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Predicting the impact of biochar additions on soil hydraulic properties

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HIGHLIGHTS

- Biochar's impact on soil's saturated conductivity was examined.
- The impact of biochar additions can be estimated from biochar's particle size.
- A model was developed to predict the direction and magnitude of alteration in biochar amended soils.
- This model demystifies the impact of biochar additions on soil's saturated conductivity.

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ABSTRACT

Different physical and chemical properties of biochar, which is made out of a variety of biomass materials, can impact water movement through amended soil. The objective of this research was to develop a decision support tool predicting the impact of biochar additions on soil saturated hydraulic conductivity (K_{sat}). Four different kinds of biochar were added to four different textured soils (coarse sand, fine sand, loam, and clay texture) to assess these effects at the rates of 0%, 1%, 2%, and 5% (w/w). The K_{sat} of the biochar amended soils were significantly influenced by the rate and type of biochar, as well as the original particle size of soil. The K_{sat} decreased when biochar was added to coarse and fine sands. Biochar with larger particles sizes (60%; >1 mm) decreased K_{sat} to a larger degree than the smaller particle size biochar (60%; <1 mm) in the two sandy textured soils. Increasing tortuosity in the biochar amended sandy soil could explain this behavior. On the other hand, for the clay loam 1% and 2% biochar additions universally increased the K_{sat} with higher biochar amounts providing no further alterations. The developed model utilizes soil texture pedotransfer functions for predicting agricultural soil K_{sat} as a function of soil texture. The model accurately predicted the direction of the K_{sat} influence, even though the exact magnitude still requires further refinement. This represents the first step to a unified theory behind the impact of biochar additions on soil saturated conductivity.

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1. Introduction

The saturated hydraulic conductivity (K_{sat}) of soil is a function of soil texture, soil particle packing, clay content, organic matter content, soil aggregation, bioturbation, shrink–swelling, and overall soil structure (Hillel, 1998; Moutier et al., 2000; West et al., 2008). The K_{sat} is one of the main physical properties that aids in predicting complex water movement and retention pathways through the soil profile (Keller et al., 2012; Quin et al., 2014), and it is also widely used as a metric of soil physical quality (Reynolds et al., 2000). Sandy soils provide high K_{sat} values, which leads to rapid water infiltration and drainage (Abel et al., 2013; Bigelow et al., 2004). This fast infiltration is advantageous for reducing run-off and field storm event flooding, but it is also an environmental risk since rapid infiltration rates decrease the time and opportunities for attenuation of dissolved nutrients and agrochemicals before reaching groundwater resources (Li et al., 2013). Conversely, clay-rich soils need to be remediated to improve water drainage/infiltration for enhanced crop productivity (Anikwe, 2000; Benson and Trast, 1995). Since the dawn of agriculture, we having been using crop residues/organic amendments to accomplish these hydraulic improvements; however, since organic additions are typically mineralized, the achieved benefits are of finite duration (i.e., Schneider et al., 2009). However, biochar provides

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the opportunity for a material that is more resistant to microbial mineralization than biomass (Zimmerman, 2010).

The impact of biochar on the soil hydraulic properties is a complex interaction of soil and biochar physical properties. Several studies have reported that the incorporation of biochar to soil increased the K_{sat} (Herath et al., 2013; Moutier et al., 2000; Oguntunde et al., 2008), but other studies have observed decreased K_{sat} following biochar additions (Brockhoff et al., 2010; Githinji, 2014; Uzoma et al., 2011b). The effect of different biomass sources and the particle size of biochar and soil additions have not been exhaustively studied, despite the fact that hydraulic impacts have been known to be soil texture dependent (Tryon, 1948).

A variety of agronomic effects of soil biochar additions on crop yields have been shown in many studies (Chan et al., 2007; Feng et al., 2014; Glaser et al., 2002; Steiner et al., 2007). Even though the exact mechanism is not fully known, the improvement of crop productivity have been attributed to the increase in soil available nutrients (Asai et al., 2009; Uzoma et al., 2011a) and enhanced soil physical properties (e.g., decrease in soil bulk density, increase in water holding capacity) after the incorporation of biochar (Brockhoff et al., 2010; Akhtar et al., 2014). However, despite the critical importance of saturated hydraulic conductivity to agricultural soil water dynamics, there are a limited number of studies addressing the direct impacts of biochar on K_{sat} effects (Asai et al., 2009; Atkinson et al., 2010; Laird et al., 2010; Kameyama et al., 2012). These studies have observed differing impacts from no effect, increases and decreases with no conclusive guidelines for improving soil hydraulic properties with biochar additions; primarily resulting in the same conclusions since the 1950s where the impact depends on soil and biochar properties (Tryon, 1948).

The objectives of this research were to (1) evaluate the K_{sat} when wood or plant based biochar is added to four different soil texture classes (coarse sand, fine sand, loam, and clay) and (2) develop a prediction tool to aid in forecasting biochar impacts on the biochar amended soil K_{sat} value.

2. Materials and methods

2.1. Soils

Soils that were evaluated here were based on overall soil textures: coarse sand, fine sand, silt loam, and a clay loam texture soil. The silt loam was collected from the 0 to 5 cm depth interval from the University of Minnesota's Research and Outreach Station in Rosemount, MN (44°45′N, 93°04′W) from a Waukegan silt loam (Fine-silty sandy-skeletal, mixed, superactive, mesic Typic Hapludoll) and the Webster clay loam (Fine loamy, mixed, superactive, mesic Typic Endoaquoll) was collected from the 0 to 5 cm interval from a poorly drained site at the University of Minnesota Southern Research and Outreach Center in Waseca, MN (44°04′N, 93°31′W). The two sands were commercial mixes of a high purity washed and kiln dried silica sand (Quikrete Companies, Atlanta, GA USA). A course and fine sand were selected to span different particle sizes. All soils were air-dried, sieved to <2 mm, and stored at room temperature before use.

Particle size distribution of the soils was determined by manual dry sieving of a 150 g subsample of soil. There were five different sized sieves used arranged in decreasing sizes from 2.0, 1.0, 0.5, 0.1, and 0.05 mm. Dry sieving was used with 20 min agitation. The mass of soil retained on each sieve was measured to generate the cumulative particle size distribution.

2.2. Biochars

The four biochars used for experiments were selected primarily due to the different particle sizes that existed in these biochars (Fig. 1, Table 1). These biochars were derived from the following feedstock materials: Hardwood wood pellets (*Quercus robur*; PelletKing Amherst, NH USA), pine wood chips (50:50; *Pinus ponderosa* & *Pinus banksiana*; KD Landscape Supply & Recycling, Medina, MN USA), hardwood chip (~33:33:34; *Quercus robur*; *Acer saccharum*; *Fraxinus Americana*; KD Landscape Supply & Recycling, Medina, MN USA), and oat hulls (*Avena sativa*; General Mills, Fridley, MN USA). A programmable furnace equipped with a retort (model #5116HR; Lindberg, Watertown, WI), an inert atmosphere (N_2; 4 L min^{-1}) during heating and cooling, and a final temperature of 500 °C with a 4 h hold time was used to produce biochar. Proximate and ultimate analysis data are also shown for these biochars which were conducted according to ASTM D3172 and D3176, respectively (Hazen Research; Golden, CO USA) (Table 1). For this study, we did not grind or further process the biochar due to the potential chemical alteration of the biochar surface with grinding (e.g., Solomon and Mains, 1977).

Particle size distribution of biochar was determined by manual dry sieving of a 150 g subsample of homogenized biochar. There were seven different sized sieves used arranged in decreasing sizes from 8.0, 4.0, 2.0, 1.0, 0.5, 0.1, and 0.05 mm. Dry sieving was used with 20 min agitation. The mass of biochar retained on each sieve was measured to generate the cumulative particle size distribution.

2.3. Preparation of columns

The four different biochars were each combined at 1%, 2%, and 5% by weight with four different soils (coarse-, fine-, loam, and clay) and thoroughly mixed to provide a homogeneous mixture. To determine the hydraulic conductivity, the soil, biochar, or soil mixtures were gently repacked into a soil column (polyvinylchloride; 6 cm diameter × 20 cm high) to approximately a 5 cm height with light tamping and vibration of the column to eliminate any gaps and voids during packing. The targeted density was 1.2 g cm^{-3}. Four independent replicates of each potential soil treatment were implemented.

2.4. Saturated hydraulic conductivity

Saturated hydraulic conductivity (K_{sat}) was measured using a falling head method (Klute and Dirksen, 1986). A piece of filter paper was placed on the soil surface to minimize soil disturbance when filling with water. Tap water was gently poured into column until it was full (20 cm height of column) and hydraulic testing was performed after steady flow conditions were attained, usually after 3–4 repetitive flushing of the entire column. The average drop in hydraulic head over a known time period was used to calculate the K_{sat} value for each sample by the following equation (Klute and Dirksen, 1986):

$$k = \frac{L}{t} ln\left(\frac{h_o}{h_f}\right),$$

where L is the length of the soil sample (5 cm), t is the time period (s), h_o is the initial height of water in the column referenced to the soil column outflow (cm), and h_f is the final height of water also referenced to the soil outflow (cm). Since the diameters of the column and water column were equivalent these factors canceled out from the equation.

2.5. Bulk density

The bulk density of each individual column was determined by dividing the known mass of the oven dried sample added to the columns by the measured sample volume. This soil volume