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Contrasting effects of biochar versus manure on soil microbial communities and enzyme activities in an Aridisol

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HIGHLIGHTS

- Biochar, manure, and biochar + manure effects were studied in the field.
- Microbial communities and enzyme activities were affected by manure but not biochar.
- Mycorrhizal root colonization was negatively affected by manure but not biochar.

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ABSTRACT

Biochar can increase microbial activity, alter microbial community structure, and increase soil fertility in arid and semi-arid soils, but at relatively high rates that may be impractical for large-scale field studies. This contrasts with organic amendments such as manure, which can be abundant and inexpensive if locally available, and thus can be applied to fields at greater rates than biochar. In a field study comparing biochar and manure, a fast pyrolysis hardwood biochar (22.4 Mg ha^{-1}), dairy manure (42 Mg ha^{-1} dry wt), a combination of biochar and manure at the aforementioned rates, or no amendment (control) was applied to an Aridisol ($n = 3$) in fall 2008. Plots were annually cropped to corn (*Zea maize* L.). Surface soils (0–30 cm) were sampled directly under corn plants in late June 2009 and early August 2012, and assayed for microbial community fatty acid methyl ester (FAME) profiles and six extracellular enzyme activities involved in soil C, N, and P cycling. Arbuscular mycorrhizal (AM) fungal colonization was assayed in corn roots in 2012. Biochar had no effect on microbial biomass, community structure, extracellular enzyme activities, or AM fungi root colonization of corn. In the short-term, manure amendment increased microbial biomass, altered microbial community structure, and significantly reduced the relative concentration of the AM fungal biomass in soil. Manure also reduced the percent root colonization of corn by AM fungi in the longer-term. Thus, biochar and manure had contrasting short-term effects on soil microbial communities, perhaps because of the relatively low application rate of biochar.

1. Introduction

Biochar is a form of black carbon (C) created by thermal degradation of organic material (e.g., wood, manure, leaves, etc.) in a low or zero oxygen environment (pyrolysis). It is distinguished from charcoal and similar materials by its use as a soil amendment (Lehmann and Joseph, 2009). Biochar C is recalcitrant in nature (Spokas, 2010) and its reactive surfaces are capable of sorbing and exchanging nutrients and native organic matter (Liang et al., 2006); therefore, there is a great interest in utilizing biochar as a soil amendment to sequester C and improve soil fertility in agricultural soils.

Biochar's ability to enhance soil fertility has been demonstrated in tropical soils, where long-term biochar inputs have helped create highly fertile soil known as Terra Preta, or Amazonian Dark Earth (Sombroek, 1966; Glaser et al., 2001). Furthermore, Amazonian Terra Preta soils have greater microbial biomass, and

Abbreviations: AM fungi, arbuscular mycorrhizal fungi; FAME, fatty acid methyl ester; LSD, least significant difference; MRBP, multi-response blocked permutation; PCA, principal components analysis.

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in some cases, greater bacterial diversity than the surrounding area (Kim et al., 2007). Biochar has also been found to positively affect the abundance of arbuscular mycorrhizal (AM) and ectomycorrhizal fungi in soil (Ishii and Kadoya 1994; Warnock et al., 2007), as well as the percent root colonization of host plants (Solaiman et al., 2010). Thies and Rillig (2009) hypothesized that biochar could have a positive effect on the soil microbial communities by providing a habitat where bacteria and fungi could escape from predators as well as find substrates to meet many of their diverse C, energy, and mineral nutrient needs. This may also lead to a change in soil microbial community composition and diversity.

Laboratory incubation studies that involve biochar amendment to arid and semi-arid soil provided support for a positive effect of biochar on microbial activity. For example, biochar amendment increased soil CO_2 evolution when biochar was added at rates of 20 Mg ha^{-1} to a Mollisol (Rogovska et al., 2011), 40 Mg ha^{-1} to three Mollisols (Streubel et al., 2011), and 45 Mg ha^{-1} to a Mollisol and an Aridisol (Smith et al., 2010). These observations were attributed to an increase in the quantity of easily degradable C sources present in the biochar (Smith et al., 2010), and an improved microbial habitat due to reductions in soil bulk density and improved gas exchange in biochar-amended soil (Rogovska et al., 2011). Ippolito et al. (2014) conducted a 12-month incubation study in which biochar was applied to an Aridisol at rates of 0, 20, 40, or 200 Mg ha^{-1}. The authors also observed increased and sustained CO_2 production in all biochar-amended treatments over the 12-month period. However, the 40 and 200 Mg ha^{-1} biochar rates altered the relative proportion of bacterial and fungal fatty acids, and shifted the microbial community toward greater amounts of bacteria and fewer fungi.

Microbial communities and their enzymes are the primary regulators of many soil processes, including nutrient cycling, and changes to microbial community structure and enzyme activity might indicate potential long-term effects of biochar on soil nutrient cycling processes. In the studies noted above, biochar amended to soil at relatively high rates affected microbial activity (20 Mg ha^{-1} or more) and microbial community structure (40 Mg ha^{-1} or more). Such rates have also been proven to affect the availability of plant nutrients in soil, perhaps because microbial communities were affected. For example, Ippolito et al. (2012b) observed a decrease in P and NO_3-N leaching from two Aridisols when biochar was applied at approximately 40 Mg ha^{-1}. Other studies with Aridisols and Mollisols have shown increases in plant-available soil nutrients with biochar applications of up to 40 Mg ha^{-1} (Brewer et al., 2012; Ippolito et al., 2012a; Laird et al., 2010a,b). In contrast, Van Zwieten et al. (2010) noted no change in extractable soil nutrients after 10 Mg ha^{-1} biochar was applied to an Aridisol. However, biochar application rates of 40 Mg ha^{-1} or more may be impractical for field studies due to biochar's cost and limited availability, in contrast to organic amendments such as manure which can be abundant and inexpensive if locally available, and thus can be applied at greater rates than biochar in the field.

In a short-term field experiment, Lentz and Ippolito (2012) studied biochar effects on the chemical properties of the Portneuf soil series up to two years following application of either 22.4 Mg ha^{-1} biochar, 42 Mg ha^{-1} manure, or both. The authors observed no change in extractable soil nutrients with biochar application, whereas manure significantly affected soil fertility. No data were collected on the response of soil microbial communities or enzymes, however, and it is plausible that the soil fertility results could be due to differential responses of microbial communities and their enzyme activities to biochar and manure. Therefore, the objective of this study was to compare the effects of biochar, manure, and co-application of biochar and manure on soil microbial community biomass and structure, AM fungi, and enzyme activities in the field trials of Lentz and Ippolito (2012), as a means to explain the contrasting fertility results. Microbial responses were quantified from fresh soil samples collected in 2012, four years after amendment application, and cryopreserved samples from the first growing season in 2009, so that longer- and shorter-term effects of biochar and manure could be assessed.

2. Materials and methods

2.1. Study site, soil, and amendments

A long-term field study was established in fall 2008 near Kimberly, Idaho (42°31′N, 114°22′W, elevation of 1190 m) to quantify the effects of a single biochar or manure application on crop productivity and soil fertility. In 2012, the study's objectives were expanded to include soil biological properties and root colonization by AM fungi. The soil was a Portneuf silt loam (coarse-silty, mixed superactive, mesic Durinodic Xeric Haplocalcids), pH 7.6, containing 20% clay, 56% silt, 24% sand, 1.2% organic carbon, and having an 8.8% calcium carbonate equivalency. For 33 years prior to this study, the site was cropped to an alfalfa–corn–bean–grain rotation, and no manure had been applied since 1986. Additional details of the study site are described in Lentz and Ippolito (2012).

Manure and biochar chemical characteristics are presented in Table 1. Dairy cattle (*Bos* species) solid manure was obtained from unconfined piles from a local dairy. The material contained little or no straw bedding and comprised 55.3% solids at time of application. The biochar material was provided by Dynamotive Energy Systems (West Lorne, Ontario, Canada) and was marketed under the name CQuest. It was derived from oak and hickory hardwood sawdust and created by fast pyrolysis at 500 °C. The biochar had an ash content of 14% as determined by the ASTM methods for wood charcoal (600 °C). The biochar had an oxygen:carbon ratio of 0.22, a surface area of 0.75 m^2 g^{-1}, and a pH of 6.8. Additional details regarding the manure and biochar treatments are provided in Lentz and Ippolito (2012).

2.2. Experimental design

The experimental design was a randomized complete block design with three replicates and four treatments (control, biochar, manure, and biochar plus manure). Plots were 4.6 m wide and 5.2 m long and included eight planted rows. Each plot was separated by a 1.5 m-wide border. Due to limited biochar availability, it was not possible to enlarge the plots or add additional blocks. Treatments were applied once in November 2008. Details of the field operations are provided in Lentz and Ippolito (2012), but in

Table 1
Selected chemical properties of biochar and manure applied to the experimental plots in November 2008. Adapted from Lentz and Ippolito (2012).

Property	Units	Biochar	Manure
pH		6.8	8.8
EC	dS m^{-1}	0.7	13.4
Ash	%	14	N/A[†]
Total C	%	66.2	26.4
Total N	%	0.32	2.15
Organic N	%	0.32	2.12
NO_3-N	mg kg^{-1}	1.5	80.6
NH_4-N	mg kg^{-1}	1.2	220
K	mg kg^{-1}	3400	13,500
Ca	mg kg^{-1}	3700	22,000
Mg	mg kg^{-1}	1500	8230
Na	mg kg^{-1}	200	3750
P	mg kg^{-1}	300	4080

† N/A = Not Applicable.