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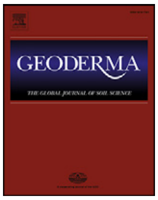

Multi-year and multi-location soil quality and crop biomass yield responses to hardwood fast pyrolysis biochar

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ABSTRACT

Biochar can remediate degraded soils and maintain or improve soil health, but specific and predictable effects on soil properties and crop productivity are unknown because of complex interactions associated with climate patterns, inherent soil characteristics, site-specific crop and soil management practices, and the source, production characteristics, and amount of biochar applied. This multi-location field study was designed and conducted to determine if consistent response patterns could be elucidated by controlling the type and amount of biochar applied, depth of incorporation, and soil/crop management practices as much as possible for six U.S. locations. When averaged for five reporting locations, biochar or biochar plus manure (bio + man) treatments significantly ($P < 0.001$) increased surface (0–15 cm) soil organic carbon (SOC) levels by 48 or 47%, respectively, relative to control treatments. The SOC levels for the manure only treatment were not significantly different from the control. No other measured soil properties showed significant biochar or biochar × manure interactions, even though applying manure significantly increased extractable K, Mg, Na, and P levels. Analysis of three or four years of pooled biomass yield data from the six locations showed a significant location effect ($P < 0.001$), but treatment effects were not significant. However, dividing annual plot yields by the average for all control plots at each location created a dataset of relative yields that showed a significant location × treatment interaction and higher normalized yields (36%) due to biochar ($P = 0.017$) at one of the six locations. Overall, we conclude that hardwood biochar produced by fast pyrolysis can be an effective soil amendment for increasing SOC levels within a broad range of temperate soils, but crop yield responses should be anticipated only when specific soil quality problems limit productivity.

1. Introduction

Biochar, the solid co-product of thermochemical bioenergy production, has recently received considerable attention as a soil amendment because it has the potential to simultaneously sequester C, improve soil quality, and increase crop productivity (Lehmann, 2007, Laird, 2008 and Laird et al., 2009). These positive agronomic and environmental outcomes, however, are often not fully realized especially for temperate region soils.

The C in biochar is generally regarded as highly recalcitrant to microbial degradation in soils and is anticipated to have a half-life ranging from 100 s to 1000s of years in soil environments (Lehmann et al., 2009 and Lehmann et al., 2015). The long half-life of biochar C is supported by substantial although largely anecdotal evidence of ancient (>1000 years old) biochar C in soils that was produced by natural vegetation fires or deliberately incorporated into agricultural soils by indigenous agricultural societies (Glaser et al., 2001, Skjemstad et al., 2002 and Laird et al., 2008). Less clear is the impact of biochar amendments on the rate of biogenic soil organic matter mineralization and the stabilization (humification) of fresh residue biomass (Ameloot et al., 2013). Several studies have reported evidence that biochar may stimulate mineralization of biogenic soil organic matter (Hamer et al., 2004, Wardle et

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al., 2008 and Zimmerman et al., 2011). By contrast, other studies have reported synergistic interactions whereby biochar apparently enhances stabilization of fresh manure or crop residue C (Fang et al., 2015, Weng et al., 2015 and Chen et al., 2015). Both of these processes may occur simultaneously; for example, in a soil microcosm study biochar additions increased CO_2 emissions suggesting enhanced microbial activity and faster SOC mineralization, but when both biochar and manure were added to the soil the rate of mineralization of the manure C was reduced (Rogovska et al., 2011). A meta-analysis of literature data (Ameloot et al., 2013) indicated that increased CO_2 emissions from soils after biochar addition may result from priming of native SOC, biodegradation of labile fractions of the biochar C, and/or the abiotic release of CO_2 from carbonates and chemi-sorbed CO_2. The meta-analysis also found that the stability of biochar C in soils increased with the peak pyrolysis temperature and C content of the resulting biochar. The viability of using soil biochar amendments for C sequestration to help mitigate climate change depends on the net long-term impact of the amendments on SOC. Multi-year coordinated field trials using the same biochar and management protocols are needed to determine whether soil by climate interactions influence the impact of biochar amendments on SOC under field conditions.

In the absence of a C credit market or other programs to incentivize C sequestration, the economic viability of the emerging biochar industry depends on the ability of biochar to increase crop yields. A meta-analysis (Jeffery et al., 2011) of 17 studies found considerable variability (range from −28% to +39%), but an overall small mean positive (10%) crop yield response to biochar applications. Jeffery et al. (2011) reported the greatest positive responses for trials conducted on acidic and coarse textured soils, suggesting that the ability of biochar to function as a liming agent and to increase retention of plant available water by soils are important, if not the dominant, mechanisms by which biochar amendments increase crop yields. Another comprehensive study integrating data from 84 studies (Crane-Droesch et al., 2013) found a positive crop yield response to biochar applications for soils with low cation exchange capacity (CEC) and low soil organic C (SOC) levels; however, no relationship between biochar properties and crop yield responses was detected. Crane-Droesch et al. (2013) concluded that biochar has potential to increase crop yields in highly weathered soils of the humid tropics but is less likely to increase yields in nutrient rich temperate region soils. A third meta-analysis of data from 114 studies also found considerable variability in soil and crop response to biochar applications, but significant increases in mean SOC, pH, microbial biomass, total N, plant available P and K, and a small mean increase in above ground biomass production (Biederman and Harpole, 2013).

The pattern emerging from the literature is that positive crop yield responses to biochar applications are commonly observed on sandy, acidic, and highly weathered soils, while little or no yield response is often observed for high quality temperate region soils (Spokas et al., 2012). There are, however, exceptions to this rule: In two separate studies, Rogovska et al. (2014, 2016) reported maize grain yield increases in response to biochar applications on Iowa Mollisols when high levels of surface residue were present, but no response when crop residues were reduced or removed. The most plausible explanation was that biochar mitigated an allopathic response to high residue levels by adsorbing phytotoxic compounds released during residue decomposition. By contrast, Lentz and Ippolito (2012) found no maize silage yield response to biochar applications on irrigated calcareous soils in Idaho the first year after application and a 36% yield decrease relative to controls the second year of the study. Subsequent analysis (Lentz et al., 2014) showed that biochar reduced net N mineralization and soil CO_2 emissions, indicating that biochar reduced gross N mineralization and increased immobilization. The yield reduction in year 2 was associated with unusually high soil ammonium-*N* concentrations (relative to nitrate-*N*). This suggests that biochar inhibited ammonium-*N* uptake by the corn plants, perhaps by sequestering soil NH_4-N. We are beginning to understand the mechanisms and processes by which biochar influences crop yields; however, all of the studies reviewed above are 'one-off' studies in which different types of biochar, soils, climates, crops, and management protocols were employed. There are no coordinated multi-location studies that assess the differential soil quality and crop yield response to biochar under different climates and on different soils.

Our goal was to assess soil property and crop biomass yield responses to common biochar and manure application protocols across multiple locations with diverse soils, climates, but common fertilizer (inorganic and manure) and cropping system management protocols. We hypothesized; 1) synergistic interactions between manure and biochar would enhance soil quality and boost crop biomass yields, 2) complex soil-climate-biochar interactions would result in different soil quality and crop yield responses in different locations, and 3) the common biochar used in this study would be similarly effective for C sequestration across multiple soils and climates.

2. Materials and methods

2.1. Experimental site description

This experiment was conducted in field plots located at six USDA-ARS locations across the USA (Table S1). Individual plot size ranged from 16 to 34 m^2, had management histories of either no-till or conservation tillage (Table S1) and either continuous corn (*Zea mays* L.) (5 sites) or sorghum (*Sorghum bicolor* L.) (1 site). The field plots were established in the fall of 2008 at three locations (Ames IA, Kimberly ID, and St. Paul MN), Fall of 2009 for two locations (Prosser WA and Big Springs TX), and one location in 2010 (Bowling Green KY; Table S2). The four treatments at each location were: (1) *control* (no amendments); (2) *manure* (a manure application based on local soil test values); (3) *biochar* (a 20 Mg ha^{-1} biochar application); and (4) *bio + man* (a combined manure + biochar application using the same rates as for the manure and biochar treatments). The biochar and manure were manually applied and then incorporated with rotary tillage (0.15 m deep). The treatments were applied once at the beginning of the experiment with three replications of each treatment at each location.

2.2. Hardwood biochar production and characterization

A hardwood biochar was produced using fast pyrolysis (500–600 °C) by Dynamotive Technologies Corp. (West Lorne, Ontario, Canada) using sawdust generated during the production of wood flooring. Thus, the feedstock was mixed species of hardwood. The chemical and physical properties of the biochar are given in Table S3. The biochar was shipped to the individual sites in sealed drums.

2.3. Agronomic management

Corn was planted at five locations and sorghum was planted at the sixth location; the plots were managed and crop yield data collected for either three or four crop years at each location (Table S2). All plots received N-P-K fertilization following best management practices at each location (Table S2). Each location chemically managed weeds and insect pressure according to local best management practices, again universally across all treatments. Three locations (IA, MN, and KY) relied on natural precipitation, and two locations (ID and WA) required supplemental irrigation to ensure crop production (Fig. S1).

Above ground biomass (grain + stover) yields were estimated for each plot by hand harvesting (stalks cut ~25-mm above the soil surface) a known area (varied by location) selected randomly from the central portion of each plot. We calculated the total above-ground crop productivity (kg ha^{-1}) as the sum of the dry grain yield and above ground stalks & leaves. At the ID location, the grain yield was not collected separately (silage processing).