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Biochar impact on Midwestern Mollisols and maize nutrient availability

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ABSTRACT

Biochar applications have been shown to increase crop yields on acidic and low activity soils in the tropics but fewer positive yield responses have been reported for temperate soils. We hypothesized that even without a yield response, applying biochar to a Midwestern Mollisol could improve soil quality and plant nutrient availability because of the carbon it supplies and its conditioning effect. Eighteen small field plots (23.7 m^2) on a glacial-till derived soil were established by incorporating 0 to 96 Mg ha^{-1} of hardwood biochar to a depth of 30 cm. Several soil quality indicators, plant nutrient availability, uptake, and yield of two consecutive maize (*Zea mays* L.) crops were monitored. Biochar application significantly increased soil pH, readily available water (RAW) content (defined as volumetric water available between −10 kPa and −100 kPa) and soil organic C (SOC). It decreased bulk density (BD), but had no consistent effect on soil infiltration rates, CEC, or nutrient uptake. Biochar application did increase grain yield during the first year by 11 to 55% following very high stover application rates (3.5× the typical amount), presumably because biochar mitigated adverse effects of allelochemicals released from the decomposing maize residue. There was no detectable biochar effect on maize yield during the second year when the crop was limited by severe drought.

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1. Introduction

Biochar is increasingly being discussed as a potential amendment to sequester carbon and improve soil quality. Biochar amendments to agricultural soils have been shown to reduce nutrient leaching and to have positive effects on soil physical, chemical and microbiological properties (Lehmann et al., 2003; Liang et al., 2006; Laird et al., 2010a, b; Basso et al., 2013; Parvage et al., 2013), that may act in synergy and result in improved crop performance. However, soil responses to biochar applications are strongly influenced by the material's specific chemical and physical characteristics as well as the site-specific soil–biochar interactions. Therefore, predicting the exact effect of particular biochar on soil physicochemical properties and crop yield can pose a challenge (Biederman and Harpole, 2013).

The degree of uncertainty associated with characterizing biochars' behavior in soils also relates to differences in environment and soil type under which trials have been carried out. Generally, favorable effects of biochar applications on soil quality and crop productivity have been observed on highly weathered, nutrient-poor tropical soils. In these studies, biochar had positive effect on both, soil characteristics and crop performance, that were partly attributed to reduced Al toxicity in the rhizosphere (Glaser et al., 2002). These findings might not be relevant to other climatic regions or soils where Al toxicity is not an issue (Atkinson et al., 2010; Glaser et al., 2002; Lehmann, 2007; Lehmann et al., 2006). Limited field studies indicated that biochar addition to temperate region soils causes small and transient changes in agroecosystems where native soil fertility is sufficiently high (Jones et al., 2012). Thus application of biochar to soils of temperate regions may have no or limited effect on crop yields, unless biochar can ameliorate specific soil related productivity constrains (Guerena et al., 2013; Karer et al., 2013).

Increased water holding capacity and availability to plants on medium and coarse textured soils during periods of moisture stress is one potential benefit of applying biochar to temperate soils. Numerous reports indicate a positive soil water effect of biochar because of its high porosity and surface area. Glaser et al. (2002) demonstrated an 18% increase in biochar-amended soils relative to adjacent soils, while Basso et al. (2013) reported a 29 to 84% increase. A 10% increase in barley (*Hordeum sativum*) yield from a biochar amended Chernozem during a prolonged drought was attributed to increased plant available water (Karer et al., 2013).

High internal porosity of biochar creates a soil conditioning agent that can lower bulk density, affect pore size distribution, and potentially influence water percolation rates and nutrient leaching (Bell and Worrall, 2011). Similar to water sorption, capillary forces, along with electrostatic and complexation forces of biochar surfaces can also affect sorption capacity for organic and inorganic compounds. Biochar can

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thus have either positive or negative environmental and agronomic effects on fertilizers, pesticides and allelochemicals through adsorption (Kulmatiski and Beard, 2006; Laird et al., 2010a; Lehmann et al., 2003).

While controlled experiments under laboratory and greenhouse conditions provide valuable findings, relatively little research has been done to address the impact of biochar additions on soils of temperate regions under field production conditions. Our objective was to quantify effects of biochar application on selected soil physico-chemical properties within a Midwestern USA Mollisol while monitoring nutrient availability, uptake and yield by maize over a two-year period.

2. Materials and methods

2.1. Biochar

Biochar was obtained from ICM, Inc. (Colwich, KS) who used a low-temperature auger bed gassifier operated between 500 and 575 °C to produce high carbon biochar from mixed hardwood [primarily oak (*Quercus* spp.), elm (*Ulmus* spp.) and hickory (*Carya* spp.)] woodchips. Particle size ranged from 0.1 mm to 2.0 cm with the majority of particles <1.0 mm. Volatiles, fixed C, ash, and moisture content were determined by proximate analysis using ASTM standard method D 1762-84 (2007), while total C, H, N, O, and S were determined by ultimate analysis (ASTM standard D3176-89, 2002). The biochar pH, (pH 8.8) was measured in DI water using a 1:50 solid to liquid ratio after 1 h of equilibration (Gaskin et al., 2008). Proximate and ultimate analytical results are given in Table 1. Overall, the biochar consisted of 78% C, 8% ash, and 13% volatile matter.

2.2. Experimental design

Field plots (23.7 m^2) were established on Clarion loam (fine-loamy, mixed, superactive, Mesic Typic Hapludolls) in October 2010 at the Iowa State University Boyd Research Farm in Boone County, Iowa. The field had been in a maize/soybean rotation from 2006 through 2008 and continuous maize since 2009.

Six biochar application rates, 0, 19.2, 38.3, 57.5, 76.6, and 95.8 Mg ha^{-1}, were replicated three times thus providing 18 field plots in the main experiment. Three additional plots, adjacent to the main experiment but not receiving biochar or rotary tillage were included as “standard management” controls for comparison. The experimental site is located on slightly to severely eroded Clarion soil with inherent soil quality, based on the relative degree of erosion, grading from the poorest (severely eroded) in the southwest corner to the best (slightly eroded) in the northeast corner. A 1.5 m buffer strip surrounded each plot to prevent potential confounding due to biochar movement by wind, water or tillage.

Biochar was surface applied in the fall of 2010 and immediately incorporated utilizing both rotary and moldboard plow tillage. This resulted in a relatively uniform distribution of biochar to a depth of approximately 30 cm and incorporated crop residue (6.5 Mg ha^{-1}) from the 2010 maize crop, but created a potentially erosive surface condition prior to the winter months. Therefore, an additional 22.6 Mg ha^{-1} of chopped maize residue was spread uniformly on the soil surface of the main experimental plots (but not the standard management plots) to minimize potential soil loss via erosion. In the spring of 2011, all plots were tilled with a tandem disk to incorporate the chopped residue before planting.

Table 1
Chemical properties of biochar determined by ultimate and proximate analysis. The results are reported on air-dry basis.

Proximate and ultimate analysis			
Constituent	g kg^{-1}	Constituent	g kg^{-1}
Moisture	7.4	H	17.6
Ash	76.6	N	6.4
Volatile	134.6	S	0.1
Fixed C	781.4	O	51.1

2.3. Fertilization practices

All plots received 44.8 kg ha^{-1} of P_2O_5 and 40.2 kg ha^{-1} of N as DAP and 67.2 kg ha^{-1} K as KCl after collecting initial soil samples but before biochar application in November 2010. During the 2011 growing season all plots received a total of 377 kg ha^{-1} of N as 32% UAN fertilizer in a split application. This high level of N fertilization was applied to mitigate the risk of N immobilization resulting from the high rate of maize residue applied the previous fall. After harvest in the fall of 2011, all plots and received 78.5 kg ha^{-1} of P_2O_5, 19.6 kg ha^{-1} S, 23.5 kg ha^{-1} N, 2.1 kg ha^{-1} Zn as MEZS, and 78.5 kg ha^{-1} of K as KCl. An additional 50 kg ha^{-1} of N as 32% UAN was applied at planting, and 180 kg ha^{-1} N (UAN) was applied using a split application on May 30 and June 8, 2012.

2.4. In-season measurements

Maize (‘Pioneer Brand 36 V75’) was planted on May 9, 2011 at a seeding rate of 79,074 seeds ha^{-1}. Resistance to penetration in the root zone (0 to 15 cm) as well volumetric soil moisture content (0 to 6 cm) was measured using a Penetrologger equipped with Theta moisture sensor (Eijkelkamp Inc., Giesbeek, The Netherlands) in mid-July. Ten measurements were collected and averaged across each plot. Plant tissue samples were taken after tasseling but prior to silking by collecting the leaf attached directly below the ear. Three leaf samples were taken from each of the four middle rows of each plot and dried at 50 °C to constant weight.

Maize (‘Pioneer Brand P0461’) was planted on April 27, 2012 at a seeding rate of 84,980 seeds ha^{-1}. During 2012 growing season surface volumetric moisture content was measured daily from June 21 to July 3 with a Theta moisture sensor. Infiltration and runoff rates were measured for a representative area in each plot using a sprinkle infiltrometer (Cornell University, Ithaca, NY).

2.5. Soil water retention and bulk density

Surface soil bulk density was determined on undisturbed soil cores collected in July 2012. Five samples were collected per plot using metal rings with an inner diameter of 7.5 cm and a height of 8.5 cm (Grossman and Reinsch, 2002). Soil water retention was determined on undisturbed surface soil samples collected after crop harvest in 2012. Three soil samples per plot were collected using metal rings (5 cm diameter by 3.8 cm height). Water retained at −10, −33, −100, and −500 kPa matric potential was determined by the pressure plate method (Dane and Hopmans, 2002) using a Pressure Plate Extractor (Soil Moisture Equipment Corp., Santa Barbara, CA, USA). The intact soil cylinders held in metal rings were initially saturated from the bottom up with 0.001 M $CaCl_2$ for 24 h at 20 °C, placed on a pressure plate, and pressure was incrementally increased to −10 and then −33 kPA. Water retained at −100 and −500 kPa was determined using soil placed in rubber rings (3 cm diameter by 1 cm height) and saturated from the bottom with 0.001 M $CaCl_2$ at 20 °C. Readily available water (RAW) content of each sample was determined by calculating the difference in volumetric water content held at −10 and −100 kPa (Fassman and Simcock, 2012).

2.6. Soil and plant analyses

One composite soil sample consisting of five cores (0–15 cm depth) was taken per plot in September of 2010 prior to biochar and synthetic fertilizer application (initial samples) and again on October 2012, two

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