–20 cm) in contrast to its occurrence at 60–100 m in TPI soil samples. With regard to the control adjacent soil samples (oxisol and ultisols), similar AMF species were detected, with 8 species identified and 3 unidentified. *Racocetra castanea* was found only in the control soil at subsurface layer (0–20 cm) together with *Glomus tortuosum* (20–40 cm depth) occurred exclusively in adjacent soils and most species (11) were in common between the TPI and adjacent soils. This microbiological analysis showed that the abundance of AMF was greater in TPI than in control soils. AMF richness decreases only at great depth; however, diversity remained similar.

Lastly, there is more nuances in the study of TPI, the Terra preta (very dark, with broken potsherds and highly nutrient content) form under sites of home inhabitation, and the Terra mulata (light brown and with less nutrient content), which is less well documented. Thus, Amazonian dark earths are subdivided into: terra preta and terra mulata (black earths and brown earths respectively) (Kern and Kämpf 1989; Arroyo-Kalin 2008) that associates with respectively, past settlement areas and cultivated fields (Arroyo-Kalin 2010). TPI usually exhibit highly elevated levels of phosphorus (P), calcium (Ca) and other essential minerals for plants (Figs. 17.6 and 17.7). Terra mulata present less nutrient content, light brown, being adjacent to TPI.

Fig. 17.6  Sites of Terra Preta de Índio in the Jiquitaia Farm (Lat 2° 37′S, Long 59° 40′W). The vegetation is secondary forest capoeira type, with approximately 40 years of age. Soil samples are usually collected from the 0–20 cm and 20–40 cm depth layers. Clockwise, from upper left: Overview of the area with Latossolo Amarelo with A anthropic horizon (Terra Preta de Índio) at Rio Preto da Eva, AM; Representative profil (Photo-credit: NPS Falcão) and spores of AMF retrieved from soil samples (Photo-credit: M Pagano)
sites. It is believed that it was formed through intensive agriculture involving burning and mulching under low oxygen (Hecht 2003, Fraser et al. 2011).

17.4 AM Inoculation for Agro-Ecosystems

The mycorrhizal inoculation technologies or to manage native arbuscular mycorrhizal fungus communities can serve to replace or reinforce the mycorrhizal potential in degraded ecosystems (Wahbi et al. 2016). For example, to manage AMF soil infectivity in agrosystems it was proposed reductionist and holistic schemes that could be combined: the reductionist pattern aims to improve plant performance in disturbed soils by adding specialized AMF inocula adapted to the environmental conditions and to the target crop. Still, the objectives of the holistic pattern are to preserve and restore the composition of native AMF communities (Wahbi et al. 2016). However, benefits can be obtained from the integration of AMF in agricultural practices through the combination of the “reductionist” and “holistic” approaches (Wahbi et al. 2016).
The management of AMF in the rhizosphere provides an alternative to high inputs of fertilizers and pesticides in sustainable plant production systems (Reviewed by Azcón-Aguilar and Barea 1997). Moreover, crop yield increases showed the potential to be used by farmers (Douds et al. 2005). However, AM inoculation technology is limited by the lack of production of commercial inocula, because a difficult multiplication on artificial growth media without a host (Sieverding 1991).

Some researchers suggested a careful choice of compatible host/mycorrhiza/substrate combination for crop success (Azcón-Aguilar and Barea 1997). Many methods are used to handle AMF, inoculating them on host plants, and replicating large amounts of inoculum. In vivo cultures of AMF species from different regions are preserved in ex-situ collections (Giovannetti and Avio 2002).

Other techniques have been developed to produce large quantities of soil-free inoculum, based on hydroponic and aeroponic cultivation systems (Jarstfer and Sylvia 1995). The roots transformed by Agrobacterium rhizogenes are also effective as inocula which generally utilized carrot, but they are generally used as experimental model systems for research purposes (Giovannetti and Avio 2002). But these inoculation procedures are highly expensive and only utilized in agriculture of high value products.

An alternative source of inocula is to use roadsides around crop fields as a repository for the conservation of AMF diversity affected by Land use (Dai et al. 2013). It has become customary to use AM spores as inoculum (Read 2003) and using three representative genera of AMF (mixed inocula) is a common inoculation strategy.

In South America, several works showed the feasibility and importance of AM inoculation in a large number of economic value and fruit plants. The applications of mycorrhizas in agriculture and environmental issues are still incipient. AMF inoculant for farm application requires large-scale multiplication fungi. The expensive technology of inoculum production comprises formation of single cultures of AMF. A cheaper method is the “on farm” system (farmers can produce their inoculum) (Douds et al. 2008, 2010), native AMF being more efficient due to local adaptation to the environment (Sreenivassa 1992). Infective propagules of AMF (spores, hypha and colonized roots) can be used as inoculum (Sieverding 1991).

In fertile soils from Argentina (Pampa Ondulada region), the effects of agronomic practices on the AMF communities, was reported by using pyrosequencing or a morphological approach (Colombo et al. 2014) showing that soil management has a negative effect on AMF community biodiversity. This study greatly improved the knowledge about AM fungi in South America where the molecular diversity of AM fungi was practically unknown.

Maize crop in Argentina is, after soybeans, the second most important crop (with the highest planted area, followed by wheat, citrus, sugarcane, and sunflower (Boix and Zinck 2008). However, non-tillage and contemporary hybrids with high yield that accumulation of crop residues affect the balance of biological and chemical cycles disturbing the P and Zn levels (Ratto and Miguez 2006). In this sense, Astiz et al. (2014) suggested that soil characteristics could be used to select potentially beneficial inoculum to compensate Zn deficiency in maize. The inoculum of indigenous AMF from sites presenting different levels of P and Zn resulted in changes in
root colonization by AMF and response to inoculation in both Zn uptake and dry matter production. The inoculum indigenous from a site with low P and high Zn content was the lowest efficient. Thus, to compare agricultural fields with high and low soil biota abundance and diversity to assess soil biota potential when soil communities are well developed is urgently needed (Bender and van der Heijden 2014).

Interestingly, in Colombia, the edaphic factors such as Soil pH had a direct relationship with species richness and with the diversity index, but, height above sea level can also affect the AMF community composition. Thus, a heterogeneous distribution in patches with little influence of the type of crop management (mono or polyculture) can be found. This highlight the constraints of developing specific biofertilizers for crops that contain AMF and not including natural adaptations to the different characteristics of the varied agriculture soil types (Mahecha-Vásquez and Sierra 2017). We lack the field studies that are needed to understand with confidence how to do an effective AMF inoculation.

With regard to the ecological restoration of species-rich grasslands that are of priority for conservation of biodiversity, reports have showed many options for that task in South America (Table 17.2). Torrez et al. (2016) determined if plant species recolonization of degraded nutrient-poor grasslands could be increased by adding a local source of AMF inoculum at different distances from intact remnant grasslands. There are effects by the well-dispersed generalist plant species, particularly at 20 m from the intact patches, the role of below-ground processes being crucial for restoration success that can be improved by AMF additions in the short term and at relatively close distances to intact grassland patches (Teste 2016). In Fig. 17.8 we show a protocol to add AM fungi to disturbed ecosystems.

### Table 17.2 Some book or reviews dealing with AMF and ecological restoration in South America

| Reports on AMF and plant restoration                                      | Biome/Country               | References                  |
|--------------------------------------------------------------------------|-----------------------------|------------------------------|
| Restored environments                                                   | Argentina, Brazil           | Pagano (2012)                |
| Riparian forest                                                          | Brazil                      | Braghirolli et al. (2012)    |
| Arbuscular mycorrhizas in degraded land restoration                      | Brazil                      | Soares and Carneiro (2010)   |
| Native species for restoration and conservation of biodiversity in South America | Argentina, Brazil           | Pagano et al. (2012), Pagano (2016) |
In this chapter, the examination and use of arbuscular mycorrhizas in different crop systems has been mentioned and the needs for more information to understand agro-ecosystems and soils under different management have been highlighted. Throughout the chapter, the study of the occurrence of mycorrhizas in agriculture in South America were showed as still incipient. Morphological identification procedure of AMF continues to be important, although the specific training and experience. Moreover, better technology for commercial mycorrhizal inoculum is needed. Finally, this chapter argues that agro-ecosystems generally present low AMF diversity; however, organically managed fields are more similar to natural ecosystems, Amazonian dark earth being a model of highly fertile soils. Consequently, further
research is necessary on this field, especially regarding the applications of mycorrhizas.

**Acknowledgements**  All authors contributed to this chapter. Dr Neimar F. Duarte - Pró-Reitor de Pesquisa, Inovação e Pós-Graduação, Instituto Federal de Minas Gerais, Brazil is gratefully acknowledged. Dr Gabriel Grilli was supported by FCEFyN (CONICET-Universidad Nacional de Córdoba).

**References**

Aguilera P, Cornejo P, Borie F, Barea JM, von Baer E, Oehl F (2014) Diversity of arbuscular mycorrhizal fungi associated with *Triticum aestivum* L. plants growing in an Andosol with high aluminum level. Agriculture, Ecosystems and Environment 186: 178–184

Astiz IP, Barbieri PA, Echeverría HE, Rozas HRS, Covacevich F (2014) Indigenous mycorrhizal fungi from Argentina increase Zn nutrition of maize modulated by Zn fertilization Soil Environ. 33,1: 23–32

Azcón-Aguilar C, Barea JM (1997) Applying mycorrhiza biotechnology to horticulture: significance and potentials. Scientia Horticulturae 68: 1–24

Azevedo LCB, Stürmer SL, Lambais MR (2014) Early changes in arbuscular mycorrhiza development in sugarcane under two harvest management systems. Brazilian Journal of Microbiology 45: 3, 995–1005

Ambrosano EJ, Azcón R, Cantarella H (2010) Crop rotation biomass and arbuscular mycorrhizal fungi effects on sugarcane yield. Sci agric 67:6

Arroyo-Kalin M (2008) Steps towards an ecology of landscape: A geoarchaeological approach to the study of anthropogenic dark earths in the central Amazon region, Brazil. PhD thesis, University of Cambridge

Arroyo-Kalin M (2010) The Amazonian formative: crop domestication and anthropogenic soils. Diversity 2(4):473–504

Boix LR, Zinck JA (2008) Land-Use Planning in the Chaco Plain (Burruyacú, Argentina). Part 1: Evaluating Land-Use Options to Support Crop Diversification in an Agricultural Frontier Area Using Physical Land Evaluation. Environmental Management 42: 1043–1063

Bompadre, MJ Pérgola M, Bidondo LF, Colombo RP, et al. (2014) Evaluation of arbuscular mycorrhizal fungi capacity to alleviate abiotic stress of olive (*Olea europaea* L.) Plants at different transplant conditions. e Scientific World Journal, Article ID 378950, 12 p.

Bouffaud ML, Bernaud E, Colombet A, Van Tuinen D, Wipf D, Redecker D (2016) Regional-scale analysis of arbuscular mycorrhizal fungi: the case of Burgundy vineyards. J. Int. Sci. Vigne Vin 50, 1: 1–8

Bradford MA (2014) Good dirt with good friends. Nature 505: 486–487

Bender SF, Van der Heijden MGA (2014) Soil biota enhance agricultural sustainability by improving crop yield, nutrient uptake and reducing nitrogen leaching losses. Journal of Applied Ecology 52(1)

Braghirolli FL, Sgrott AF, Pescador R, Uhlmann A, Stürmer SL (2012) Arbuscular mycorrhizal fungi in riparian forest restoration and soil carbon fixation. Rev Bras Ciênc Solo 36:3

Cardoso IM, Kuyper TW (2006) Mycorrhizas and tropical soil fertility. Agric. Ecosyst. Environ. 116: 72–84

Castillo CG, Borie F, Oehl F, Sieverding E (2016) Arbuscular mycorrhizal fungi biodiversity: prospecting in Southern-Central zone of Chile. A review. Journal of Soil Science and Plant Nutrition 16 (2): 400–422
Cely MVT, de Oliveira AG, de Freitas VF, de Luca MB et al. (2016) Inoculant of Arbuscular Mycorrhizal Fungi (Rhizophagus clarus) Increase Yield of Soybean and Cotton under Field Conditions. Frontiers in Microbiology 7, Article 720
Chaparro J, Sheflin A, Manter D, Vivanco J (2012) Manipulating the soil microbiome to increase soil health and plant fertility. Biology and Fertility of Soils 48: 489–499
Chliyeh M, Kachkouch W, Zouheir T, Touhami AQ et al. (2016) Evolution of a composite endomycorrhizal inoculums in function of time in the level of the olive plants rhizosphere. IJAPBC 5(1), ISSN: 2277–4688
Coelho IR, Pedone-Bonfim MVL, Silva FSB, Maia LC (2014) Optimization of the production of mycorrhizal inoculum on substrate with organic fertilizer. Brazilian Journal of Microbiology 45, 4: 1173–1178
Cogo FD, Guimarães PTG, Poyú Rojas E, Sagglin Júnior OJ, Siqueira JO, Carneiro MAC (2017) Arbuscular mycorrhiza in Coffea arabica l.: Review and meta-analysis. Coffee Science, 12, 3: 419–443
Colombo RP, Bidono LF, Silvani VA, Carbonetto MB, Rascovan N, Bompadre MJ, Pérgola M, Cuenca G, Godeas AM (2014) Diversity of arbuscular mycorrhizal fungi in soil from the Pampa Ondulada, Argentina, assessed by pyrosequencing and morphological techniques Canadian Journal of Microbiology 60, 12: 819–827
Covacevich F, Echeverría HE (2008) Receptivity of an Argentinean pampas soil to arbuscular mycorrhizal Glomus and Acaulospora strains. World Journal of Agricultural Sciences 4, 6: 688–698
Covacevich F, Echeverría HE (2009) Mycorrhizal occurrence and responsiveness in tall fescue and wheatgrass are affected by the source of phosphorus fertilizer and fungal inoculation. Journal of Plant Interactions 2: 101–112
Covacevich F, Echeverría HE, Aguirrezaba LAN (2007) Soil available phosphorus status determines indigenous mycorrhizal colonization of field and greenhouse-grown spring wheat from Argentina. Applied Soil Ecology 35: 1–9
Covacevich F, Marino MA, Echeverría HE (2006) The phosphorus source determines the arbuscular mycorrhizal potential and the native mycorrhizal colonization of tall fescue and wheat grass in a moderately acidic Argentinean soil. European Journal of Soil Biology 42: 127–138
Curaqueo G, Meier S, Borie F, Nava R (2014a) Biochar and Arbuscular Mycorrhizal Fungi: An Alternative to Contributing to Agroecosystem Sustainability The 20th World Congress of Soil Science June 8–13, Jeju, Korea
Curaqueo G, Meier S, Khan N, Cea M, Nava R (2014b) Use of biochar on two volcanic soils: effects on soil properties and barley yield. Journal of Soil Science and Plant Nutrition 14, 4: 911–924
Czerniak MJ, Stürmer SL (2015) On-farm production of mycorrhizal inoculum using residues from the forestry industry. Revista Brasileira de Ciencia do Solo 38 (6):1712–1721
Carreno R, Trufem SFB (2001) Bononi V L. R. 2001. Arbuscular mycorrhizal fungi in rhizospheres of three phytobionts established in a riparian area. Acta bot bras 15(1):115–124
Castillo CG, Rubio R, Rouanet L, Borie F (2006) Early effects of tillage and crop rotation on arbuscular mycorrhizal fungal propagules in an Ultisol. Biol Fertil Soils 43:83
da Silva EP, Ferreira PAA, Furtini-Neto AE, Soares CRFS (2017) Arbuscular mycorrhiza and phosphate on growth of Australian Red Cedar seedlings. Ciência Florestal 27, 4: 1269–128
dos Santos RS, Ferreira JS, Scoriza RN (2017) Inoculum production of arbuscular mycorrhizal fungi native to soils under different forest covers. Rev. Ceres: 64, 2: 197–204
Dai M, Bainard LD, Hamel C, Gan Y, Lynch D (2013) Impact of Land Use on Arbuscular Mycorrhizal Fungal Communities in Rural Canada. Appl Environ Microbiol 79, 21: 6719–6729
Dela Piccola C, Novotny EH, Ryosuke T, Saito M. Growth and Symbiosis of Plants with Arbuscular Mycorrhizal Fungi in Soil Submitted to Biochar Application 2016. In: International Conference of International Humic Substances Society. 18, 2016, Kanazawa. Keystone for future earth: natural organic matter (NOM) in diverse environments: proceedings. Kobe: IHSS: Kobe University
Douds DD, Nagahashi G, Pfefeer PE, Kayser WM, Reider C (2005) On-farm production of AM fungus inoculum in mixtures of compost and vermiculite. Bioresour Technol 97:809–818

Douds DD, Nagahashi G, Reider C, Hepperly PR (2008) Choosing a mixture ratio for the on-farm production of AM fungus inoculum in mixtures of compost and vermiculite. Compost Science and Utilization 16: 52–60

Douds DD, Nagahashi G, Reider C, Hepperly PR (2010) On-farm production of inoculum of indigenous arbuscular mycorrhizal fungi and assessment of diluents of compost for inoculum production. Bioresource Technology 101 (7): 2326–2330

Druille M, Cabello MN, García Parisi PA, Golluscio RA, Omacini M (2015) Glyphosate vulnerability explains changes in root-symbionts propagules viability in pampean grasslands. Agriculture, Ecosystems and Environment 202: 48–55

Dantas BL, Weber OB, Matos EPNB, Neto JPM, Mendes Filho PF, Rossetti AG, Pagano MC (2015) Diversity of arbuscular mycorrhizal fungi in an organic orchard of semi-arid land of Ceará. Ciência Rural 45(8):1480–1486

Ellouze W, Hamel C, Vujanovic V, Gan Y, Bouzid S, St-Arnaud M (2013) Chickpea genotypes shape the soil microbiome and affect the establishment of the subsequent durum wheat crop in the semiarid North American Great Plains. Soil Biology & Biochemistry 63: 129–141

Faggiole VS, Cabello MN, Grilli G, Vasar M, Covacevich F, Ópik M (2019). Root colonizing and soil borne communities of arbuscular mycorrhizal fungi differ among soybean fields with contrasting historical land use. Agriculture, Ecosystems & Environment 269: 174–182

Faggiole VS (2016) Estudio de las comunidades de hongos formadores de micorrizas arbusculares en soja: Relación con la nutrición fosforada en agroecosistemas. Doctoral thesis. Facultad de Ciencias Naturales y Museo. Universidad Nacional de La Plata, 162 p.

Farias DH (2012) Diversity of arbuscular mycorrhizal fungi in orchards and seedling growth of micropropagated blueberry. Dissertation (Master Degree) Post-Graduation Program in Agronomy. Faculdade de Agronomia Eliseu Maciel, Universidade Federal de Pelotas

Ferreira DA, Carneiro MAC, Saggin Junior OJ (2012) Fungos Micorrízicos Arbusculares em um Latossolo Vermelho sob Manejos e Usos no Cerrado. R. Bras. Ci. Solo 36:51–61

Foley JA, Ramankutty N, Brauman KA, Cassidy ES, Gerber JS, Johnston M, Mueller ND, O’Connell C, Ray DK, West PC, Balzer C, Bennett EM, Carpenter SR, Hill J, Monfreda C, Polasky S, Rockström J, Sheehan J, Siebert S, Tilman D, Zaks DPM (2011) Solutions for a cultivated planet. Nature 478: 337–342

Falcão NP, Comerford N, Lehmann J (2003) Determining nutrient bioavailability of Amazonian Dark Earth soils – methodological challenges. In J. Lehmann, DC Kern B Glaser & WI Woods (eds), Amazonian Dark Earths: Origin, Properties, Management (pp. 255–270). The Netherlands: Kluwer Academic Publishers

FRASER JA, TEIXEIRA W, FALCAO N et al (2011) Anthropogenic soils in the Central Amazon: from categories to a continuum. Area 43(3):264–273

Giovannetti M, Avio L (2002) Biotechnology of Arbuscular Mycorrhizas. Applied Mycology and Biotechnology 2: 275–310

Gomes EA, Oliveira CA, Lana UGP, Noda RW, Marriel IE, de Souza FA (2015) Arbuscular mycorrhizal fungal communities in the roots of maize lines contrasting for Al tolerance grown in limed and non-limed Brazilian Oxisoil. J. Microbiol. Biotechnol. 25(7): 978–987

GLASER B (2007) Prehistorically modified soils of central Amazonia: a model for sustainable agriculture in the twenty-first century. Philisosophical Transactions of the Royal Society B 362(1478):187–196

Hart MM, Reader RJ (2002) Taxonomic basis for variation in the colonization strategy of arbuscular mycorrhizal fungi. New Phytologist 153 (2): 335–344

Heberle ES, Armas RD, Heberle DA, Stürmer SL et al. (2015) Mycorrhizal Fungal Communities in Cassava after Cultivation of Cover Crops as Observed by the “PCR-DGGE” Technique. R. Bras. Ci. Solo 39:1292–1301

Hippler FWR, Moreira M (2013) Dependência micorrízica do amendoimzeiro sob doses de fósforo. Bragantia 72:184–191
Hofwegen G, Kuyper TW, Hoffland E, Broek JA, et al. Opening the black box: deciphering carbon and nutrient flows in Terra Preta (2009). In: Amazonian Dark Earths: Wim Sombroek’s Vision. Woods WI, Teixeira WG, Lehmann J, Steiner C, WinklerPrins AMGA, Rebellato L (Eds.) HECHT SBISM (2003) Implications of Kayapó practices. In: LEHMANN, J.; KERN, D. C.; GLASER, B.; WOODS, W. I. (Orgs.). Amazonian Dark Earths: Origin, properties, and management. Kluwer Academic Publishers, Dordrecht

Jarstfer AG, Sylvia DM (1995) Aeroponic culture of VAM fungi. In: Varma A and Hock B (eds) Mycorrhiza. Springer-Verlag, Berlin

König F, Gonçalves CEP, Aguiar AR, Silva ACF (2014) Pampa Biome: Interactions between microorganisms and native plant species. Revista de Ciências Agrárias 37(1): 3–9

Kern DC, Kämpfe N (1989) Efeitos de antigos assentamentos indígenas na formação de solos com Terra Preta Arqueológicas na região de Oriximiná-PA. Revista Brasileira de Ciencia do Solo 13:219–225

Leal PL, Stürmer SL, Siqueira JO (2009) Occurrence and diversity of arbuscular mycorrhizal fungi in trap cultures from soils under different land use systems in the Amazon, Brazil. Brazilian Journal of Microbiology 40: 111–121

Lekberg Y, Hammer EC, Olsson PA (2010) Plants as resource islands and storage units–adopting the mycocentric view of arbuscular mycorrhizal networks. FEMS Microbiology Ecology 74: 336–345

Lekberg Y, Koide RT, Rohr JR, Aldrich-Wolfe L, Morton JB (2007) Role of niche restrictions and dispersal in the composition of arbuscular mycorrhizal fungal communities. Journal of Ecology 95: 95–105

Mahecha-Vásquez G, Sierra S, Posada R (2017) Diversity indices using arbuscular mycorrhizal fungi to evaluate the soil state in banana crops in Colombia Applied Soil Ecology 109: 32–39

Major J, Steiner C, Ditommaso A, Falcão NP, Lehmann J (2005) Weed composition and cover after three years of soil fertility management in the central Brazilian Amazon: compost, fertilizer, manure and charcoal applications. Weed Biol Manag 5: 69–76

Nobre CP, Costa MG, Goto BT, Gehring C (2018) Arbuscular mycorrhizal fungi associated with the babassu palm (Attalea speciosa) in the eastern periphery of Amazonia, Brazil. Acta Amazonica 48: 321–329

Oehl F, Koch B (2018) Diversity of arbuscular mycorrhizal fungi in no-till and conventionally tilled vineyards. Journal of Applied Botany and Food Quality 91: 56–60

Oehl F, Sieverding E, Ineichen K, Ris EA, Boller T, Wiemken A (2005) Community structure of arbuscular mycorrhizal fungi at different soil depths in extensively and intensively managed agroecosystems. New Phytol. 165: 273–283

Öpik M, Vanatoa A, Vanatoa E, Moora M, Davison J, Kalwij JM, Reier U, Zobel M (2010) The online database MaarjAM reveals global and ecosystemic distribution patterns in arbuscular mycorrhizal fungi (Glomeromycota). New Phytologist 188: 223–241

Pagano MC, MA Lugo, FS Araújo, MA Ferrero, E Menoyo, Diego Steinaker (2012) Native Species for Restoration and Conservation of Biodiversity in South America in: Native Species: Identification, Conservation and Restoration. Nova Science Publishers Editors: Lluvia Marín, Dimos Kovač (eds)

Pagano MC (2012) Mycorrhiza: occurrence in natural and restored environments. Nova Science Publishers

Pagano MC (2016) Recent Advances on Mycorrhizal Fungi, Springer, Fungal Biology book series

Pagano MC, Covacevich F (2011) Arbuscular Mycorrhizas in Agroecosystems. In: Fulton SM (ed) Mycorrhizal Fungi: Soil, Agriculture and Environmental Implications. Nova Science Publishers, New York

Pagano MC, Ribeiro-Soares J, Cançado LG, Falcão NPS, et al. (2016) Depth dependence of black carbon structure, elemental and microbiological composition in anthropic Amazonian dark soil. Soil and Tillage Research 155, 298–307
Thougnon Islas AJ, Hernandez Guijarro K, Eyherabide M, Sainz Rozas HR, Echeverría HE, Covacevich F (2016) Can soil properties and agricultural land use affect arbuscular mycorrhizal fungal communities indigenous from the Argentinean Pampas soils? Applied Soil Ecology 101: 47–56

Tsai SM, O’neill B, Cannavan FS, Saito D, Falcão NPS, Kern DC, Grossman J, Thies J et al. (2009) The Microbial World of Terra Preta. In: Woods WI, Teixeira WG, Lehmann J, Steiner C, WinklerPrins A, Rebellato L (eds) Amazonian Dark Earths: Wim Sombroek’s Vision. Springer, Dordrecht

Teste FP (2016) Restoring grasslands with arbuscular mycorrhizal fungi around remnant patches. Applied Vegetation Science 19, 1.

Torrez V, Ceulemans T, Mergeay J, de Meester L, Honnay O (2016) Effects of adding an arbuscular mycorrhizal fungi inoculum and of distance to donor sites on plant species recolonization following topsoil removal. Applied vegetation Science 19:7–19

Velázquez MS, Fabisik JC, Abarca CL, Allegrucci N, Cabello M (2018) Colonization dynamics of arbuscular mycorrhizal fungi (AMF) in *Ilex paraguariensis* crops: Seasonality and influence of management practices. Journal of King Saud University – Science https://doi.org/10.1016/j.jksus.2018.03.017

Wahbi S, Sanguin H, Baudoin E, Tournier E, Maghraoui T, Prin Y, Hafidi M, Duponnois R (2016) Managing the Soil Mycorrhizal Infectivity to Improve the Agronomic Efficiency of Key Processes from Natural Ecosystems Integrated in Agricultural Management Systems. Springer International Publishing Switzerland, 17 K.R. Hakeem et al. (eds.), Plant, Soil and Microbes, https://doi.org/10.1007/978-3-319-27455-3_2

Warnock DD, Lehmann J, Kuyper TW, Rillig MC (2007) Mycorrhizal responses to biochar in soil – concepts and mechanisms.

Weber OB (2014) Biofertilizers with arbuscular mycorrhizal fungi in agriculture. In: Solaiman ZM, Abbott LK, Varma A (eds). Mycorrhizal fungi: use in sustainable agriculture and restoration. Soil biology: 41. Springer-Verlag, Berlin