Chapter 2

THE CONTRIBUTION OF MYCORRHIZAL FUNGI

Marcela Claudia Pagano* and Ado Jorio

Department of Physics, Federal University of Minas Gerais, Belo Horizonte, Minas Gerais, Brazil

****Corresponding author email: marpagano@gmail.com***

Abstract: There is mounting research on microbial diversity and their products, especially those associated with soil amendments such as biochar and compost. There is increasing recognition of the effects of biochar, which, applied in suitable amounts and forms, can stimulate soil microbial activity, soil microbes, and the symbiotic microorganisms, such as mycorrhizal fungi. Mycorrhizas may have an important role in determining the impact of biochar on plant communities. Biochar influences carbon (C) sequestration in soils as a simple instrument to counterbalance C emissions related to the burning of fossil fuels. Among soil microorganisms, most plant species associate with mycorrhizas and/or other symbiont. Mycorrhizas permit the plant to perform better under unfavorable conditions, mostly carried out at the soil superficial layers. Due to their key position in the soil–root interface, the study of mycorrhizas in combination with biochar/ compost has the potential to make a significant contribution to the biochar effect. The appreciation of alternatives to cope with environmental constraints, such as the use of soil amendments such as biochar and compost, is also of interest for understanding the drought effect on crops. This chapter explores current information on mycorrhizas in agroecosystems with respect to the benefits of biochar/ compost amendments.

Keywords: soil microbes; mycorrhizas; biochar; compost; black carbon; *terra preta do Índio*; fungi; Raman spectroscopy; fertilizer; soil amendments; plant symbioses; carbon sequestration

1. INTRODUCTION

The interest in climate change is rising with increased recognition that global changes can negatively affect biodiversity and ecosystem services (Winfree, 2013; Pagano, 2013; van der Wal *et al*., 2013; Sala *et al*., 2000). Similarly, the interest in ecologically sustainable plantations and agroforestry systems is also growing with a greater understanding of the adverse effects of agricultural intensification (Borie *et al*., 2006; Duarte *et al*., 2013) and the potential of terrestrial carbon (C) sequestration (see King, 2011). However, plantations and crops affect the soil's physical and chemical properties, modifying the number, diversity and activity of the soil microbiota, including both free and symbiotic fungal populations (Cardoso and Kuyper, 2006; Kahiluoto et al., 2009; Nyfeler *et al*., 2011; Pagano *et al*. 2011).

Legumes that host N-fixing bacteria and plant species associated with mycorrhizas, which enhance nutrient uptake, can offer a route for the return of C substrate directly to microbes and soil (Azcón and Barea, 2010). Additionally, the increased microbial nitrogen (N) inputs can intensify soil C stocks by influencing decomposition processes (reviewed by Stockmann *et al*., 2013). For example, the rhizobial and mycorrhizal symbioses with plants have been increasingly studied with respect to their benefits. Consequently, it is known that different arbuscular mycorrhizal fungi (AMF) communities can be found in degraded vs. pristine forest (Haug *et al*., 2010; Pagano *et al*., 2011; Soteras *et al*., 2013; De Souza *et al*., 2013), which can consequently affect reforestation, plant production or plant succession.

In addition, there are some alternatives to cope with various environmental constrains, for example the use of soil amendments. Among them, the use of biochar and compost, which can stimulate soil microbial activity (Ogawa, 1994a; Nishio, 1996), have rapidly increased their inclusion in projects worldwide. Biochar application can also stimulate AMF colonization (Ogawa and Okimori, 2010; Saito, 1990) and rhizobia, which can fix atmospheric N_2 supply to leguminous vegetation (Nishio and Okano, 1991). Some field experiments in Indonesia have showed that biochar could increase yield of maize together with 500 kg/ha of NPK (15 : 15 : 15) fertiliser application (Yamato *et al*., 2006). Benefits of biochar to plant nutrition and microbial activity have been found in the humid tropics (Lehmann and Rondon, 2006) as well as in temperate forest (Zackrisson *et al*., 1996; Pietikäinen *et al*., 2000). Furthermore, ancient anthropic soils found in the humid tropics show high fertility over long time usage, and serve as historical model for biochar (Falcão *et al*., 2003; Glaser and Birk, 2012; Jorio *et al*., 2012).

This chapter explores current information on biochar and compost in plantations with respect to the benefits of AMF symbioses. Possible mechanisms through which biochar affects the relationship between crops and mycorrhizal fungi, as well as research paths that are necessary for the increased understanding of mycorrhizal benefits, are discussed.

2. SOIL AMENDMENTS

Forests store ~45% of terrestrial C and can sequester large amounts of C (Bonan, 2008). Carbon uptake by forests contributes to terrestrial C sink of anthropogenic C emission from fossil fuel and land use change (Denman *et al*., 2007). However, soil C sequestration can be 4 times higher: 2344 Gt of organic C is stored at the top 3 m of soil (54% of which is stored in the first meter), reducing global warming. This counteracts with 9 Gt of anthropogenic CO_2 liberated in the atmosphere, ~~which improves global warming~~ (Stockmann *et al*., 2013).

It is known that biochar may help to sequester C in soils as a simple instrument to counterbalance C emissions related to the burning of fossil fuels (Lehmann and Joseph, 2009 a,b; Atkinson *et al*., 2010; Powlson *et al*., 2011), though it may also act as soil amendment to improve soil fertility.

Other indirect effects of biochar addition are the following: increased water and nutrient retention, improvements in soil pH, increased soil cation exchange capacity, effects on phosphorus (P) and sulfur (S) transformations and turnover, neutralization of phytotoxic compounds in the soil, improved soil physical properties, promotion of mycorrhizal fungi, and alteration of soil microbial populations and functions (the mechanisms are not yet understood). Biochar addition may alter the microorganism populations that stimulate plant health and resistance to biotic stresses (Reviewed by Elad *et al*., 2011).

Moreover, some authors have suggested that biochar induction of responses in systemic plant resistance results in controlling diseases (reviewed by Elad *et al*., 2011). It is also known that biochar can be used to mitigate salt stress effects (Thomas *et al*., 2013).

In addition, because black-C can be found in varied environments, it is crucial to elucidate alterations of its natural oxidation under different climatic and soil regimes. Black-C oxidation may be improved by biotic (Hamer *et al*., 2004) and abiotic processes, such as greater temperature (Cheng *et al*., 2006) and moisture. Opposite, black-C oxidation may diminish with better aggregate protection (Glaser *et al*., 2000; Brodowski *et al*., 2005) e.g. in fine-textured soils (See Cheng *et al*., 2008).

Several studies reported experiments using laboratory-produced biochar, but only a few showed the elemental concentrations and specific surface area of the samples (Baldock and Smernik, 2002; Czimczik *et al*., 2002; Nguyen *et al*., 2004; Zhu *et al*., 2005; Brown *et al*., 2006; Turney *et al*., 2006). Nevertheless, it is known that the final formation temperature and gas composition during heating influence char properties (Brown *et al*., 2006). Additionally, the temperature of formation is difficult to measure and is rarely known in natural chars (Hammes *et al*., 2006).

Due to the relevance of this topic a Conference on biochar the "INTERNATIONAL CONFERENCE BCD" 2013 (Biochars, Composts, and Digestates) — Production, Characterization, Regulation, Marketing, Uses and Environmental Impact, took place in Italy. Among the topics discussed were recent scientific results: (i) research from companies and current issues related to technological processes, analysis and characterization; (ii) sustainable uses and certification, regulation and marketing sides of biochar; and (iii) compost and digestate applications, waste, soil and water sciences, agriculture and environmental sciences and ecotoxicology (International Conference BCD, 2013). In this Conference 80 oral presentations and 107 research posters were registered, including composting of olive mill waste, management of urban biodegradable waste, rice cropping systems amended with waste-derived material, action of humic substances to name just a few.

The effects of biochar soil amendment on the different soil-plant-microbe interactions that may have a role in plant health have been little studied. Among the extended benefits of biochar is also improvement of plant responses to disease. Historical and new black-C samples have been examined worldwide, including samples collected from the remnants of historical charcoal (Cohen-Ofri *et al*., 2006, 2007; Cheng *et al*., 2008), black-C from Amazonian dark soils, also known as TPI (*Terra Preta do Índio*) (Falcão *et al*., 2003; Glaser and Birk, 2012; Jorio *et al*., 2012) and newly produced black-C (Sohi *et al*., 2010).

Biochar has been compared to the historical black-C samples retrieved from Amazonian dark earth. However, evidence suggests that besides incorporating charcoal into the soil, the Amazonians practiced intensive soil composting (Reviewed by Briones, 2012). The following reference gives a detailed review of the effect of biochar for environmental management (Lehmann and Joseph, 2009a).

In parallel, there is greater availability of research on the compost as a peat substitute as well as on their known effects on biocontrol agents for plant disease management (see Martin and Brathwaite, 2012). The use of peat is critically viewed as a limited natural resource of unsustainable use (Joosten and Clarke, 2002).

Since 1898 approximately 14,752 peer reviewed journal papers on compost have been reported all over the world (Scopus survey conducted in March 2014), of which 259 are due to be out in 2014. Composting is the controlled microbial aerobic decomposition and stabilization of organic substrates. The result is a stable product without pathogens and viable weed seeds that is employed in the cultivation of plants. Additionally, there is substantial interest on compost teas (the liquid obtained from compost) as plant diseases suppressors (Martin and Brathwaite, 2012).

In order to improve access to technical information on compost and its potential to mitigate soil-borne diseases, more attention is nowadays paid to research and review papers compiling all this information (Martin and Brathwaite, 2012). Traditionally, compost has been created in rural farming areas of most developing tropical countries using small-scale, slow-rate, open composting methods, particularly heap and pit structures (Persad, 2000), whereas in urban areas and most developed countries, larger scale techniques involving windrow or in-vessel have been adopted.

However, with growing rates of organic waste generation (in both rural and urban areas), technologies with higher turnovers, able to produce more stable end products, such as windrow and in-vessel systems, have been proposed (Reviewed by Martin and Brathwaite, 2012). Nowadays, innovative technologies have increasingly won the market. In Italy, for example, companies such as Tersan Puglia Composting Plant and Biovegetal® Fertilizers Production Plant, transform urban organic waste, crop residues and agro-industrial waste into organic fertilizers (Fig. 1a). This is achieved in a composting plant in the industrial area of the city of Bari. In Brazil, compost (leaves, stems, grass and animal faeces) is transformed at the Federal University of Minas Gerais-Campus (Fig. 1b). After 6 months of maturity, the product is used for ornamental plant cultivation throughout the Campus. In Europe and elsewhere, organic waste is generally separated from the rest of urban waste (glass, paper, plastic, woods, metals, etc.). The level of separate collection is increasing worldwide. In Italy, for example, ~38% of municipal waste is separated. The growing worldwide attention to the high levels of wastes will lead to a constant increase in their separation.

Research on biochar is more recent. The first published reports on biochar in the Scopus database were in 2000, after the first report on compost (non in the SCOPUS), which was in 1898 from Germany. In the last years approximately 1,291 peer reviewed journal papers on biochar were reported all over the world (Scopus survey conducted in March 2014) of which 16 are due to be out in 2014. Biochar may help in reforestation projects and reclamation of degraded rangelands (Stavi, 2012), improving our understanding of belowground ecology. Conservation practices such as agroforestry systems and application of biochar in soil are considered the most promising options to efficiently sequester large amounts of carbon in the long run (Stavi and Lal, 2013).

Nowadays biochar may also help to deal with wetland restoration practices. In the USA, Ballantine *et al*. (2012) found better soil properties, essential for ecological functioning, thus being useful for restoration ecology. Both biochar and compost contain high levels of stable carbon and can be incorporated in the soil to improve soil quality. Thus, the use of biochar and compost can increase soil organic C level compared to no amendment in long field experiments (D'Hose *et al*., 2013).

3. MORPHOLOGY AND COMPOSITION OF HISTORICAL BLACK-C

Black carbon, the residue of incomplete combustion of biomass or fossil fuel, is considered a chemically and biologically very stable carbon that can persist in nature for a long time (Schmidt and Noack, 2000; Knicker, 2007). Research into active management of BC as a means to sequester atmospheric carbon dioxide in soils is increasingly encouraged. However, the long-term persistence of black-C does not mean that the properties of black-C persist after its deposition. Cheng *et al*. (2006) showed rapid oxidation of black-C in short-term incubations, and altered black-C properties (formation of oxygen-containing functional groups). Moreover, black-C transport (Hockaday *et al*., 2006), erosion (Rumpel *et al*., 2006), stability (Bird *et al*., 1999; Czimczik and Masiello, 2007), and cation retention (Liang *et al*., 2006,2008) will depend on the oxidation in soils. Up to now, detailed research on the natural oxidation of black-C in soils remains scarce and little is known about such aspects as to how fast or to what extent black-C is oxidized.

Ancient anthropic soils in the humid tropics provide interesting model for a stable soil that exhibit unusually long fertility, being chemically and microbially stable. The high fertility has been ascribed to the millenary black-C found in these black earth soils (Falcão *et al*., 2003; Glaser and Birk, 2012; Jorio *et al*., 2012). By applying materials science tools, including scanning and transmission electron microscopy, energy dispersive X-ray, electron energy loss spectroscopy and Raman spectroscopy, it has been show that the stable carbon materials found in the Amazonian dark earth (names TPI-carbons, from “*Terra Preta de Índio*”), exhibit a complex morphology, with particles ranging in size from micro- to nanometers, from the core to the surface of the carbon grains, and are rich on specific elements that are important for fertility and carbon stability (Jorio *et al*., 2012, Ribeiro-Soares *et al*., 2013; Archanjo *et al*., 2014, 2015).

Scanning Electron Microscopy (SEM) images of TPI-carbon grains exhibit morphology in the micro-scale that is similar to that of charcoal, and consistent with the type of black carbon appearing naturally in nature (Jorio *et al*., 2012; Archanjo *et al*., 2015). The TPI-carbon grains exhibit a “fractal-like” structure, where a “compact core surrounded by porous shell” structure repeats itself when zooming in at different scales, from hundreds of micrometers down to nanometers (Jorio *et al.*, 2012; Jorio and Cançado, 2012; Archanjo *et al.*, 2014; Ribeiro-Soares *et al.*, 2013).

The chemical composition at the microscopic level has been obtained for hundreds of grains, revealing that besides carbon, silicon, and oxygen, common to all grains, elements like Al, Fe, Cl, Ca, Mg, P, K Ti, Na, Mn, Ti and Pt can be found (Jorio *et al.*, 2012; Archanjo *et al.*, 2014, 2015). The main observations are (i) the core is composed mostly by carbon, but oxygen and calcium are spread over the whole structure; (ii) the other elements are located majorly in the grain shell. Metal oxide-rich nanoparticles were visible on a scale of 10–100 nm. The presence of Ca and P in the TPI-carbons has been attributed to bone fragments and animal residue.

To probe the chemical state of both the core and the external regions of the TPI-carbon grains, spatially localized electron energy loss spectroscopy (EELS) have been performed, demonstrating a aromatic carbon structure (Jorio *et al.*, 2012). Raman spectroscopy measurements are consistent with aromatic carbon nanocrystallites (Jorio *et al.*, 2012b; Ribeiro-Soares *et al.*, 2013). EELS show four well-defined main peaks related to aromatic-C, phenol-C, aromatic carbonyl and carboxyl. The relative peak intensities for the EELS spectral peaks indicate that the core is more graphitic than the surface, the external region of the grain demonstrating a deeper level of oxidation, which caused an increase in the abundance of phenol, carbonyl and carboxylic groups. Spatially-resolved mapping of each chemical group have been performed, and chemical maps confirms that the grain core has a tendency to be more aromatic (graphitic) than the grain surface (shell) (Archanjo *et al.,* 2015). In addition, the results clearly show the aging induced oxidation is not homogeneous in the sample, with the spatial resolution of 15 nm revealing chemical domains that go from 20 nm^2 up to hundreds of nm^2 (Archanjo *et al.,* 2015).

Theoretical calculations based on density functional theory have been performed to explore the role of oxygen and calcium for the TPI-carbon stability (Archanjo *et al.,* 2014). Other theoretical studies address the stability dependence on the TPI-carbon nanocrystallite size (Jorio *et al.,* 2012). Insights about the in-plane dimension of the nanocrystalline structures composing these grains were obtained from Raman spectroscopy analysis, and the crystallite size distribution for TPI-carbons were found in the 3–8 nm range, while for charcoal, it was typically found between 8 and 12 nm (Jorio *et al.,* 2012; Jorio and Cançado, 2012; Ribeiro-Soares *et al.,* 2013).

All these works demonstrate the uniqueness of TPI-carbon morphology, scaling from microns to nanometers. Morphology and composition likely plays important role on the functionality of the historical black-C, providing a model to a chemically and microbially stable soil environment. It has been observed that increasing soil depth in a *Terra Preta de Índio* site, decreased soil nutrient content and associated microbiota abundances (Pagano *et al*., unpublished). Understanding the interplay between black-C morphology and microbiota might elucidate the importance of black-C in soil fertility.

4. MYCORRHIZAL PLANTS AND BIOCHAR

To date, few studies (e.g., Solaiman *et al*., 2010; Warnock *et al*., 2010) have focused on the effects of biochar on the mycorrhizal fungi (Table 1). Other reports only mention mycorrhiza, but with focus on biochar with regard to soil organic matter protection (Stockmann *et al*., 2013) or to soil aggregation (George *et al*., 2012) to name just a few.

Biochar application can have positive effects on beneficial soil microorganisms, improving the mycorrhizal root colonisation, biological N_2 fixation by rhizobia (associated only with legumes) and activity of plant growth promoting organisms in the rhizosphere (see Solaiman *et al*., 2010; Quilliam *et al*., 2013).

Table 1. Database survey conducted in March 2014 (Scopus) for journal articles dealing with arbuscular mycorrhizas (AMF) and biochar

Key words	Number of journal articles
Biochar	1,528
Microbes + biochar	21
Mycorrhizas + biochar	14
Biochar + ectomycorrhiza	3

AMF = arbuscular mycorrhizal fungi.

Table 2 illustrates reviews or papers dealing with biochar and AMF. For a review of some pioneering works in biochar research, see Ogawa and Okimori (2010). Ogawa (1998) was among those interested in the use of symbiotic microorganisms and charcoal. He observed that most symbiotic biota prefer to propagate in or around char. However, knowledge about how biochar affect soil aggregation and whether mycorrhizal fungi or active-C source might be needed to increase water stable aggregates in biochar-amended soils is still limited. It has been shown that the highest concentration of black-C was observed in the finest size fraction (< 0.53 μm) of soil aggregates (Brodowski *et al*., 2006). Nevertheless, a preferential embedding of black-C particles has been suggested compared to other organic compounds within soil aggregates (reviewed by Mukherjee and Lal, 2013).

Table 2. Sample reviews and papers dealing with arbuscular mycorrhyzal fungi (AMF) and biochar

Focus	**Country/ Review**	**References**
Biochar, mycorrhizal fungi, and nitrogen fertilizer	North America/ greenhouse experiment	LeCroy et al. (2013)
Charosphere	UK	Quilliam et al. (2013)
Biochar, ectomycorrhizal fungi	Canada	Robertson et al. (2012)
Terra preta, biochar	Several countries	Briones (2012)
Carbon sequestration, soil microbes	Review	Ennis et al. (2012)
Biochar effect	Review	Elad et al. (2011)
Carbon remediation and microbes	Review	King (2011)
Biochar use in agriculture and forestry	Review	Ogawa and Okimori (2010)
Mycorrhizas in managed environments	Several countries	Solaiman et al. (2010)
Biochar effects on soil biota	Review	Lehmann et al. (2011)
Biochar effects on soil organisms, Mycorrhizas	Review	Thies and Rillig (2009)
Arbuscular mycorrhizas	Field experiment in Colombia	Warnock et al. (2010)
Mycorrhizas	Review	Warnock et al. (2007)

Based on the scarce published research on biochars and mycorrhizas reviewed here, application stimulates arbuscular mycorrhizal colonisation increasing P supply to plants. Solaiman *et al*. (2010) tested different rates of biochar addition to soils together with two types of commercial fertilizers (soluble and slow-release mineral fertilizers) on wheat in field conditions. Moreover, mineral fertilisers contain several beneficial and non-pathogenic fungi including mycorrhizas (*Glomus intraradices*) and bacteria (*Azospirillum*, *Azotobacter*, among others benefic microorganisms). They showed that at 30 kg/ha of soluble fertiliser, the highest rate of biochar (6 t/ha) increased the uptake of all nutrients by plants. With regard to root colonization by AMF, the inoculated treatment presented higher root colonization, which increases with biochar addition, especially in unirrigated samples. The presence of mycorrhizal fungi can increase the surrounding soil explored by hypha, which can cope with the drought stress during the dry period. Furthermore, soil amendments can influence the mycorrhizal colonization and establishment of plants. Biochar was shown to directly stimulate mycorrhizal root colonization resulting in better plant growth and yield of wheat. Additionally, a positive residual effect of biochar application on mycorrhizal root colonization, plant growth and nutrition of wheat was found after 2 years.

Quilliam *et al*. (2013) analyzed the relation between biochar addition in agricultural soil and the associated microbiota. They proposed the term charosphere for the soil surrounding the biochar, directly influenced by the chemical and physical properties of the char, which can in turn influence soil plant microbe interactions. In order to determine the level of microbial colonization of field-aged (3 years) biochar, the authors showed only sparse colonization by microorganisms. They found that it was difficult to identify the advantages of colonizing fresh or newly applied biochar, as most microorganisms will be unable to utilize the limited resources. There was heterogeneity of colonization (microorganisms were frequently found in the longitudinal remains of the vascular tissue of the feedstock), increase the implications of biochar addition to soils. The authors suggest that along the years, microbial colonization of biochar can be improved through the influence of abiotic factors. Thus, a partial microbial decomposition of biochar will provide both nutrient supply and habitat. Finally, they suggest that the physical breakdown of biochar may accelerate microbial colonization, and this can be achieved by biochar powders amendment.

Some studies in Table 2 report that biochar addition can enhance soil properties and the early growth of pine and alder in sub-boreal forest soils, but ectomycorrhizal abundance does not change (Robertson *et al*. 2012). However, some cases showed that the combined treatment of biochar, mycorrhizal fungi, and high nitrogen can decrease aboveground plant biomass, but it can promote mycorrhizal root colonization (LeCroy *et al*. 2013). The authors ascribe the effect to an induced parasitism of the mycorrhizal fungus in the presence of nitrogen and biochar along the experiments. However, AMF colonization of biochar in soils with mycorrhizae and less nitrogen showed more surface oxidation. They conclude that soil nitrogen can act as a switch controlling the capacity of char to influence the AMF association and, consecutively, the degree to which the fungi oxidize the char surface.

Lehmann *et al*. (2011) compiled information on biochar effects on soil biota. They discussed biochar addition as inoculant carrier, instead of peat. They highlighted the possible incorporation of mycorrhizal inoculum to biochar and the lack of debate on this topic. As biochar will remain in the soil it may affect the inoculated microorganisms. For instance, Ogawa (1989) reported the preservation of spores of *Gigaspora margarita* for more than 6 weeks into balls of biochar. Other studies (Rutto and Mizutani 2006) showed reduced mycorrhizal symbiosis in combination with activated carbon. Nevertheless, the properties of biochar (pH, origin, production, etc.) should be appropriated for the inoculated microorganisms. In the future, a combination of approaches to design biochars as inoculant transporters may be very useful, but soil type should be also considered (Lehmann *et al*., 2011).

5. MYCORRHIZAL PLANTS AND COMPOST

We know that recycling organics from agricultural and urban wastes can help to deal with serious environmental challenges. However, our understanding of the factors that affect compost management is limited. Composting has developed rapidly in order to manage poultry, swine and cattle remains, but also to rehabilitate degraded soils. Moreover, due to the rising cost of peat and transmission of several soil-borne diseases, peat is frequently substituted by compost (see Raviv, 2011, 2013).

Benefits of compost to soils and vegetation are well researched. Compost (a source of organic matter) decreases bulk density and soil erosion; intensifies aggregate stability, soil aeration, water infiltration and retention. Furthermore, compost carries micro and macro nutrients, providing a wider range of nutrients than inorganic fertilizers, with less nitrate leaching and water contamination (Gagnon *et al*., 1997; Mamo *et al*., 1999). However, better knowledge of the C and N turnover from composts and in the soil organic matter pools will be crucial for a specific control of negative impact on the ground water (see Amlinger *et al*., 2003). It is worth mentioning that an international journal named Compost Science and Utilization by Taylor & Francis Group has been published (4 issues per year) since 1995.

The positive effect of adding organic substrates and humic substances of particular concentrations on the growth of numerous plants is well documented (Thangarajan *et al*., 2013; Scharenbroch *et al*., 2013; Nikbakht *et al*., 2008; Verlinden *et al.*, 2009). Copious reports on compost have been published; however, mycorrhizas, a special group of fungi, are still understudied. Mycorrhizas are not typically viewed in the same mode as compost addition. This can be due to the difficulties in inocula preparation as AMF are not culturable microorganisms (Smith and Read, 2008).

In the last years approximately 112 peer reviewed journal papers on compost and mycorrhizas were reported all over the world (Scopus survey conducted in March 2014), of which 4 were out in 2014. 58 % of these journal papers comprise research dealing with arbuscular mycorrhizas. Among them, Tanwar *et al*. (2013) tested different sugarcane bagasse substrate and one arbuscular mycorrhizal (AM) species (*Funneliformis mosseae*) in order to improve plant growth. Moreover, Daynes *et al*. (2013) tested sterilised Compost (< 2 mm) inoculated with indigenous microbes and AMF (mostly *Glomus* sp.) in a controlled pot experiment. They showed that Compost (at least 6%), living roots and AMF resulted in a more stable soil structure.

Bashan *et al*. (2012) showed that, in the Sonoran Desert, Mexico, small quantities of compost supplementation (cow manure and wheat straw) and bioinoculation helped three native leguminous trees in restoration of eroded soil to survive. For inoculation they tested plant growth promoting bacteria (*Azospirillum brasilense* and *Bacillus pumilus*), and native AMF (from sorghum plants inoculated with *Glomus* spp. of a consortium of native species collected under mesquite trees). Those microorganisms can enhance drought resistance of plants. Compost was mixed with soil and added to each planting hole at a proportion of 1:8 (735 g : 10 kg, w/w). Interesting, survival and growth of the trees depended on the plant species.

Marosz (2012) showed that green waste compost and AMF can improve the nutrient uptake of woody plants grown under salt stress (principal deicing agents on roads). Application of compost enhanced the growth of certain species of trees and shrubs, and the inoculation of mycorrhizal fungi (AM fungal propagules), before planting trees sensitive to salinity, were useful in such stressful conditions.

For instance, the AMF inocula used in experiments can consist of several fungi species, mainly from *Glomus* or other as yet not completely identified taxonomically species (site-specific mixture species). Inoculum can consist of AM fungal propagules (spores, colonized roots) mixed with sphagnum peat. The inoculum is placed under the roots of trees or shrubs during planting. The knowledge about this issue is surprisingly scant, taking into account that inoculation with mycorrhizas greatly affects plant and soil health.

In 2010, Viti *et al*. tested the agricultural use of compost in both conventional and organic maize production showing that, while the use of the compost as an amendment may exert a restricted impact on AMF, it can significantly modulate the composition of plant growth-promoting rhizobacteria in the rhizosphere of maize. They found only species of *Glomus*.

All these reports show that *Glomus* is generally associated with compost. It will be expected due to the prevalence of this Genus in agricultural experiments and field trials (Oehl *et al*., 2005, Mirás-Avalos *et al*., 2011) highly susceptible to disturbance. This is due to the life-history of *Glomus*, which is generally considered an r-strategist[1]. *Glomus* species belonging to the Glomeraceae 1 (GlGrA) b clade (Schwarzott *et al*., 2001) show an opportunistic behaviour similar to r-strategists (Sykorová *et al*., 2007). For instance, most different compost amendments are tested with *Glomus* as inoculant (Üstüner *et al*., 2009; Adewole and Ilesanmi, 2011). This is also because most crops, vegetables, fruits and cereals associate with *Glomus* species such as *Glomus mosseae* (nowadays named *Funneliformis mosseae*) (Miranda, 2008; Naher *et al*., 2013). This also depends on the cultivation system, as shown by differences observed in rice cultivation systems (Watanarojanaporn *et al*., 2013).

6. **CONCLUSION**

The large variety of organic matter types utilized as soil amendments including composts, crop residues, peat and organic wastes, adds to the heterogeneity of organic C delivered into ecosystems. In the context of increasing rates of organic wastes, emissions of CO_2 and other gases from industrial and agricultural development, which alter global C balance and climate C sequestration, strategies highlight the use of biochar. However, our understanding of the factors that affect biochar use and the notable variability of its biochemical qualities is limited. In the last decade, new throughput analytical techniques, such as Raman spectroscopy, have helped with biochar characterization, including the elucidation of historical black-C structure found in ancient anthropic soils. Understanding the interplay between black-C morphology and microbiota is an important direction for future research work.

Many studies have demonstrated that biochar can influence microbial activity by providing a favourable microhabitat, or that AM fungi can extend their extraradical hyphae into biochar, which helps nutrient conservation in soils. However, the weak alkalinity and strong dependence on pH of biochars may provide grounds for the variability of field observations. Since the interrelation of climate, land, water, vegetation and human activity affects ecosystems, increasing research on soil amendments and agroecosystem management is needed.

---

[1] A rapid colonizer of plant roots, which produces high numbers of spores in a brief period, traits that are favoured in unstable environments.

CONFLICT OF INTEREST
None Declare

ACKNOWLEDGMENTS
M. Pagano is grateful to the Council for the Development of Higher Education at Graduate Level, Brazil (CAPES) for the postdoctoral scholarships granted (CAPES-PNPD Process N° 23038.007147/2011-60). We acknowledge the financial support from Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for Universal Grant MCTI/CNPq N º 14/2012 (473840/2012-0).

7. REFERENCES

Adewole, M.B. and Ilesanmi, A.O. (2011) Effects of soil amendments on the nutritional quality of okra (*Abelmoschus esculentus* [L.] Moench). *Journal of Soil Science and Plant Nutrition* 11, 45–55.

Amlinger, F., Götz, B., Dreher, P., Geszti, J. and Weissteiner, C. (2003) Nitrogen in biowaste and yard waste compost: dynamics of mobilisation and availability—a review. *European Journal of Soil Biology* 39, 107–116.

Archanjo, B.S., Araujo, J.R., Silva, A.M., Capaz, R.B., Falcão, N.P.S., Jorio, A. and Achete, C.A. (2014) Chemical Analysis and Molecular Models for Calcium–Oxygen–Carbon Interactions in Black Carbon Found in Fertile Amazonian Anthrosoils. Environmental science & technology 48 (13), 7445-7452.

Archanjo, B.S., Baptista, D.L., Sena, L.A., Cançado, L.G., Falcão, N.P.S., Jorio, A. and Achete, C.A. (2015) Nanoscale Mapping of Carbon Oxidation in Biochar from Ancient Anthrosoils. Environmental Science: Processes & Impacts ,**17**, 775-779.

Atkinson, C.J., Fitzgerald, J.D. and Hipps, N.A. (2010) Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. *Plant & Soil* 337, 1–18.

Azcón, R. and Barea, J.M. (2010) Mycorrhizosphere interactions for legume improvement. In: Khan, M.S., Zaidi, A. and Musarrat, J. (eds.) *Microbes for Legume Improvement*. Springer, Vienna, pp. 237–271.

Baldock, J.A. and Smernik, R.J. (2002) Chemical composition and bioavailability of thermally altered *Pinus resinosa* (Red pine) wood. *Organic Geochemistry* 33, 1093–1109.

Ballantine, K., Schneider, R., Groffman, P. and Lehmann, J. (2012) Soil Properties and Vegetative Development in Four Restored Freshwater Depressional Wetlands. *Soil Science Society of America Journal* 76, 1482–1495.

Bashan, Y., Salazar, B.G., Moreno, M., Lopez, B.R. and Linderman, R.G. (2012) Restoration of eroded soil in the Sonoran Desert with native leguminous trees using plant growth-promoting microorganisms and limited amounts of compost and water. *Journal of Environmental Management* 102, 26–36.

Bird, M.I., Moyo, C., Veenendaal, E.M., Lloyd, J. and Frost, P. (1999) Stability of elemental carbon in a savanna soil. *Global Biogeochemical Cycles* 13, 923–932.

Bonan, G.B. (2008) Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests. *SCIENCE* 320, 1444–1449.

Borie, F., Rubio, R., Rouanet, J.L., Morales, A., Borie, G. and Rojas, C. (2006) Effects of tillage systems on soil characteristics, glomalin and mycorrhizal propagules in a Chilean Ultisol. *Soil & Tillage Research* 88, 253–261.

Briones, A.M. (2012) The secrets of El Dorado viewed through a microbial perspective. *Frontiers in Microbiology, Microbiotechnology, Ecotoxicology and Bioremediation* 3, 239, 1–6.

Brodowski, S., Amelung, W., Haumaier, L., Abetz, C. and Zech, W. (2005) Morphological and chemical properties of black carbon in physical soil fractions as revealed by scanning electron microscopy and energy-dispersive X-ray spectroscopy. *Geoderma* 128, 116–129.

Brodowski S, John B, Flessa H. and Amelung, W. (2006) Aggregate-occluded black carbon in soil. *Eur. J. Soil Sci.* 57, 539–546.

Brown, R.A., Kercher, A.K., Nguyen, T.H., Nagle, D.C. and Ball, W.P. (2006) Production and characterization of synthetic wood chars for use as surrogates for natural sorbents. *Organic Geochemistry* 37, 321–333.

Cardoso, I.M. and Kuyper, T.W. (2006) Mycorrhizas and tropical soil fertility. *Agric. Ecosyst. Environ.*116, 72–84.

Cheng, C.H., Lehmann, J., Thies, J.E., Burton, S.D. and Engelhard, M.H. (2006) Oxidation of black carbon by biotic and abiotic processes. *Org. Geochem.* 37, 1477–1488.

Cheng, C., Lehmann, J. and Engelhard, M.H. (2008) Natural oxidation of black carbon in soils: Changes in molecular form and surface charge along a climosequence. *Geochimica et Cosmochimica Acta* 72, 1598–1610.

Czimczik, C.I., Preston, C.M., Schmidt, M.W.I., Werner, R.A. and Schulze, E.D. (2002) Effect of charring on mass, organic carbon, and stable carbon isotope composition of wood. *Organic Geochemistry* 33, 1207–1223.

Czimczik, C.I. and Masiello, C.A. (2007) Controls on black carbon storage in soils. *Global Biogeochem. Cycles* 21, 3.

Cohen-Ofri, I., Weiner, L., Boaretto, E., Mintz, G. and Weiner, S. (2006) Modern and fossil charcoal: aspects of structure and diagenesis. *Journal of Archaeological Science* 33, 428–439.

Cohen-Ofri, I., Popovitz-Biro, R. and Weiner, S. (2007) Structural characterization of modern and fossilized charcoal produced in natural fires as determined by using Electron Energy Loss Spectroscopy. *Chem. Eur. J.* 13, 2306–2310.

Daynes, C.N., Field, D.J., Saleeba, J.A., Cole, M.A. and McGee, P.A. (2013) Development and stabilisation of soil structure via interactions between organic matter, arbuscular mycorrhizal fungi and plant roots. *Soil Biology & Biochemistry* 57, 683–694.

Denman, K.L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P.M., Dickinson, R.E., Hauglustaine, D., Heinze, C., Holland, E., Jacob, D., Lohmann, U., Ramachandran, S., Silva Dias, P.L., Wofsy, S.C. and Zhang, X. (2007) Couplings Between Changes in the Climate System and Biogeochemistry. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

De Souza, R.G., Da Silva, D.K.A., De Mello, C.M.A., Goto, B.T., Da Silva, F.S.B., Sampaio, E.V.S.B. and Maia, L.C. (2013). Arbuscular mycorrhizal fungi in revegetated mined dunes. *Land Degradation. Development* 24, 147–155.

D'Hose, T., Ruysschaert, G., Nelissen, V., De Vliegher, A., Willekens, K. and Vandecasteele, B. (2013) The use of compost and biochar to increase soil organic carbon content without increasing nutrient leaching International Conference Biochars, Composts, and Digestates: Book of Abstracts, Bari, 2013.

Duarte, E.M.G, Cardoso, I.M., T Stijnen, M. A. F. C. Mendonça, M S. Coelho, Cantarutti, R. B., Kuyper, T.W., Villani, E. M. A. and Mendonça, E. S. (2013) Decomposition and nutrient release in leaves of Atlantic Rainforest tree species used in agroforestry systems. *Agroforest. Syst*. 87, 835–847.

Elad, Y., Cytryn, E., Meller Harel, Y., Lew, B. and Graber, E.R. (2011) The Biochar Effect: plant resistance to biotic stresses. *Phytopathol. Mediterr.* 50, 335–349.

Ennis, C.J., Evans, A.G., Islam, M., Ralebitso-Senior, T.K. and Senior, E. (2012) Biochar: carbon sequestration, land remediation and impacts on soil microbiology. *Critical Reviews in Environmental Science and Technology* 42, 2311–2364.

Falcão, N.P.S., Comerford, N.B. and Lehmann, J. (2003) Determining Nutrient Bioavailability of Amazonian Dark Earth Soil - Methodological Challenges. In: Lehmann J, Kern DC, Glaser B, Woods W. (Org.). Amazon Dark Earth, origin, properties and management. Kluwer Academic Publishers, The Netherlands, v. 1, 2003; pp. 255–270.

George, C., Wagner, M., Kucke, M. and Rillig, M.C. (2012) Divergent consequences of hydrochar in the plant-soil system: Arbuscular mycorrhiza, nodulation, plant growth and soil aggregation effects. *Appl. Soil Ecol.* 59, 68–72.

Gagnon, B., Simard, R.R., Robitaille, R., Goulet, M. and Rioux, R. (1997) Effect of composts and inorganic fertilizers on spring wheat growth and N uptake. *Can. J. Soil. Sci*. 77, 487–495.

Glaser, B., Balashov, E., Haumaier, L., Guggenberger, G. and Zech, W. (2000) Black carbon in density fractions of anthropogenic soils of the Brazilian Amazon region. *Org. Geochem*. 31, 669–678.

Glaser, B., Haumaier, L, Guggenberger, B. and Zech, W. (2001) The 'Terra Preta' phenomenon: a model for sustainable agriculture in the humid tropics. *Naturwissenschaften* 88, 37–41.

Glaser, B., Turrion, M.B. and Alef, K. (2004) Amino sugars and muramic acid – biomarkers for soil microbial community structure analysis. *Soil Biology & Biochemistry* 36, 399–407.

Glaser, B. (2007) Prehistorically modified soils of central Amazonia: a model for sustainable agriculture in the twenty-first century. *Philosophical Transactions of the Royal Society B: Biological Sciences* 362, 187–196.

Glaser, B. and Birk, J.J. (2012) State of the scientific knowledge on properties and genesis of Anthropogenic Dark Earths in Central Amazonia (terra preta de Índio). *Geochimica et Cosmochimica Acta* 82, 39–51.

Hamer, U., Marschner, B., Brodowski, S. and Amelung, W. (2004) Interactive priming of black carbon and glucose mineralization. *Organic Geochemistry* 35, 823–830.

Hammes, K., Smernik, R.J., Skjemstad, J.O., Herzog, A., Vogt, U.F. and Schmidt, M.W.I. (2006) Synthesis and characterisation of laboratory-charred grass straw and chestnut wood as reference materials for black carbon quantification. *Org. Geochem.* 11, 1629–1633.

Haug, I. (2002) Identification of *Picea* ectomycorrhizae by comparing DNA-sequences. *Mycol. Prog*. 1, 167–178.

Haug, I., Wubet, T., Weiß, M., Aguirre, N., Weber, M., Günter, S. and Kottke, I. (2010) Species-rich but distinct arbuscular mycorrhizal communities in reforestation plots on degraded pastures and in neighboring pristine tropical mountain rain forest. *Tropical Ecology* 51, 125–148.

Hockaday, W.C., Kim, S., Grannas, A.M. and Hatcher, P.G. (2006) Direct molecular-level evidence for the degradation of black carbon in soils from ultrahigh resolution mass spectral analysis of dissolved organic matter from a fire impacted forest soil. *Org. Geochem*. 37, 501–510.

Hockaday, W.C., Grannas, A.M., Kim, S. and Hatcher, P.G. (2007) The transformation and mobility of charcoal in a fire-impacted watershed. *Geochimica et Cosmochimica Acta* 71, 3432–3445.

INTERNATIONAL CONFERENCE BCD: Biochars, Composts, and Digestates (2013) Production, Characterization, Regulation, Marketing, Uses and Environmental Impact) IBI - INTERNATIONAL 2013 CONFERENCE, October 17 to 20, 2013. Final Programme, Organizing Secretariat Bari, Italy.

Joosten, H. and Clarke, D. (2002) Wise use of mires and peatlands – Background and principles including a framework for decision-making. Saarijärvi, International Mire Conservation Group and International Peat Society. Saarijärvi, Finland. p. 7–8.

Jorio, A., Ribeiro-Soares, J., Cançado, L.G., Falcão, N.P.S., Dos Santos, H.F., Baptista, D.L., Martins Ferreira, E.H., Archanjo, B.S. and Achete, C.A. (2012) Microscopy and spectroscopy analysis of carbon nanostructures in highly fertile Amazonian anthrosoils. *Soil & Tillage Research* 122, 61–66.

Jorio, A. and Cançado, L.G. (2012) Perspectives on Raman spectroscopy of graphene-based systems: from the perfect two-dimensional surface to charcoal. *Physical Chemistry Chemical Physics* 14, 15246–15256.

Kahiluoto, H., Ketoja, E. and Vestberg, M. (2009) Contribution of arbuscular mycorrhiza to soil quality in contrasting cropping systems. *Agriculture, Ecosystems and Environment* 134, 36–45.

King, G.M. (2011) Enhancing soil carbon storage for carbon remediation: potential contributions and constraints by microbes. *Trends in Microbiology* 19, 75–84.

Knicker, H. (2007) How does fire affect the nature and stability of soil organic nitrogen and carbon? *Biogeochemistry* 85, 91–118.

LeCroy, C., Masiello, C.A., Rudgers, J.A., Hockaday, W.C., Silberg, J.J. (2013) Nitrogen, biochar, and mycorrhizae: Alteration of the symbiosis and oxidation of the char surface. *Soil Biology & Biochemistry* 58, 248–254.

Lehmann, C.J. and Rondon, M. (2006) Bio-char soil management on highly-weathered soils in the tropics. In: Uphoff, N.T., Ball, A.S., Fernandes, E. *et al*. (eds.) *Biological Approaches to Sustainable Soil Systems*, Taylor & Francis, Boca Raton, FL, pp. 517–530.

Lehmann, J. and Joseph, S. (2009a) Biochar for environmental management: An introduction. In: Lehmann, J., Joseph, S. (eds.) *Biochar for Environmental Management: Science and Technology*. Earthscan, London, pp. 1–12.

Lehmann, J. and Joseph, S. (2009b) *Biochar for Environmental Management.* Earthscan, London, Sterling, VA.

Lehmann, J. Terra preta Nova – Where to from here? (2009) In: Woods, W.I. (ed.), *Amazonian Dark Earths: Wim Sombroeks Vision*. Springer, Berlin, pp. 473–486.

Lehmann, J., Rillig, M.C., Thies, J., Masiello, C.A., Hockaday, W.C. and Crowley, D. (2011) Biochar effects on soil biota. A review. *Soil Biology & Biochemistry* 43, 1812–1836.

Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O'Neill, B., Skjemstad, J.O., Thies, J., Luizao, F.J., Petersen, J. and Neves, E. G. ~~et al.~~ (2006) Black carbon increases cation exchange capacity in soils. *Soil Sci. Soc. Am. J*. 70, 1719–1730.

Liang, B., Lehmann, J., Solomon, D., Sohi, S., Thies, J.E., Skjemstad, J.O., Luizão, F.J., Engelhard, M.H., Neves, E.G. and Wirick, S. (2008) Stability of biomass-derived black carbon in soils. *Geochimica et Cosmochimica Acta* 72, 6069–6078.

Mamo, M., Rosen, C.J. and Halbach, T.R. (1999) Nitrogen availability and leaching from soil amended with municipal solid waste compost. *J. Environ. Qual*. 28, 1074–1082.

Marosz, A. (2012) Effect of Green Waste Compost and Mycorrhizal Fungi on Calcium, Potassium, and Sodium Uptake of Woody Plants Grown Under Salt Stress *Water Air Soil Pollut.* 223, 787–800.

Martin, C.C.G. St. and Brathwaite, R.A.I. (2012) Compost and compost tea: Principles and prospects as substrates and soil-borne disease management strategies in soil-less vegetable production. *Biological Agriculture & Horticulture* 28, 1–33.

Miranda, J.C.C. (2008) *Cerrado. Micorriza arbuscular: ocorrência e manejo*, Embrapa Cerrados, Planaltina, DF (In Portuguese).

Mirás-Avalos, J.M., Antunes, P.M., Koch, A., Khosla, K., Klironomos, J.N. and Dunfield, K.E. (2011) The influence of tillage on the structure of rhizosphere and root-associated arbuscular mycorrhizal fungal communities. *Pedobiologia* 54, 235–241.

Mukherjee, A. and Lal, R. (2013) Biochar Impacts on Soil Physical Properties and Greenhouse Gas Emissions. *Agronomy* 3, 313–339.

Naher, U.A., Othman, R. and Panhwar, Q.A. (2013) Beneficial Effects of Mycorrhizal Association for Crop Production in the Tropics - A Review. *International Journal of Agriculture and Biology* 15, 1021–1028.

Nikbakht, A., Kafi, M., Babalar, M., Hia, Y.P., Luo, A. and Etemadi, N. (2008) Effect of humic acid on plant growth nutrient uptake, and postharvest life of Gerbera. *Journal of Plant Nutrition* 31, 2155–2167.

Nishio, M. Microbial fertilizers in Japan (1996) *Food & Fertilizer Technology Center.* Extension Bulletin, Taipei, FFTC, Japan, No. 430. p. 13.

Nishio, M. and Okano, S. (1991) Stimulation of the growth of Alphalpha and infection of roots with indigenous vesicular-arbuscular mycorrhizal fungi by the application of biochar. *Bulletin of the National Grassland Research Institute* 45, 61–71.

Nguyen, T.H., Brown, R.A. and Ball, W.P. (2004) An evaluation of thermal resistance as a measure of black carbon content in diesel soot, wood char, and sediment. *Organic Geochemistry* 35, 217–234.

Nyfeler, D., Huguenin-Elie, O., Suter, M., Frossard, E. and Lüscher, A. (2011) Grass-legume mixtures can yield more nitrogen than legume pure stands due to mutual stimulation of nitrogen uptake from symbiotic and non-symbiotic sources. *Agriculture, Ecosystems & Environment* 140, 155–163.

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

Ogawa, M. (1989) Inoculation methods of VAM fungi: charcoal ball method and rice hull method. In: Hattori, T., Ishida, Y., Maruyama, Y., Morita, R.Y., Uchida, A. (eds.) *Recent Advances in Microbial Ecology*. Proceedings of the 5th Int. Symp on Microbial Ecology (ISME 5). Japan Scientific Societies Press, Tokyo, pp. 247–252.

Ogawa, M. (1994a) Symbiosis of people and nature in the tropics. *Farming Japan* 28,10–34.

Ogawa, M. (1994b) Symbiosis of people and nature in the tropics. III. Tropical agriculture using charcoal. *Farming Japan* 28, 21–35.

Ogawa, M. (1998) Utilization of symbiotic microorganisms and charcoal for desert greening. Osaka Institute of Technology. Green Age 14: 5-11 Technical papers; 5–11.

Ogawa, M. and Okimori, Y. (2010) Pioneering works in biochar research, Japan. *Australian Journal of Soil Research* 48, 489–500.

Pagano, M.C.**,** Schalamuk, S., Cabello, M.N. (2011) Arbuscular mycorrhizal parameters and indicators of soil health and functioning: Applications for agricultural and agroforestal systems. In: Miransari, M. (ed.) *Soil Microbes and Environmental Health*, Nova Science Publishers, New York, USA. pp. 267–276.

Pagano, M.C. (2013) Plant and soil biota: Crucial for mitigating climate change. In: Interactions of Forests, Climate, Water Resources, and Humans in a Changing Environment. *British Journal of Environment and Climate Change* SCIENCEDOMAIN international, London, UK, 3 (2) 188-196.

Persad, R. (2000) *Agricultural science for the Caribbean*. Book 2. Nelson Thornes Ltd., Cheltenham, UK.

Pietikäinen, J., Kiikkilä, O. and Fritze, H. (2000) Charcoal as a habitat for microbes and its effects on the microbial community of the underlying humus. *Oikos* 89, 231–242.

Powlson, D.S., Whitmore, A.P. and Goulding, K.W.T. (2011) Soil carbon sequestration to mitigate climate change: a critical re-examination to identify the true and the false. *European Journal of Soil Science* 62, 42–55.

Quilliam, R.S., Glanville, H.C., Wade, S.C. and Jones, D.L. (2013) Life in the 'charosphere' - Does biochar in agricultural soil provide a significant habitat for microorganisms? *Soil Biology & Biochemistry* 65, 287–293.

Raviv, M. (2011) Suppressing soil-borne diseases of container-grown plants using composts (Conference Paper). *Acta Horticulturae* 893, 169–182.

Raviv, M. (2013) Composts in growing media: What's new and what's next? *Acta Horticulturae* 982, 39–52.

Ribeiro-Soares, J., Cançado, L.G., Falcão, N.P.S., Ferreira, E.H.M., Achete, C.A., Jorio, A. (2013) The use of Raman spectroscopy to characterize the carbon materials found in Amazonian anthrosoils. *Journal of Raman Spectroscopy* 44, 283–289.

Robertson, S.J., Rutherford, P.M., López-Gutiérrez, J.C. and Massicotte, H.B. (2012) Biochar enhances seedling growth and alters root symbioses and properties of sub-boreal forest soils. *Can. J. Soil Sci*. 92, 329–340.

Rumpel, C., Alexis, M., Chabbi, A., Chaplot, V., Rasse, D.P., Valentin, C., Mariotti, A. (2006) Black carbon contribution to soil organic matter composition in tropical sloping land under slash and burn agriculture. *Geoderma* 130, 35–46.

Rutto, K.L. and Mizutani, F. (2006) Effect of mycorrhizal inoculation and activated carbon on growth and nutrition in peach (*Prunus persica* Batsch) seedlings treated with peach root bark extracts. *Journal of the Japanese Society of Horticultural Sciences* 75, 463–468.

Saito, M. (1990) Charcoal as a micro-habitat for VA mycorrhizal fungi, and its practical implication. *Agriculture, Ecosystems & Environment* 29, 341–344.

Sala, O.E., Chapin, III F.S., Armesto, J.J., Berlow, E., Bloomfield, J., and Dirzo, R. 2000. Global Biodiversity Scenarios for the Year 2100. *Science* 287, 1770–1774.

Scharenbroch, B.C., Meza, E.N., Catania, M. and Fite, K. (2013) Biochar and Biosolids Increase Tree Growth and Improve Soil Quality for Urban Landscapes. *Journal of Environmental Quality* 42, 1372–1385.

Schmidt, M.W.I. and Noack, A.G. (2000) Black carbon in soils and sediments: Analysis, distribution, implications and current challenges. *Global Biogeochem. Cycles* 14, 777–793.

Schwarzott, D., Walker, C., Schüßler, A. (2001) *Glomus*, the largest genus of the arbuscular mycorrhizal fungi (Glomales), is nonmonophyletic. *Mol. Phylogenet. Evol.* 21, 190–197.

SCOPUS (2014) Retrieved from http: // www.scopus.com.scopeesprx.elsevier.com/ http://www-scopus-com.ez27.periodicos.capes.gov.br/home.url

Smith, S.E. and Read, D.J. (2008) Mycorrhizal Symbiosis. Elsevier, New York.

Sohi, S.P., Krull, E., Lopez-Capel, E. and Bol, R. (2010) A Review of Biochar and Its Use and Function in Soil. *Advances in Agronomy* 105, 47–82.

Solaiman, Z.M., Blackwell, P., Abbott, L.K., Storer, P. (2010) Direct and residual effect of biochar application on mycorrhizal root colonisation, growth and nutrition of wheat. *Australian Journal of Soil Research* 48, 546–554.

Soteras, F., Renison, D. and Becerra, A.G. (2013) Growth response, posphorus content and root colonization of *Polylepis australis* Bitt. Seedlings inoculated with different soil types. *New forests* 44, 577–589.

Stavi, I. (2012) The potential use of biochar in reclaiming degraded rangelands. *Journal of Environmental Planning and Management* 55, 657–665.

Stavi, I. and Lal, R. (2013) Agroforestry and biochar to offset climate change: a review. *Agron. Sustain. Dev*. 33, 81–96.

Stockmann, U., Adams, M.A., Crawford, J.W., Field, D.J., Henakaarchchi, N., Jenkins, M. Minasny, B., McBratney, A.B., de Remy de Courcelles, V., Singh, K., Wheeler, I., Abbott, L., Angers, D.A., Baldock, J., Bird, M., Brookes, P.C., Chenu, C., Jastrow, J.D., Lal, R., Lehmann, J., O'Donnell, A.G., Parton, W.J., Whitehead, D., Zimmermann, M. (2013) The knowns, known unknowns and unknowns of sequestration of soil organic carbon. *Agriculture, Ecosystems and Environment* 164, 80–99.

Sykorová, Z., Ineichen, K., Wiemken, A. and Redecker, D. (2007) The cultivation bias: different communities of arbuscular mycorrhizal fungi detected in roots from the field, from bait plants transplanted to the field, and from a greenhouse trap experiment. *Mycorrhiza* 18, 1–14.

Tanwar, A., Aggarwal, A., Yadav, A. and Parkash, V. (2013) Screening and selection of efficient host and sugarcane bagasse as substrate for mass multiplication of *Funneliformis mosseae*. *Biological Agriculture & Horticulture: An International Journal for Sustainable Production Systems* 29, 107–117.

Thangarajan, R., Bolan, N.S., Tian, G., Naidu, R. and Kunhikrishnan, A. (2013) Role of organic amendment application on greenhouse gas emission from soil. *Science of the Total Environment* 465, 72–96.
Thies, J.E. and Rillig, M.C. (2009) Characteristics of Biochar: Biological Properties. In: Lehmann, J., Joseph, S. (eds.) *Biochar for Environmental Management*, Earthscan, London, Sterling, VA, pp. 85–105.
Thomas, S.C., Frye, S., Gale, N., Garmon, M., Launchbury, R., Machado, N., Melamed, S., Murray, J., Petroff, A. and Winsborough, C. (2013) Biochar mitigates negative effects of salt additions on two herbaceous plant species. *Journal of Environmental Management* 129, 62–68.
Turney, C.S.M., Wheeler, D. and Chivas, A.R. (2006) Carbon isotopic fractionation in wood during carbonization. *Geochimica et Cosmochimica Acta* 70, 960–964.
Üstüner, Ö., Wininger, S., Gadkar, V., Badani, H., Raviv, M., Dudai, N., Medina, S. and Kapulnik, Y. (2009) Evaluation of different compost amendments with AM fungal inoculum for optimal growth of chives. *Compost Science and Utilization* 17, 257–265.
van der Wal, A., Geydan, T.D., Kuyper, T.W. and de Boer, W. (2013) A thready affair: linking fungal diversity and community dynamics to terrestrial decomposition processes. *FEMS Microbiol. Rev*. 37, 477–94.
Verlinden, G., Pycke, B., Mertens, J., Dbersaques, F.,Verheyen, K., Baert, G., J. Bries, J., Haesaert G. (2009) Application of humic substances results in consistent increases in crop yield and nutrient uptake. *Journal of Plant Nutrition* 32, 1407–1426.
Viti, C., Tatti, E., Decorosi, F., Lista, E., Rea, E., Tullio, M., Sparvoli, E. and Giovannetti, L. (2010) Compost effect on plant growth-promoting rhizobacteria and mycorrhizal fungi population in maize cultivations. *Compost Science and Utilization* 18, 273–281.
Warnock, D.D., Lehmann, J., Kuyper, T.W. and Rillig, M.C. (2007) Mycorrhizal responses to biochar in soil – concepts and mechanisms. *Plant Soil* 300, 9–20.
Warnock, D.D., Mummey, D.L., McBride, B., Major, J., Lehmann, J. and Rillig, MC. (2010) Influences of non-herbaceous biochar on arbuscular mycorrhizal fungal abundances in roots and soils: results from growth-chamber and field experiments. *Applied Soil Ecology* 46, 450–456.
Watanarojanaporn, N., Boonkerd, N., Tittabutr, P., Longtonglang, A., Young, J.P.W. and Teaumroong, N. (2013) Effect of Rice Cultivation Systems on Indigenous Arbuscular Mycorrhizal Fungal Community Structure. *Microbes Environ.* 28, 316–324.
Winfree, R. (2013) Global change, biodiversity, and ecosystem services: What can we learn from studies of pollination? *Basic and Applied Ecology* 14, 453–460.
Yamato, M., Okimori, Y., Wibowo, I.F., Anshori, S. and Ogawa, M. (2006) Effects of the application of charred bark of *Acacia mangium* on the yield of maize, cowpea and peanut, and soil chemical properties in South Sumatra, Indonesia. *Soil Science and Plant Nutrition* 52, 489–495.
Zackrisson, O., Nilsson, M.C. and Wardle, D.A. (1996) Key ecological function of charcoal from wildfire in the boreal forest. *Oikos* 77, 10–19.
Zhu, D., Kwon, S. and Pignatello, J.J. (2005) Adsorption of singlering organic compounds to wood charcoals prepared under different thermochemical conditions. *Environmental Science and Technology* 39, 3990–3998.

Figure

A B

Fig. 2.1. Large-scale composting techniques. (a) Compost produced in Italy at Biovegetal® production plant (www.biovegetal.it). (b) Compost produced on the campus of the Federal University of Minas Gerais, Belo Horizonte, Brazil (photographs by M. Pagano with permission).