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Hardwood biochar and manure co-application to a calcareous soil

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ABSTRACT

Biochar may affect the mineralization rate of labile organic C sources such as manures via microbial community shifts, and subsequently affect nutrient release. In order to ascertain the positive or negative priming effect of biochar on manure, dairy manure (2% by wt.) and a hardwood-based, fast pyrolysis biochar were applied (0%, 1%, 2%, and 10% by wt.) to a calcareous soil. Destructive sampling occurred at 1, 2, 3, 4, 6 and 12 months to monitor for changes in soil chemistry, water content, microbial respiration, bacterial populations, and microbial community structure. Overall results showed that increasing biochar application rate improved the soil water content, which may be beneficial in limited irrigation or rainfall areas. Biochar application increased soil organic C content and plant-available Fe and Mn, while a synergistic biochar–manure effect increased plant-available Zn. Compared to the other rates, the 10% biochar application lowered concentrations of NO_3-N; effects appeared masked at lower biochar rates due to manure application. Over time, soil NO_3-N increased likely due to manure N mineralization, yet soil NO_3-N in the 10% biochar rate remained lower as compared to other treatments. In the presence of manure, only the 10% biochar application caused subtle microbial community structure shifts by increasing the relative amounts of two fatty acids associated with Gram-negative bacteria and decreasing Gram-positive bacterial fatty acids, each by ~1%. Our previous findings with biochar alone suggested an overall negative priming effect with increasing biochar application rates, yet when co-applied with manure the negative priming effect was eliminated.

1. Introduction

Biochar is a pyrolysis product that may be utilized as a soil amendment. Research has focused a great deal of attention on biochar application in highly weathered soil systems (e.g., Lehmann et al., 2003; Glaser et al., 2004; Novak et al., 2009; Hass et al., 2012; Major et al., 2012; Schomberg et al., 2012). However, the use of biochar in semi-arid and arid agricultural soils (which comprise over 2 billion hectares worldwide (Brady and Weil, 1999)) is a relatively new, not extensively studied concept.

Van Zwieten et al. (2010) applied 10 Mg ha^{-1} of biochar to an Aridisol, noting no change in soil fertility status. Yet others (Laird et al., 2010a, 2010b; Brewer et al., 2012; Ippolito et al., 2012a, 2012b) have applied biochar (up to 40 Mg ha^{-1}) to Aridisols and Mollisols, and observed increases in soil extractable P, K, Mg, Fe, and Ca, and decreases in NO_3-N leaching. Increases in soil extractable nutrient concentrations may have been due simply to biochar-borne elemental addition. However, the reduction in NO_3-N leaching may have been due to nutrient retention in biochar micropores (Kameyama et al., 2012), adsorption by biochar (Laird et al., 2010b), biochar-induced microbial immobilization (Streubel et al., 2011; Sarkhot et al., 2012), or greater abundance of microorganisms able to fix or denitrify N (Ducey et al., 2013).

Specific biochar effects on microbiological activity in arid and semi-arid soils have been mostly documented in laboratory incubation studies. Increases in CO_2 evolution have been observed in Mollisols receiving between 20 and 45 Mg biochar ha^{-1} (Rogovska et al., 2011; Streubel et al., 2011; Smith et al., 2010) and in Aridisols receiving 45 Mg ha^{-1} (Smith et al., 2010). Increases in CO_2 evolution have been attributed to biochar initially containing easily degradable C compounds, and to a reduction in soil bulk density and subsequently an improvement in microorganism habitat (Rogovska et al., 2011; Smith et al., 2010). Ippolito et al. (2014) applied up to 200 Mg ha^{-1} of biochar to an Aridisol, also noting increases in CO_2 production over a 12 month

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Abbreviations: DTPA, diethylenetriaminepentaacetic acid; EL, ester linked; FAME, fatty acid methyl ester; MRPP, multi response permutation procedure; NMS, nonmetric multidimensional scaling; PLFA, phospholipid fatty acid analysis.
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incubation study. Furthermore, the authors studied microbial community composition, noting a shift toward more bacteria and less fungi with increasing biochar application. This shift was attributed to physiological stress favoring bacteria over fungi, biochar supplying labile C which favored fast growing bacteria over fungi, or to biochar resulting in increased soil water retention and improving the microclimatic conditions favorable for bacteria over fungi. The above information suggests that biochars alone may not greatly improve nutrient retention in arid and semi-arid soils, and at excessive rates may cause shifts in microbial community composition. However, applying biochars at a proper application rate, with nutrient-rich materials such as manures, may provide some benefit in terms of improvements in soil fertility without compromising the microbial community composition.

Biochar co-application with manure has not been extensively studied, despite that manure is already commonly applied to agriculture soils (6.5 million hectares in the US; USDA, 2006) where there is interest in also applying biochar. Thus, a need exists to identify the effects of biochar and manure soil co-applications. To this end, organic C sources such as manures, when added to soils, often leads to a positive priming effect due to increased microbial activity (Sorensen, 1974) associated with supplied energy sources and nutrient release. Furthermore, it is plausible that various rates of biochar can cause either a positive or negative priming effect of added labile organic C sources (e.g., Keith et al., 2011; Liang et al., 2010; Hamer et al., 2004). Based on our previous observations where biochar was applied alone (Ippolito et al., 2014), we hypothesized that relatively low biochar application rates (e.g., 1% and 2% by wt.) would cause no effect, while an excessive biochar application (e.g., 10% by wt.) would cause a negative priming effect even in the presence of manure. Thus, a 12 month laboratory incubation study was conducted with the objective to assess the effect of biochar–manure co-application on soil water content, nutrient concentrations, microbial respiration, bacterial abundance, and microbial community structure in relation to priming effect.

2. Materials and methods

2.1. Biochar, manure, and soil characteristics

A hardwood biochar (<0.5-mm particle size), made from oak and hickory sawdust, supplied by Dynamotive Energy Systems Inc. (Vancouver, British Columbia, Canada) was manufactured using fast pyrolysis at 500 °C in a fluidized-bed kiln with a 5 s residence time. The biochar ash content was determined by Hazen Laboratory (Hazen Research, Inc, Golden, CO) using a modified ASTM method D1762-84 for wood charcoal (600 °C), total C and N were determined by dry combustion (Nelson and Sommers, 1996; Thermo-Finnigan FlashEA1112; CE Elantech Inc., Lakewood, NJ), and specific surface area was determined from isotherms fitted to the Brunauer, Emmett, and Teller (BET) equation (Brunauer et al., 1938). Biochar pH and EC were determined on a saturated paste extract (Thomas, 1996; Rhoades, 1996), NO_3-N and NH_4-N content using a 2 M KCl extract (Mulvaney, 1996), and organic N content as difference between total and inorganic N. Biochar total metal concentrations were determined by $HClO_4$–HNO_3–HF–HCl digestion (Soltanpour et al., 1996) followed by elemental analysis using a PerkinElmer inductively coupled plasma-optical emission spectrometer Optima 8300 (PerkinElmer; Waltham, MA).

Dairy cattle solid manure was collected from a pen at a local open-lot dairy, and contained 55.3% solids. Total C and N, total elemental concentrations, NO_3-N and NH_4-N, and pH and EC were determined as previously described.

Soil (0–30 cm) was obtained from the edge of a field located 1.7 km southwest of Kimberly, Idaho (42°31′N, 114°22′W; mean elevation of 1190 m; annual precipitation of 251 mm). The soil, classified as Portneuf (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcid; USDA-NRCS, 2013), was air-dried, passed through a 2-mm sieve, and then analyzed for pH (Thomas, 1996) and EC (Rhoades, 1996) using a 1:1 soil:deionized water extract, total elements, and NH_4-N and NO_3-N as previously described. The sieved soil was also pulverized and analyzed for inorganic C using a modified pressure-calcimeter method (Sherrod et al., 2002) and total C and N as mentioned above. Soil organic C was determined by difference between total and inorganic C. Biochar, manure, and soil characteristic data are presented in Table 1.

2.2. Soil–biochar incubation

The effect of hardwood biochar and manure application to the Portneuf soil was investigated during a 12 month incubation study. Biochar was applied and thoroughly mixed by hand into soil at 0, 1, 2, and 10% (~0, 20, 40, and 200 Mg ha^{-1}; wt:wt). The 10% application rate was chosen to help identify upper level soil detriments by biochar application. Manure was then added to all soils at a rate of 2% (by wt.). Soil–biochar–manure mixtures (300 g total) were placed in 8 cm × 8 cm × 8 cm plastic pots using 4 replicates per treatment. Pots were lined with plastic liners to prevent leaching, placed in a growth chamber (22 °C; 30% humidity) and watered twice weekly with reverse osmosis water to 80% of field capacity. Field capacity was determined for each biochar–manure soil mixture prior to the experiment by lining four pots with cheesecloth, filling the pots with 300 g soil, saturating with reverse osmosis water, and allowing to freely drain over a 48 h period. Within the growth chamber, pots were separated by month and then randomized within each month. Pots were destructively sampled at 1, 2, 3, 4, 6, and 12 month intervals.

During monthly destructive sampling, a soil subsample was removed, placed in a ziplock storage bag, and stored in a −80 °C freezer for microbial analysis. The remainder of soils were analyzed for NO_3-N and NH_4-N as previously described, as well as

Table 1
Properties and total elemental analysis of the hardwood biochar, manure, and Portneuf soil.

Property	Units	Biochar	Manure	Portneuf soil
Surface area	$m^2\ g^{-1}$	0.75	ND	ND
pH		6.8	8.8	8.2
EC	$dS\ m^{-1}$	0.7	13.4	0.3
Ash	%	14	ND	ND
Total C	%	66.2	26.4	3.53
Inorganic C	%	ND[a]	ND	2.33
Organic C	%	ND	ND	1.20
Total N	%	0.32	2.15	0.08
Organic N	%	0.32	2.12	0.08
NO_3-N	$mg\ kg^{-1}$	1.5	80.6	18.1
NH_4-N	$mg\ kg^{-1}$	1.2	220	0.57
K	$mg\ kg^{-1}$	3400	13,500	2590
Ca	$mg\ kg^{-1}$	3700	22,000	74,500
Mg	$mg\ kg^{-1}$	1500	8230	13,100
Na	$mg\ kg^{-1}$	200	3750	280
P	$mg\ kg^{-1}$	300	4080	330
Al	$mg\ kg^{-1}$	300	3520	720
Fe	$mg\ kg^{-1}$	1400	4480	700
Zn	$mg\ kg^{-1}$	14.1	167	27.7
Mn	$mg\ kg^{-1}$	118	169	218
Cu	$mg\ kg^{-1}$	16.8	76.5	4.83
Ni	$mg\ kg^{-1}$	4.9	3.4	6.6
Mo	$mg\ kg^{-1}$	<0.05	0.49	<0.01
Cd	$mg\ kg^{-1}$	<0.05	0.34	0.12
Pb	$mg\ kg^{-1}$	2.0	1.9	6.4
B	$mg\ kg^{-1}$	12.3	27.3	14.7

[a] ND = not determined.