Biomass or biochar – which is better at improving soil hydraulic properties?

K.A. Spokas[1], R. Weis[1], G. Feyereisen[1], D.W. Watts[2], J.M. Novak[2], T.J. Lim[3] and J.A. Ippolito[4]

[1]United States Department of Agriculture, University of Minnesota, Saint Paul, MN, USA; [2]United States Department of Agriculture, Florence, SC, USA; [3]Rural Development Administration, Jeonju-si, Jeollabuk-do 560-500, Republic of Korea; [4]United States Department of Agriculture, Kimberly, ID, USA.

Abstract

When amended to soils, both biochar and biomass impact soil hydraulic properties. However, the exact comparison between these two material forms is not known. The objective of this research was to evaluate and compare the impacts of raw biomass chips with biochar produced from the same feedstock. Both raw biomass (pine chips; *Pinus taeda*) and a corresponding pine-chip biochar (slow pyrolysis; 2 h, 500°C) were added to a sandy-textured Ultisol at three different rates and four incremental particle-size fractions (1-2, 0.5-1, 0.2-0.5, and <0.2 mm). Results demonstrated that the immediate impact on hydraulic conductivity (K_{sat}) of the amended soil was influenced by application rate and particle size, with remarkable similarity between the two amendments. All additions significantly reduced both the soil bulk density and K_{sat} ($P<0.05$). These alterations in the hydraulic properties were postulated to be due to alterations in soil particle packing (i.e., tortuosity). Alterations in pore geometry, with blocking of larger macropores by the amendment, could explain this behavior, and this was supported by the similar behavior between raw feedstock and biochar of equal particle sizes. Thus, the immediate alterations in the hydraulic properties of an amended soil were primarily a function of the particle size of the material, regardless of whether or not the raw feedstock had been converted to biochar. With decreasing particle size, both additions increased water-holding capacity at saturation. This suggests that small-particle-size additions to a sandy-textured soil would reduce infiltration rates and net water gained per precipitation event due to the reduced soil moisture potential gradient and K_{sat}. However, the effects are a function of the amendment particle size distribution and the original soil texture.

Keywords: hydraulic conductivity, particle size, pore size, soil amendment

INTRODUCTION

The particle-size distribution of soil strongly dictates its capacity to hold soil moisture (Hillel, 1998). Organic wastes have been added to soil since historic times in efforts to improve soil moisture properties (Khaleel et al., 1981). Typically, organic material application results in increases in hydraulic conductivity regardless of soil texture. This could be a result of the incorporated organic materials bearing a large particle size (>2 mm), thereby altering the soil particle-size distribution (Bose, 2012). An additional mechanism involved in this improvement is increased moisture sorption by the organic material (Gupta et al., 1977). Water sorption on organic surfaces is believed to be controlled by surface functional groups containing oxygen moieties. These oxygen moieties are believed to form hydrophilic domains that allow for hydrogen bonding with water molecules (Novak et al., 2012), which would be aided by amendments with elevated surface areas (Shepherd et al., 2002). In addition, hydraulic improvements can be augmented by soil aggregation processes resulting from the stimulated microbial activity from organic amendments (Shepherd et al., 2002). Together, these processes lead to new soil structural packing arrangements, pore geometries, and tortuosity, which alter soil hydraulic properties.

Historically, a chief mechanism for achieving these improvements has been through organic matter amendments. Even though there is relatively rapid mineralization of organic additions (Schneider et al., 2009), this stimulation of microbial activity does result in improved soil properties. For instance, research has confirmed additional benefits in soil physical characteristics with time, such as increasing mean particle diameter (soil structure), aggregate stability, and increased hydraulic conductivity (Aggelides and Londra, 2000; Schneider et al., 2009). Research on organic materials, such as raw pine chips, has shown that smaller particle sizes increase soil water-holding capacity (saturation to wilting point), with a corresponding decrease in total air-filled porosity (Nelson, 2011). In addition to altering soil physical textures, the particle size of soil amendments also influences a variety of processes, such as greenhouse gas production rates (Fangueiro et al., 2012; Sigua et al., 2014; Tejada et al., 2014), bulk density (Zhao et al., 2012), cation exchange capacities (Altland et al., 2014), and pH alterations (Altland et al., 2014).

Biochar has been hypothesized as a material to improve soil moisture characteristics (Novak et al., 2012), while offering longer-term impacts due to the fact that the material is more resistant to mineralization than the corresponding unpyrolyzed feedstock (Karhu et al., 2011; Zimmerman et al., 2011). Similar to unpyrolyzed feedstock, an alteration in soil moisture-holding capacity resulting from biochar addition could lead to reduced plant moisture stress (Mulcahy et al., 2013) and have positive implications for plant productivity during periods of water deficit and reduced irrigation water use. Perhaps different from unpyrolyzed feedstock, the pore water within the biochar is assumed to become available to the soil system during periods of water deficit (Uzoma et al., 2011). Yet, there are no studies that have actually confirmed or attempted to simulate this water availability, since this has been based solely on volumetric or gravimetric moisture contents, or differences in limited soil moisture potential assessments (Scott et al., 2014).

Biochar additions have been claimed to improve soil water-holding and water-transport properties (Scott et al., 2014), especially in sandy-textured soils. However, raw biomass incorporated into a sandy soil has also been reported to improve moisture capacities (Novak and Watts, 2013). Therefore, to determine which amendment is superior for hydraulic improvements, we evaluated both raw pine chips and pine-chip biochar for their impact on soil moisture retention curves and saturated hydraulic conductivity over a range of particle sizes in a sandy loam-textured Ultisol.

MATERIALS AND METHODS

Soil

Soil was collected from an agricultural field in the Coastal Plain region of the southeastern USA (Florence, SC; Norfolk soil series). This soil is classified as a fine-loamy, kaolinitic, thermic, Typic Kandiudult and has poor water retention characteristics, since it formed in marine sediments (Novak et al., 2012). The soil was air-dried and then sieved (<2 mm) to remove any gravel or plant debris. Overall, the soil had a soil organic carbon content of 0.39%, a pH of 5.9, and a soil texture of 80.7% sand, 16.7% silt, and 2.6% clay (loamy sand; USDA soil textural classification).

Pine chip feedstock and biochar

Pine chips were collected from logging debris located in Cordesville, SC, USA. After collection, the pine chips were kept at room temperature and in an air-dried state (10% w/w moisture). To reduce the particle size, collected pine chips were then hammer-milled (PPH1000D; Pellet Pro Davenport, IA, USA) and passed through a Wiley mill (Thomas Scientific, Sweedesboro, NJ, USA) to achieve <6 mm particle size. A subsample of these flakes was then converted into biochar. Biochar was made using a programmable furnace equipped with a retort (model 5116HR; Lindberg, Watertown, WI, USA) under a N_2 atmosphere at 500°C for 2 h. Elemental analysis of pines chip and biochar followed the ultimate and proximal analysis for coal (Hazen Laboratories, Golden, CO, USA) following ASTM D-3172 and 3176 standard methods (Table 1). Finally, the pine chips and biochar were further dry-sieved into four separate size fractions: 2-1, 1-0.5, 0.5-0.25 and <0.25 mm.

Table 1. Chemical composition of raw pine chips and pine-chip biochar. All values are given on percentage dry weight basis.

Product	Proximal				Ultimate				
	Moisture	Ash	Volatile matter	Fixed carbon	S	Ca	H	N	O
Raw feedstock	9.92	4.16	80.88	14.95	0.02	51.88	5.65	0.08	38.21
Biochar (500°C)	4.08	2.61	22.39	75.00	<0.02	88.83	3.14	0.45	4.97

Amendment application

The individual sieved particle-size fractions (2-1, 1-0.5, 0.5-0.25, and <0.25 mm) of both the pine chips and biochar were separately added to the Norfolk soil at the three rates evaluated in this experiment (0, 5, and 10%, w/w). The experimental design was a complete randomized experiment, with three different factors (two amendment types × three application levels × four particle sizes) and conducted with three replications of each combination. The experiments were completed within 3 months after soil mixing, thus limiting the impacts assessed to purely physical, and ignoring longer-term microbe-aided impacts (Shepherd et al., 2002).

Soil moisture potential curve determination

The drying portion of the soil moisture potential curve was measured using an automated evaporation ku-pF apparatus (UGT GmbH, Muncheberg, Germany). This instrument allows a maximum of 10 samples to be run concurrently, with the robotic arm switching between the cylinders every 10 minutes. There are two moisture tensiometers that are connected to each cell, and, once properly deaired, they are accurate between 0 to 100 kPa of soil moisture potential. All treatments of the particle-size groupings of both biochar and raw pine-chip additions were handled in a similar fashion. The soil sample was placed into a cylindrical sample holder and gently tapped to fill the sample ring. After tamping, the soil was levelled with the top by scraping. Samples were then saturated in a distilled water bath, wetting the sample from the bottom (until saturated), and the tensiometers were installed and then placed on the ku-pF instrument. For several days to weeks of monitoring, soil water-tension readings from the embedded tensiometers and weights of the test cells were recorded at 10 minute intervals for all eight samples. This monitoring was continued until both tensiometers "popped" (ψ=-80 to -100 kPa) in each sample cell. Due to evaporation, the weight of each test cell changed as a function of time, along with the measured water tension. Data were processed according to the method outlined in Schindler and Müller (2006). This allowed the calculation of mean water tension and the corresponding volumetric moisture. Bulk densities were calculated from the weight of the sample materials added to the test cell of known volume (245 cm^3). Data from each individual triplicate were then fitted to calculate van Genuchten's coefficients (van Genuchten, 1980), using the interactive *soilwater* function within the **soilphysics** package in R (da Silva and de Lima, 2015).

Hydraulic conductivity measurement

An automated falling-head permeameter system was utilized to measure the saturated conductivity on each soil sample (UMS KSAT Benchtop Saturated Hydraulic Conductivity Instrument, Decagon, Pullman, WA, USA). The sample was transferred into the KSAT device again by gently tapping and packing the cylinder until the bulk density matched the soil moisture potential curve assessment. The sample was then placed in the apparatus and initially saturated by allowing five pore volumes of water to flow through the sample prior to testing. The K_{sat} was determined through the manufacturer's software (KSat; Version 2.1) utilizing a falling-head methodology.

Soil moisture modeling

A previously validated soil moisture model was used (STM2; Spokas and Forcella, 2009). This model permits a comparison of the annual cycle of soil moisture potential and volumetric moisture, utilizing the measured soil hydraulic properties (van Genuchten's coefficients). The model was used in the "advanced mode", and the individual soil moisture properties were entered for the control, pine chip, and biochar at 10% (w/w) and the <0.25 mm particle size. The 30-year average climate for Florence, SC, USA, was used to model the impact of biochar, raw pellet, and the control soil for a typical annual cycle to observe the potential impacts of these additions on the soil moisture profile.

Statistical treatment of data

Significance of the biochar treatment was tested by one-way analysis of variance (ANOVA), and Tukey's HSD test (at P<0.05) was applied for differences in means. All statistical analyses were completed using R (R Core Team, 2014).

RESULTS AND DISCUSSION:

For both amendments, the bulk density decreased when compared with the control (unamended soil) (Table 2), which suggests alterations in the packing arrangements due to the amendments. For bulk density, the rate of application was the only significant factor; there was no dependency of material type (i.e., pyrolyzed or unpyrolyzed material; P<0.05). Both amendments also increased the volumetric soil moisture capacity at saturation as compared with the control (P<0.05; Table 2).

Table 2. Summary of bulk density and the results of fits of van Genuchten's parameters.

Addition	Size (mm)	Rate	BD (g cm^{-3})	Θ_R	Θ_S	α (kPa^{-1})	n
Control	-	0	1.57^{a}	0.14^{a}	0.33^{f}	0.15^{d}	2.16^{abcd}
Raw pine chips	<0.25	5	1.33^{cde}	0.17^{a}	0.44^{abcd}	0.17^{cd}	2.65^{abc}
	0.25-0.5	5	1.36^{bc}	0.12^{a}	0.42^{bcde}	0.24^{bcd}	1.96^{abcd}
	0.5-1.0	5	1.36^{bc}	0.12^{a}	0.38^{cdef}	0.18^{cd}	1.94^{abcd}
	1-2	5	1.38^{bc}	0.14^{a}	0.35^{def}	0.17^{cd}	2.05^{abcd}
	<0.25	10	1.15^{def}	0.17^{a}	0.53^{a}	0.21^{cd}	2.80^{a}
	0.25-0.5	10	1.07^{f}	0.13^{a}	0.50^{ab}	0.37^{a}	1.96^{abcd}
	0.5-1.0	10	1.11^{f}	0.07^{a}	0.44^{abcd}	0.33^{ab}	1.68^{d}
	1-2	10	1.13^{ef}	0.08^{a}	0.41^{bcdef}	0.25^{bcd}	1.68^{d}
Biochar	<0.25	5	1.36^{cd}	0.11^{a}	0.37^{def}	0.16^{cd}	1.93^{bcd}
	0.25-0.5	5	1.35^{cd}	0.05^{a}	0.37^{cdef}	0.22^{bcd}	1.50^{d}
	0.5-1.0	5	1.39^{abc}	0.15^{a}	0.38^{cdef}	0.18^{cd}	1.93^{bcd}
	1-2	5	1.38^{bc}	0.16^{a}	0.37^{def}	0.16^{cd}	1.90^{cd}
	<0.25	10	1.1^{f}	0.17^{a}	0.47^{abc}	0.20^{cd}	2.79^{ab}
	0.25-0.5	10	1.13^{ef}	0.13^{a}	0.36^{def}	0.24^{bcd}	2.02^{abcd}
	0.5-1.0	10	1.07^{f}	0.12^{a}	0.37^{def}	0.24^{bcd}	1.70^{d}
	1-2	10	1.09^{f}	0.09^{a}	0.41^{bcdef}	0.27^{abc}	1.77^{d}

BD, Bulk density. Θ_R, Θ_S, α, and n are van Genuchten's parameters for residual moisture content, saturated moisture content, inverse of the air entry potential, and a parameter related to the pore-size distribution, respectively.

Means with the same letters are not significantly different as evaluated through Tukey's HSD test in the **agricolae** package library in R (de Mendiburu, 2014).

Similar observations have been documented for water retention increasing in the low retention range (<100 kPa) following organic material additions (Khaleel et al., 1981). Interestingly, the raw pine chips increased saturated soil moisture content to a greater degree than the biochar additions, particularly noticeably at the 10% (w/w) addition. This difference could increase water-holding capacity at saturation. This difference could be related to the fact that water molecule sorption is highly dependent on oxygen surface moieties, and oxygen has been lost from the biochar during the pyrolysis (38 to 5% O; Table 1). Thereby, the capacity of biochar to absorb and hold onto water through hydrogen bonding is greatly reduced (Puri et al., 1961). However, biochar still caused an increased in soil moisture content at saturation (Table 2) and thus other phenomena, such as alterations in macroporosity by particle size distribution and increased tortuosity, are likely responsible for these near-saturated water improvements with biochar application. Despite numeric differences, the alteration in the residual moisture was not significant across all treatments (Table 2). The alteration in the α factor was only significant for the 10% pine chip at the 0.25-0.5 and 0.5-1 mm size fractions and for 10% biochar at only the 1-2 mm size fraction. The α factor is related to the air entry value (Tinjum et al., 1997). There was no significant difference in the n parameter (Table 2), which is related to the shape of the soil water characteristic curve.

Hydraulic conductivity

Despite the reduction in soil bulk density (Table 2), there was also an observed reduction in the hydraulic conductivity for both the pine chip and biochar particles at the 10% (w/w) level (Figure 1A). There was no statistical dependency on the material type (biochar or raw pine chips); therefore, the data were pooled to examine the relationships between particle size and addition rate. Both the <0.25 and 0.25-0.50 mm particle-size additions resulted in a reduced hydraulic conductivity across both rates, and the larger particle-size additions did not alter (0.5-1 mm) or increased (1-2 mm) the K_{sat} (Figure 1B). Similar have been results were observed with other biochar additions to sandy-textured soils (e.g., Brockhoff et al., 2010).

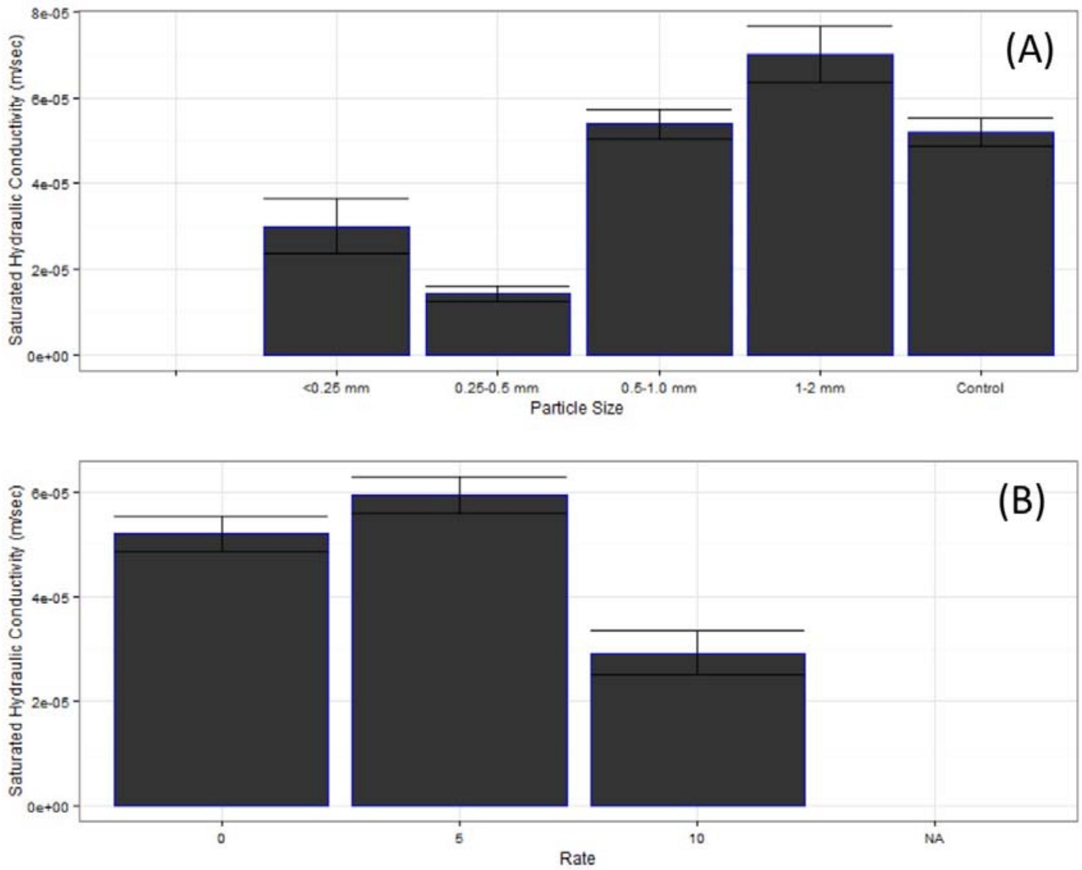

Figure 1. Comparing the impact of particle size (A) and amendment application rate (B) on soil hydraulic conductivity. Because of the similarity in the response of the biochar and raw biomass particles, the results were pooled across material type.

Simulation modeling

The impact of raw pine chips and pine-chip biochar on an annual cycle (assuming no alteration in the soil moisture potential curve with time; Table 2) was assessed for the 30-year average climate for Florence, SC, UAS (34.2°N 79.7°W; annual mean air temperature 17.4°C; 1180 mm total precipitation). The amendments of 10% (w/w) of <0.25 mm biochar and pine chip, along with the unamended soil (control), were modeled for this typical climate data. Figure 2 illustrates the average rainfall (Figure 2A) and air temperature (Figure 2B) and the corresponding results for the volumetric soil moisture and soil moisture retention curves at 1, 5, 10, and 20 cm depths for the control and amended soils (Figure 2C, D).

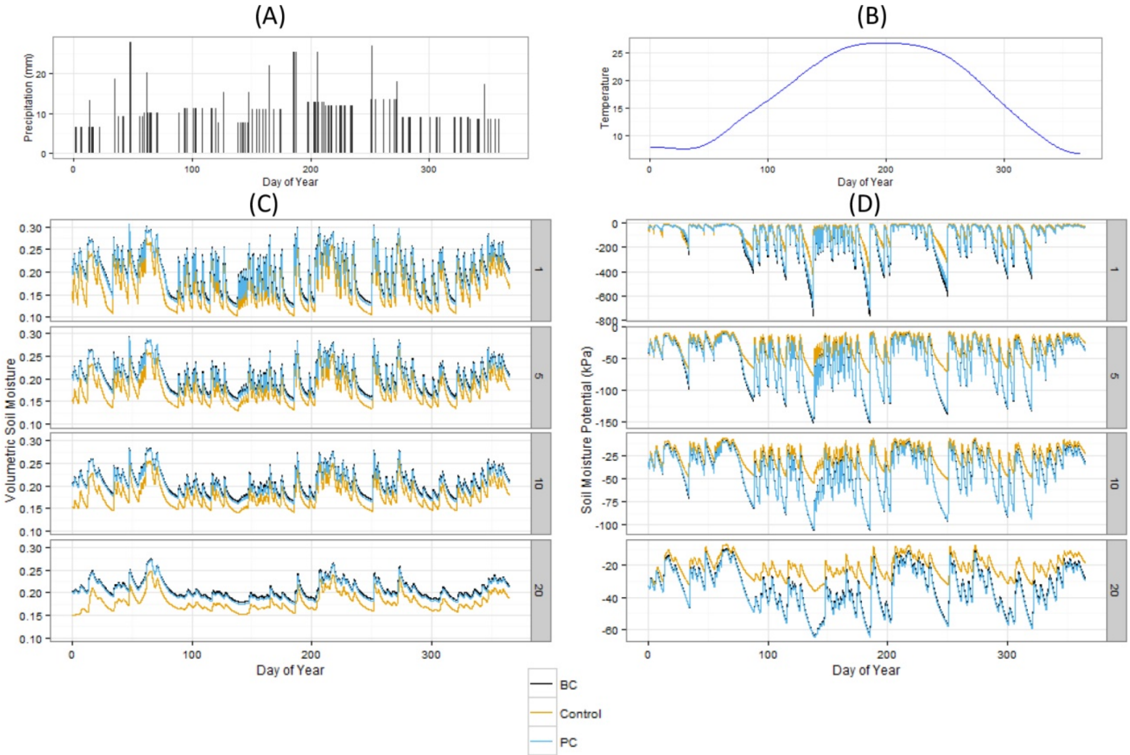

Figure 2. Predicted precipitation (A) and air temperature (B) for Florence, SC, USA, which were used as inputs to the STM2 model to simulate a 10% (w/w) addition of <0.25 mm particle-size biochar (BC) and pine chip (PC) amendments to a sandy loam soil (control) for four different depths (1, 5, 10, and 20 cm; labeled in the gray margins of the graphs) illustrating volumetric soil moisture (C) and soil moisture potential (kPa) (D).

Both the biochar and pine-chip additions contained a larger amount of soil moisture (Figure 2C). However, this was also accompanied by a lower soil moisture potential (Figure 2D), indicating that this higher moisture is actually less available. This is due to the similar-structured pores in both the biochar and pine-chip materials (data not shown). Because of the reduced saturated conductivity, when there is a precipitation event, the model predicts a reduced rate of infiltration into the profile, thus reducing the recharge volume of moisture from each precipitation event in the biochar- and pine chip-amended soil. On the other hand, this reduced hydraulic conductivity translates into more time for the infiltration front to be in contact with plant roots. This will be a larger advantage in sandy-textured soils, and could explain biochar's improved yields in sandy-textured soils (Jeffery et al., 2011). Whether this is of agronomic importance will be a function of the soil hydrodynamics and climate at each individual site.

The major differences between biochar-amended and control soils will likely be manifested during periods of drought stress. In other words, the biochar- or pine chip-amended plot might contain more absolute soil moisture, but it would be held more strongly by the amended soil. This is analogous to the soil moisture relationship of different soil texture classes (Hillel, 1998).

CONCLUSIONS

This study investigated the impact of raw pine chip and biochar amendments by particle size on soil hydraulic properties. The data from this study support the conclusion that the immediate impacts are similar for both materials; however, if the biochar survives for a longer time in the soil system, a one-time application could lead to longer-term improvements than are typically obtained from a one-time organic amendment application (due to mineralization losses). On the other hand, organic amendment applications will likely be required to equal infrequent biochar applications. Regular organic addition will result in a larger microbial stimulation, as a result of continual increases in degradable organic matter added to the soil.

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