Chemosphere 142 (2016) 136–144

Contents lists available at ScienceDirect

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

Predicting the impact of biochar additions on soil hydraulic properties

T.J. Lim[a], K.A. Spokas[b,c,*], G. Feyereisen[b,c], J.M. Novak[d]

[a] Rural Development Administration, Horticultural & Herbal Crop Environment Division, Suwon, South Korea
[b] USDA-ARS, Soil and Water Management Unit, St. Paul, MN, United States
[c] University of Minnesota, Department of Soil, Water and Climate, St. Paul, MN, United States
[d] USDA-ARS, Coastal Plain Soil, Water and Plant Conservation Research Center, Florence, SC, United States

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.

ARTICLE INFO

Article history:
Received 1 November 2014
Received in revised form 11 June 2015
Accepted 22 June 2015
Available online 2 July 2015

Keywords:
Biochar
Saturated hydraulic conductivity
Soil texture

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.

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

* Corresponding author at: USDA-ARS, Soil and Water Management Unit, 1991 Upper Buford Circle, 439 Borlaug Hall, St. Paul, MN, United States.
E-mail address: kurt.spokas@ars.usda.gov (K.A. Spokas).

http://dx.doi.org/10.1016/j.chemosphere.2015.06.069
0045-6535/Published by Elsevier Ltd.

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

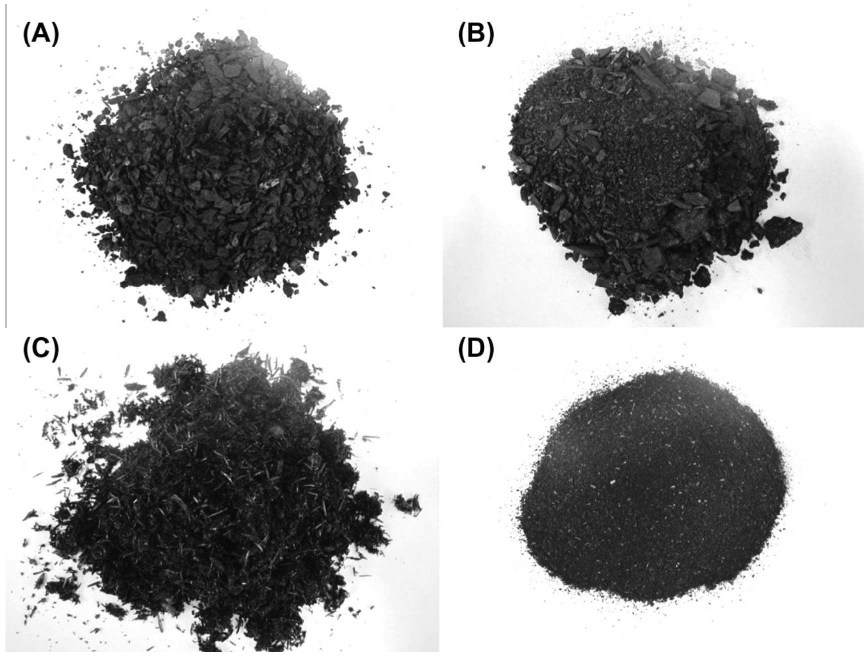

Fig. 1. Photos of the various biochar used in this experiment: (A) pine chip, (B) hardwood chip, (C) oat husk, and (D) hardwood pellet (sieved to <4 mm).

Table 1
Chemical and physical properties of the four different biochars.

Biochar	ρ_{BD} (g/cm^3)	d_{50} (mm)	C	N	O	H	S	Ash	% Moisture (air dried)
			(% Dry weight basis)						
Wood pellet	0.50	0.7	77.6	0.4	11.3	3	<0.1	7.7	4.8
Pine chip	0.54	3.8	64.3	3.1	6.2	1.2	<0.1	25.2	11.3
Hardwood chip	0.32	1.6	71	0.2	22	4	0.1	2.7	6.7
Oat husk	0.34	2.1	32	2.5	43	8	<0.1	14.5	55.4

measurement occurred immediately after the hydraulic conductivity assessments.

2.6. Statistical analysis

Averages and standard deviations of the quadruplicates were calculated. The statistical interactions between biochar type, biochar amendment rates, and soil type were evaluated by a 3-way analysis of variance (ANOVA). Fisher protected least significant differences were used to compare treatment means at the 95% ($p = 0.05$) significance level.

3. Results and discussion

3.1. Particle size distributions

Images of the four biochars are shown in Fig. 1, and the corresponding particle size distributions of the soil and biochars are in Fig. 2. Hardwood chip biochar possessed the largest particle size fraction with >88% of the total particles being >1 mm and then pine chip was next with 44% of particles >1 mm (Fig. 2). The oat husk (44%; <0.5 mm) and wood pellet (57%; <0.5 mm) biochars possessed smaller particle sizes (Table 1; Fig. 2). This data suggests that the particle size of the biochar can be controlled by pre- and post-treatment of the biomass or biochar, with one example of this being larger wood chip sizes (Fig. 1). These observations support the possibility of developing specific particle sizes for targeted hydraulic improvements. However, biochar particle size is not a static property, as the particle themselves can physically disintegrate (Naisse et al., 2015; Spokas et al., 2014) and impact microbial degradation rates (Sigua et al., 2014).

3.2. Bulk density

The soil type, amendment rate of biochar, and biochar additions had a statistically significant influence on the soil bulk density after application ($P < 0.05$; Table 2). The incorporation of biochar lowered the bulk density by increasing total soil pore volume (Jones et al., 2010; Oguntunde et al., 2008). This decrease in bulk density following biochar incorporation has also been observed in other studies (e.g., Mukherjee et al., 2014; Pathan et al., 2003; Laird et al., 2010) and is expected due to the lower particle density of the biochar materials compared to soils (Laird et al., 2010; Brewer et al., 2014; Rogovska et al., 2014). Interestingly, the difference between the weighted averaged of the two materials and the measured bulk density was the largest for the clay textured soil, with ranges from 14% to 20% lower bulk densities (Table S1). For the sandy texture soils, the differences were not as large, ranging from 1% to 16% and the differences for the loam textured soil were even further reduced (−2% to 6%; Table S1). This suggests that biochar does alter the packing of soil particles, thereby creating additional external soil porosity.

The hardwood chip biochar (the largest particle size) resulted in the lowest bulk density among the biochars (Table 2). However, this was expected since it also contained the lowest bulk density of the biochar evaluated here (0.32 g cm^{-3}; Table 1). In other words, for the equivalent mass addition, the lower bulk density

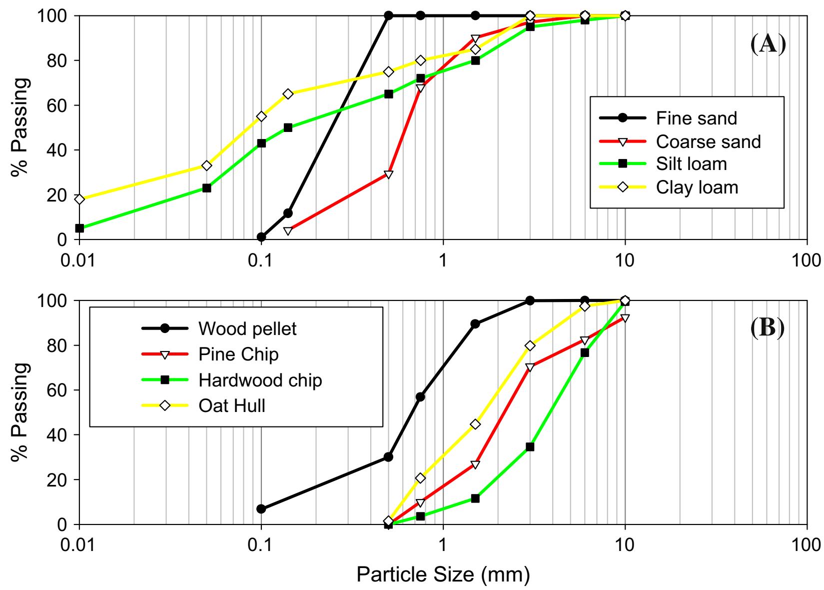

Fig. 2. Particle size distribution for (A) the original four soil materials and (B) the four biochars.

results in a higher total volume being added to the soil. The hardwood chip biochar at 1% and 5% additions reduced the bulk density by 4% and 20% in coarse sand, respectively (Table 2). In the fine sand, a similar decrease was observed, with the 1% and 5% biochar lowering the bulk density by 4% and 20%. The reductions were greater in the clay loam soil, with decreases observed of 18% and 26%, respectively (Table 2). The soil type that was impacted the least by the range of biochar additions was the loam textured soil. We attribute this lack of alteration in the bulk density to the diversity of soil particle sizes already present in the soil providing buffering to these particle size additions (Fig. 2).

3.3. Hydraulic conductivity

The K_{sat} of the amended soils was significantly influenced by particle size and rates of biochar application, as well as the particle size of soil (Table 2). The K_{sat} of the un-amended coarse sand, fine sand, loam, and clay textured soil was 248.9, 107.7, 30.8, and 10.3 mm h^{-1}, respectively (Fig. 3). Particle size distribution strongly controls the resulting pore geometry and thereby the K_{sat} ($P < 0.001$), as already noted (Vereecken, 1995).

Fig. 3 illustrates the K_{sat} values of the soils and biochar materials when sieved to a particular size class. The significant observation is that similar sized materials have the same K_{sat} when examined by particle size divisions, which is similar to the impact of soil particles of differing mineralogy (McKeague et al., 1982). This strongly suggests that the impact of biochar additions on K_{sat} can be modeled as a particle size effect.

Soil amendment with biochar possessing a larger particles sizes (60%; >1 mm) had a more significant impact on decreasing K_{sat} than the smaller particle size biochar (60%; <1 mm) (Figs. 3 and 4). For example, application of 5% wood pellet decreased K_{sat} 53% in coarse sand and 75% in find sand, whereas the application 5% of hardwood chip biochar reduced K_{sat} by 96% and 86% in the coarse and fine sand, respectively (Figs. 3 and 4). In addition, the increase in the application rates of biochar sharply decreased the K_{sat} in coarse sand, manifesting the highest absolute drop in the K_{sat} observed in this experiment (Table 2). This drop in K_{sat} can be advantageous in sandy textured soils, since the plant roots would be in contact with the infiltration front for a longer duration. This could lead to higher biomass yields due to the reduced infiltration rates.

For instance, K_{sat} values acquired by incorporation of 1%, 2%, and 5% hardwood chip decreased the K_{sat} to 68.8, 31.9, and 10.5 mm h^{-1} from 249 mm h^{-1} in coarse sand and 69.1, 55.8, and 15.4 mm h^{-1} from 108 mm h^{-1} in fine sand, respectively. For a 50 cm thick root zone, this would equate to a difference of 2 days for the coarse sand 5% hardwood chip compared to the control soil for movement of the infiltration front. These results are in agreement with earlier studies that also confirmed that K_{sat} in sandy soils typically decreased after biochar addition (Brockhoff et al., 2010; Pathan et al., 2003), particular with biochar of small particle sizes (<1 mm). This dependency on amendment particle size has also been observed for zeolite (Huang and Petrovic, 1994) and gypsum (Keren et al., 1980) additions to soils.

There has been research into the macro- and micro-porosity of biochar (e.g., Yu et al., 2006; Joseph et al., 2010; Kinney et al., 2012), since the overall assumption has been that biochar will lead to an improved water holding capacity due to the numerous micro- and nano-scale pores that are observed within the biochar particles (Atkinson et al., 2010; Gray et al., 2014). From soil capillary forces, a given height of water rise in a capillary column can be related to the pore radius by the following equation:

$$h = \frac{2\gamma \cos(\theta_{contact})}{gr(\rho_{water})}$$

where h is the height of rise in the capillary column (pore) (m), γ is the surface tension of water [@ 25 °C = 71.97 kg s^{-2}], $\theta_{contact}$ is the contact angle (assumed = 0° rad), g is the acceleration due to gravity (9.8 m s^{-2}), ρ_{water} is the density of water (999.97 kg m^{-3}), and r is the radius of the pore (m). Therefore, the largest pore that will be holding water at a soil moisture potential of −1500 kPa (~150 m water column) is 0.2 μm (Gardner et al., 1999). In other words, soil pores <0.2 μm are not of agronomic significance, since this soil moisture will not be plant available as well as not significantly to saturated soil water flow. The biochar particles would effectively behave as a solid particle and their resulting impact on K_{sat} would be soil texture and biochar particle size dependent (Fig. 2). However, for clay loam soils, 1% and 2% (w/w) biochar additions increased K_{sat}, with 5% of biochar addition providing no further increases or decreases (Fig. 4). In the clay textured soil, the incorporation of small amounts of biochar (with particle sizes larger than

Table 2
The change of bulk density and saturated hydraulic conductivity (K_{sat}) after four rates of different biochar were added to coarse sand, fine sand, and clay soil.

Soil texture	Biochar addition	Incorporation rate (w w^{-1})	Bulk density (g cm^{-3})	K_{sat} (mm h^{-1})
Coarse sand	Control	0	1.67 (0.02)	248.9 (19.4)
	Wood pellet	1	1.64 (0.04)	193.7 (12.2)
		2	1.58 (0.05)	156.9 (11.9)
		5	1.47 (0.04)	117.7 (18.2)
	Pine chip	1	1.61 (0.02)	109.8 (5.1)
		2	1.53 (0.04)	70.9 (4.3)
		5	1.34 (0.03)	35.9 (4.0)
	Hardwood chip	1	1.59 (0.02)	68.8 (5.1)
		2	1.53 (0.04)	31.9 (4.2)
		5	1.36 (0.06)	10.5 (0.9)
	Oat husk	1	1.60 (0.02)	112.3 (8.3)
		2	1.53 (0.03)	45.1 (3.2)
		5	1.35 (0.04)	30.2 (2.9)
Fine sand	Control	0	1.63 (0.05)	107.7 (9.8)
	Wood pellet	1	1.60 (0.03)	86.9 (1.9)
		2	1.57 (0.02)	65.5 (5.4)
		5	1.40 (0.04)	26.6 (1.2)
	Pine chip	1	1.56 (0.06)	77.7 (0.8)
		2	1.45 (0.03)	63.9 (0.9)
		5	1.22 (0.04)	28.5 (1.4)
	Hardwood chip	1	1.56 (0.05)	69.1 (0.9)
		2	1.49 (0.06)	55.8 (1.0)
		5	1.31 (0.04)	15.4 (0.3)
	Oat husk	1	1.57 (0.03)	64.2 (0.8)
		2	1.49 (0.04)	52.6 (1.2)
		5	1.34 (0.05)	34.2 (5.1)
Clay	Control	0	1.36 (0.06)	10.3 (0.9)
	Wood pellet	1	1.16 (0.04)	16.5 (1.0)
		2	1.13 (0.02)	18.5 (1.0)
		5	1.08 (0.05)	18.2 (0.9)
	Pine chip	1	1.11 (0.02)	17.6 (0.8)
		2	1.05 (0.04)	18.9 (1.3)
		5	1.00 (0.03)	13.2 (2.8)
	Hardwood chip	1	1.13 (0.05)	14.4 (0.3)
		2	1.06 (0.06)	18.5 (0.3)
		5	0.98 (0.04)	10.2 (2.2)
	Oat husk	1	1.15 (0.04)	18.5 (0.4)
		2	1.11 (0.02)	19.9 (0.5)
		5	1.05 (0.05)	20.2 (3.5)
Loam	Control	0	1.15 (0.02)	30.8 (2.1)
	Wood pellet	1	–	–
		2	1.16 (0.02)	29.8 (3.2)
		5	1.10 (0.04)	28.4 (1.9)
	Pine chip	1	–	–
		2	1.14 (0.02)	30.2 (1.8)
		5	1.12 (0.02)	31.3 (2.5)
	Hardwood chip	1	–	–
		2	1.16 (0.03)	28.1 (2.9)
		5	1.12 (0.03)	27.8 (2.8)
	Oat husk	1	–	–
		2	1.12 (0.03)	31.1 (2.3)
		5	1.18 (0.04)	29.7 (3.9)
Source of variation				
Particle size (S)			***	***
Biochar (B)			ns[†]	***
Incorporation rate (R)			***	***
S × B			ns	***
S × R			***	***
B × R			ns	ns

** and *** represent significant at 1% and 0.1% probability levels, respectively.
[†] ns represent non significant.

1 mm) increased K_{sat}, which is contrary to the impact observed in the coarser textured soils.

Soil pores larger than 30 μm will increase water holding capacity from saturated ($\Psi = 0$ kPa) to gravity drained (field capacity) conditions ($\Psi = -33$ to 100 kPa), but this water quickly drains and typically is not counted as part of the plant available water (Hillel, 1998). Herath et al. (2013) reported the biochar particles (>0.5 mm) were associated with the increase of macroporosity in soil. Therefore, biochar additions do alter the saturated conductivity, but these alterations are largely due to particle packing differences (tortuosity) and not due to the internal porosity of the biochar. These differences in particle packing may (Novak et al., 2012) or may not (Chang et al., 1977) change the total soil moisture holding capacity. For coarse textured soils, small particle sized

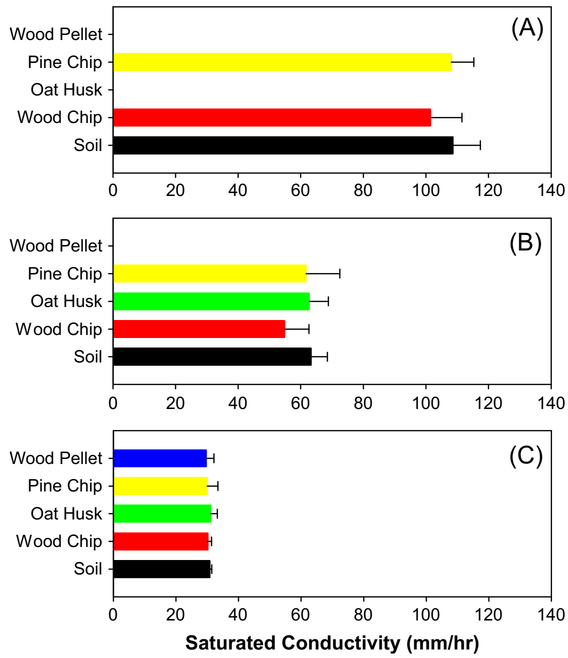

Fig. 3. Comparing saturated conductivity of particle size fractions for the various materials from (A) 7–8 mm, (B) 4–6 mm, and (C) 1–2 mm. Note there are no values for >2 mm for the wood pellet biochar and the 7–8 mm for the oat husk biochar, due to the lack of those particle size classes in the respective biochar. There are no statistically significant differences in the saturated conductivity of each particle size class of these materials ($P > 0.05$; ANOVA).

amendments (e.g., wood ash, zeolites, diatomaceous earth) have typically improved overall water holding capacity of the soil, but typically do not alter the agronomic plant available water (Bigelow et al., 2004), which is the moisture held between field capacity and the wilting point. On the other hand, organic material addition (i.e. peat, compost) typically do lead to improved plant available water due to the larger particle sizes and added hydrophilic surfaces (Aggelides and Londra, 2000).

Despite the lack of uniform alteration in the net water holding capacity from biochar additions, the differences in saturated hydraulic conductivity could impact the overall field water balance between infiltration, evaporation, and run-off. In addition, the differences in infiltration rate of biochar amended soils could change with time (Novak et al., 2015). This data also suggests that the critical factor for K_{sat} improvement is particle size versus hydrophobicity or biochar's intra-porosity (e.g., Jeffery et al., 2015).

3.4. Model development

An initial tool developed in Microsoft Excel™ was used to calculate the impacts of biochar additions on K_{sat}. Barnes et al. (2014) utilized the d_{50} of biochar addition to attempt to predict K_{sat} of the mixtures. However, this method was not successful due to the impact of biochar on soil particle packing and bulk density (Table S1). Based on the lessons learned in that study, we decided to use a simplified model for the biochar: either it was a large (>1 mm) or small (<1 mm) particle size amendment. Despite the fact that this technique is not the traditional sand particle size boundaries, this might account for some of the physical

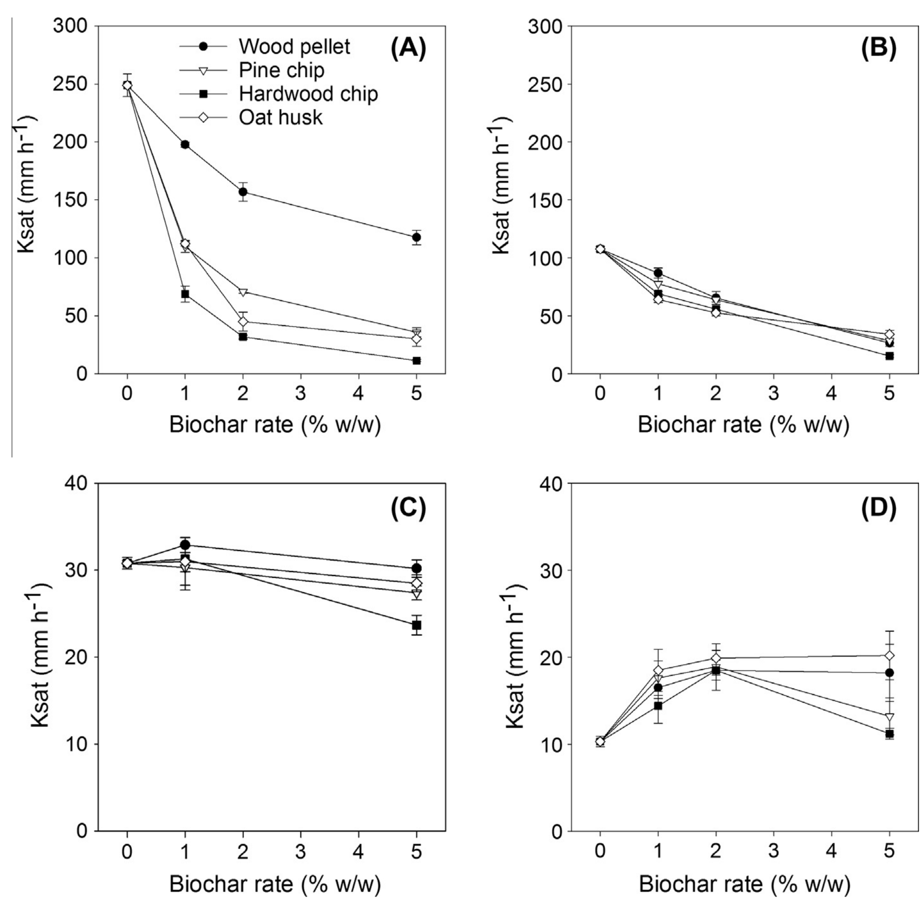

Fig. 4. Changes in saturated hydraulic conductivity as a result of the 4 different biochars at 0%, 1%, 2%, and 5% (w/w) with different textured soils of (A) coarse sand, (B) fine sand, (C) loam, and (D) clay soil. The average of the four replicates and the associated standard deviation of the replicates are shown in the figure.

Table 3
Comparison of literature results with model results.

Author & year	Soil texture (%)			Biochar particle size (mm)	Application rate of biochar (w/w)	Reported results (cm d^{-1})	Model prediction (cm d^{-1})			
	Sand	Silt	Clay				0%	1%	3%	5%
Asai et al. (2009)	18	34	48	<2	~1%, 2%, and 3%	⇔	7	7	7.5	7.87
	27	45	28	<2	~1%, 2%, and 3%	⇧ 20 → 36	14.3	14.6	15.3	15.95
Brockhoff et al. (2010)	99.8	0.1	0.1	NA	0–5%	⇩ 2035 → 700	368	344	263	211
Hardie et al. (2014)	72.8	16.8	10.5	3.84	~5%	⇔	156	157	159	161
Herath et al. (2013)	Silt loam (Typic Fragiaqualf)			1.06	~1%	⇧ 242 → 320	21.7	22.2	23.1	24.0
	Silt loam (Typic Hapludand)			1.10	~1%	⇧ 242 → 579	21.7	22.2	23.1	24.0
Laird et al. (2010)	Fine loamy (Typic Hapludolls)			<0.5	0–2%	⇔	12.0	12.1	12.1	12.2
Lei and Zhang (2013)	40	35	25	<2	5%	⇔	2.0	2.0	2.2	2.3
Pathan et al. (2003)	94	2	4	<0.20	0–10%	⇩	222	199	165	140
	96	1	3			⇩	257	229	186	156
Rogovska et al. (2014)	Loam (Typic Hapludolls)			<1.0	~0–3%	⇔	102	98	91	86
Uzoma et al. (2011a,b)	95	1.3	3.7	<0.18	~0–3%	⇩ 2822 → 1888	240	211	177	150
Ghodrati et al. (1995)	Hammonton loamy sand			<0.10 76–79% silt	30%	⇩ 85–88%	76.9	30% ⩾ 19.9		

disintegration potential of the biochar as well (Parr and Mitchell, 1930; Naisse et al., 2015; Spokas et al., 2014).

The biochar addition was assumed to impact a particular particle size fraction: sand or clay. The reason for this separation was the fact that the soil pedotransfer functions (PTF) utilized were based on the clay and sand size fractions (Table S1). Overall, these particular models were selected since they included the two textural classes and have been shown to be good estimators for overall soil K_{sat} prediction (Ferrer Julià et al., 2004), even though the specific accuracy can be questioned (Duan et al., 2011). The spreadsheet averaged results from these 4 different PTFs to arrive at the estimation of the K_{sat} for the biochar amended sample. Since this was the first attempt at a universal tool for hydraulic impacts from biochar application, we focused initially on predicting the direction and order of magnitude impacts on the saturated hydraulic conductivity as a function of the biochar addition. This tool was validated using the data collected in this experiment, as well as other existing literature studies on the impact of biochar additions on K_{sat} (Table 3).

From this model, we see that the complex interactions of the biochar particle size and soil texture were predicted from this tool (Table 3). This model correctly predicted for the sandy textured soils a decrease in K_{sat} due to the obstructions in the soil matrix from the biochar particles, increasing the tortuosity of the soil (Kameyama et al., 2012). These decreases in K_{sat} occur even though one might expect the lower bulk density to result in higher K_{sat} values. The impact of biochar on K_{sat} can be solely predicted from the size classification of biochar particles, versus the d_{50} and bulk density attempted previously (Barnes et al., 2014). Biochar particles are also subject to physical fragmentation (Spokas et al., 2014), which could clog conductive pores in the soil matrix (Reddi et al., 2005; Dikinya et al., 2008).

For loam soils, which already have a diverse and well balanced particle size distribution, a 1–5% biochar addition will not significantly alter the hydraulic conductivity (Table 3). Therefore, this results in biochar additions having minimal alteration on hydraulic properties for loam textured soils. These trivial impacts have already been documented in the published studies (Table 3). As seen in the modeling (Fig. S1) and substantiated by the existing studies with high amendment rates (Ghodrati et al., 1995), extremely high amendment rates would be needed to alter loamy textured soils (Shelley and Daniel, 1993).

This model represents the first tool for predicting biochar use for soil hydraulic alteration projects. The model predicts the direction of saturated hydraulic conductivity alterations following biochar additions for a particular soil texture. Despite not always matching the absolute magnitude of the hydraulic conductivity (Table 3), this model presents a means of justifying biochar use to remediate hydraulic deficiencies. This model permits the forecasting of whether the biochar addition will increase or decrease the K_{sat} as a function of the biochar particle size and the original soil texture, thereby demystifying this physical interaction.

4. Conclusions

Saturated hydraulic conductivity (K_{sat}) is influenced by the particle size distribution of biochar, the application rate, and the original soil textures. In coarse and fine sand, the increase of biochar application rates decreased the K_{sat} value showing larger particles sizes (60%; >2 mm) had a more significant impact on decreasing K_{sat}. The incorporation of biochar in the poorly drained clay based soil conversely increased the K_{sat} value. These effects are a function of the original soil texture and the biochar particle size distribution, which was accurately predicted with a simple soil texture based PTF model. This model universally applies to all biochars, despite differences in surface chemistry and porosity, if the particle size of the biochar and soil are known. We envision that this tool begins to answer the engineering questions of how much biochar would need to be added to ameliorate water movement for both well drained sandy soils and poorly drained clay rich soils. However, further research is needed to understand the duration of these effects, particularly with the friable nature of biochar particles.

Acknowledgements

The authors would like to acknowledge the exceptional laboratory work conducted by Martin DuSaire, Eric Nooker, Laura

Colosky, Lee Yang, and Rena Weis. In addition, the authors would also like to acknowledge the partial funding from the Minnesota Corn Growers Association/Minnesota Corn Research Production Council and the Minnesota Agricultural Utilization Research Institute (AURI). The authors would also like to acknowledge General Mills Inc. (Fridley, MN) for the donation of the oat hull material for this research. This research is part of the USDA-ARS Biochar and Pyrolysis Initiative and USDA-ARS GRACEnet (Greenhouse Gas Reduction through Agricultural Carbon Enhancement Network) programs.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.chemosphere.2015.06.069.

References

Abel, S., Peters, A., Trinks, S., Schonsky, H., Facklam, M., Wessolek, G., 2013. Impact of biochar and hydrochar addition on water retention and water repellency of sandy soil. Geoderma 202–203, 183–191.
Aggelides, S.M., Londra, P.A., 2000. Effects of compost produced from town wastes and sewage sludge on the physical properties of a loamy and a clay soil. Bioresour. Technol. 71, 253–259.
Akhtar, S.S., Li, G., Andersen, M.N., Liu, F., 2014. Biochar enhances yield and quality of tomato under reduced irrigation. Agric. Water Manage. 138, 37–44.
Anikwe, M.A.N., 2000. Amelioration of a heavy clay loam soil with rice husk dust and its effect on soil physical properties and maize yield. Bioresour. Technol. 74, 169–173.
Asai, H., Samson, B.K., Stephan, H.M., Songyikhangsuthor, K., Homma, K., Kiyono, Y., Inoue, Y., Shiraiwa, T., Horie, T., 2009. Biochar amendment techniques for upland rice production in Northern Laos 1. Soil physical properties, leaf SPAD and grain yield. Field Crop. Res. 111, 81–84.
Atkinson, C., Fitzgerald, J., Hipps, N., 2010. Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. Plant Soil 337, 1–18.
Barnes, R.T., Gallagher, M.E., Masiello, C.A., Liu, Z., Dugan, B., 2014. Biochar-induced changes in soil hydraulic conductivity and dissolved nutrient fluxes constrained by laboratory experiments. PloS One 9, e108340.
Benson, C.H., Trast, J.M., 1995. Hydraulic conductivity of thirteen compacted clays. Clays Clay Miner. 43, 669–681.
Bigelow, C.A., Bowman, D.C., Cassel, D.K., 2004. Physical properties of three sand size classes amended with inorganic materials or sphagnum peat moss for putting green rootzones. Crop Sci. 44, 900–907.
Brewer, C.E., Chuang, V.J., Masiello, C.A., Gonnermann, H., Gao, X., Dugan, B., Driver, L.E., Panzacchi, P., Zygourakis, K., Davies, C.A., 2014. New approaches to measuring biochar density and porosity. Biomass Bioenergy 66, 176–185.
Brockhoff, S.R., Christians, N.E., Killorn, R.J., Horton, R., Davis, D.D., 2010. Physical and mineral-nutrition properties of sand-based turfgrass root zones amended with biochar. Agron. J. 102, 1627–1631.
Chan, K.Y., Van Zwieten, L., Meszaros, I., Downie, A., Joseph, S., 2007. Agronomic values of greenwaste biochar as a soil amendment. Aust. J. Soil Res. 45, 629–634.
Chang, A.C., Lund, L.J., Page, A.L., Warneke, J.E., 1977. Physical properties of fly ash-amended soils. J. Environ. Qual. 6, 267–270.
Dikinya, O., Hinz, C., Aylmore, G., 2008. Decrease in hydraulic conductivity and particle release associated with self-filtration in saturated soil columns. Geoderma 146, 192–200.
Duan, R., Fedler, C.B., Borrelli, J., 2011. Comparison of methods to estimate saturated hydraulic conductivity in Texas soils with grass. J. Irrigat. Drain. Eng. 138, 322–327.
Feng, L., Li, G.T., Lin, Q.M., Zhao, X.R., 2014. Crop yield and soil properties in the first 3 years after biochar application to a Calcareous soil. J. Integr. Agric. 13, 525–532.
Ferrer Julià, M., Estrela Monreal, T., Sánchez del Corral Jiménez, A., Garcıa Meléndez, E., 2004. Constructing a saturated hydraulic conductivity map of Spain using pedotransfer functions and spatial prediction. Geoderma 123, 257–277.
Gardner, C.M., Laryea, K., Unger, P.W., 1999. Soil Physical Constraints to Plant Growth and Crop Production. Food and Agriculture Organization of the United Nations – Land and Water Development Division, Rome, Italy.
Ghodrati, M., Sims, J., Vasilas, B., 1995. Evaluation of fly ash as a soil amendment for the Atlantic Coastal Plain: I. Soil hydraulic properties and elemental leaching. Water, Air, Soil Pollut. 81, 349–361.
Githinji, L., 2014. Effect of biochar application rate on soil physical hydraulic properties of a sandy loam. Arch. Agron. Soil Sci. 60, 457–470.
Glaser, B., Lehmann, J., Zech, W., 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal – a review. Bio. Fertil. Soils 35, 219–230.
Gray, M., Johnson, M.G., Dragila, M.I., Kleber, M., 2014. Water uptake in biochars: the roles of porosity and hydrophobicity. Biomass Bioenergy 61, 196–205.
Hardie, M., Clothier, B., Bound, S., Oliver, G., Close, D., 2014. Does biochar influence soil physical properties and soil water availability? Plant Soil, 1–15.
Herath, H.M.S.K., Camps-Arbestain, M., Hedley, M., 2013. Effect of biochar on soil physical properties in two contrasting soils: an Alfisol and an Andisol. Geoderma 209–210, 188–197.
Hillel, D., 1998. Environmental Soil Physics: Fundamentals, Applications, and Environmental Considerations. Academic Press, New York.
Huang, Z.T., Petrovic, A.M., 1994. Physical properties of sand as affected by clinoptilolite zeolite particle size and quantity. J. Turfgrass Manage. 1, 1–15.
Jeffery, S., Meinders, M.B., Stoof, C.R., Bezemer, T.M., van de Voorde, T.F., Mommer, L., van Groenigen, J.W., 2015. Biochar application does not improve the soil hydrological function of a sandy soil. Geoderma 251, 47–54.
Jones, B.E.H., Haynes, R.J., Phillips, I.R., 2010. Effect of amendment of bauxite processing sand with organic materials on its chemical, physical and microbial properties. J. Environ. Manage. 91, 2281–2288.
Joseph, S.D., Camps-Arbestain, M., Lin, Y., Munroe, P., Chia, C.H., Hook, J., van Zwieten, L., Kimber, S., Cowie, A., Singh, B.P., Lehmann, J., Foidl, N., Smernik, R.J., Amonette, J.E., 2010. An investigation into the reactions of biochar in soil. Aust. J. Soil Res. 48, 501–515.
Kameyama, K., Miyamoto, T., Shiono, T., Shinogi, Y., 2012. Influence of sugarcane bagasse-derived biochar application on nitrate leaching in calcaric dark red soil. J. Environ. Qual. 41, 1131–1137.
Keren, R., Kreit, J., Shainberg, I., 1980. Influence of size of gypsum particles on the hydraulic conductivity of soils. Soil Sci. 130, 113–117.
Keller, T., Sutter, J.A., Nisse, K., Rydberg, T., 2012. Using field measurement of saturated soil hydraulic conductivity to detect low-yielding zones in three Swedish fields. Soil Till. Res. 124, 68–77.
Kinney, T.J., Masiello, C.A., Dugan, B., Hockaday, W.C., Dean, M.R., Zygourakis, K., Barnes, R.T., 2012. Hydrologic properties of biochars produced at different temperatures. Biomass Bioenergy 41, 34–43.
Klute, A., Dirksen, C., 1986. Hydraulic conductivity and diffusivity: Laboratory methods. In: Klute, A. (Ed.), Methods of Soil Analysis. Part 1. Second ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI, pp. 687–734
Laird, D.A., Fleming, P., Davis, D.D., Horton, R., Wang, B., Karlen, D.L., 2010. Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. Geoderma 158, 443–449.
Lei, O., Zhang, R., 2013. Effects of biochars derived from different feedstocks and pyrolysis temperatures on soil physical and hydraulic properties. J. Soils Sed. 13, 1561–1572.
Li, Y., Gao, R., Yang, R., Wei, H., Li, Y., Xiao, H., Wu, J., 2013. Using a simple soil column method to evaluate soil phosphorus leaching risk. Clean-Soil, Air, Water 41, 1100–1107.
McKeague, J.A., Wang, C., Topp, G.C., 1982. Estimating saturated hydraulic conductivity from soil morphology. Soil Sci. Soc. Am. J. 46, 1239–1244.
Moutier, M., Shainberg, I., Levy, G.J., 2000. Hydraulic gradient and wetting rate effects on the hydraulic conductivity of two calcium Vertisols. Soil Sci. Soc. Am. J. 64, 1211–1219.
Mukherjee, A., Lal, R., Zimmerman, A.R., 2014. Effects of biochar and other amendments on the physical properties and greenhouse gas emissions of an artificially degraded soil. Sci. Total Environ. 487, 26–36.
Naisse, C., Girardin, C., Lefevre, R., Pozzi, A., Maas, R., Stark, A., Rumpel, C., 2015. Effect of physical weathering on the carbon sequestration potential of biochars and hydrochars in soil. GCB Bioenergy 7, 488–496.
Novak, J.M., Busscher, W.J., Watts, D.W., Amonette, J.E., Ippolito, J.A., Lima, I.M., Gaskin, J., Das, K.C., Steiner, C., Ahmedna, M., Rehrah, D., Schomberg, H., 2012. Biochars impact on soil-moisture storage in an ultisol and two aridisols. Soil Sci. 177 (310–320), 3. http://dx.doi.org/10.1097/SS.1090b1013e31824e35593.
Novak, J., Sigua, G., Spokas, K., Busscher, W., Cantrell, K., Watts, D., Glaz, B., Hunt, P., 2015. Plant macro-and micronutrient dynamics in a biochar-amended wetland muck. Water, Air, Soil Pollut. 226, 1–9.
Oguntunde, P.G., Abiodun, B.J., Ajayi, A.E., Van de Giesen, N., 2008. Effects of charcoal production on soil physical properties in Ghana. J. Plant Nutr. Soil Sci. 171, 591–596.
Parr, S.W., Mitchell, D.R., 1930. The slacking of coal and its proper interpretation. Ind. Eng. Chem. 22, 1211–1212.
Pathan, S.M., Aylmore, L.A.G., Colmer, T.D., 2003. Properties of several fly ash materials in relation to use as soil amendments. J. Environ. Qual. 32, 687–693.
Reddi, L.N., Xiao, M., Hajra, M.G., Lee, I.M., 2005. Physical clogging of soil filters under constant flow rate versus constant head. Can. Geotech. J. 42, 804–811.
Reynolds, W.D., Bowman, B.T., Brunke, R.R., Drury, C.F., Tan, C.S., 2000. Comparison of tension infiltrometer, pressure infiltrometer, and soil core estimates. Soil Sci. Soc. Am. J. 64, 478–484.
Rogovska, N., Laird, D.A., Rathke, S.J., Karlen, D.L., 2014. Biochar impace on Midwestern Mollisols and maize nutrient availability. Geoderma 230–231, 340–347.
Schneider, S., Coquet, Y., Vachier, P., Labat, C., Roger-Estrade, J., Benoit, P., Pot, V., Houot, S., 2009. Effect of urban waste compost application on soil near-saturated hydraulic conductivity. J. Environ. Qual. 38, 772–781.
Shelley, T., Daniel, D., 1993. Effect of gravel on hydraulic conductivity of compacted soil liners. J. Geotech. Eng. 119, 54–68.
Sigua, G.C., Novak, J.M., Watts, D.W., Cantrell, K.B., Shumaker, P.D., Szögi, A.A., Johnson, M.G., 2014. Carbon mineralization in two ultisols amended with different sources and particle sizes of pyrolyzed biochar. Chemosphere 103, 313–321.

Solomon, J.A., Mains, G.J., 1977. A mild, protective and efficient procedure for grinding coal: cryocrushing. Fuel 56, 302–304.
Spokas, K.A., Novak, J.M., Masiello, C.A., Johnson, M.G., Colosky, E.C., Ippolito, J.A., Trigo, C., 2014. Physical disintegration of biochar: an overlooked process. Environ. Sci. Technol. Lett. 1, 326–332.
Steiner, C., Teixeira, W., Lehmann, J., Nehls, T., de Macedo, J., Blum, W., Zech, W., 2007. Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. Plant Soil 291, 275–290.
Quin, P.R., Cowie, A.L., Flavel, R.J., Keen, B.P., Macdonald, L.M., Morris, S.G., Singh, B.P., Young, I.M., Van Zwieten, L., 2014. Oil mallee biochar improves soil structural properties – a study with X-ray micro-CT. Agric. Ecosyst. Environ. 191, 142–149.
Tryon, E.H., 1948. Effect of charcoal on certain physical, chemical, and biological properties of forest soils. Ecol. Monogr. 18, 81–115.
Uzoma, K.C., Inoue, M., Andry, H., Fujimaki, H., Zahoor, A., Nishihara, E., 2011a. Effect of cow manure biochar on maize productivity under sandy soil condition. Soil Use Manage. 27, 205–212.
Uzoma, K.C., Inoue, M., Andry, H., Fujimaki, H., Zahoor, A., Nishihara, E., 2011b. Influence of biochar application on sandy soil hydraulic properties and nutrient retention. J. Food Agric. Environ. 9, 1137–1143.
Vereecken, H., 1995. Estimating the unsaturated hydraulic conductivity from theoretical models using simple soil properties. Geoderma 65, 81–92.
West, L.T., Abrew, M.A., Bishop, J.P., 2008. Saturated hydraulic conductivity of soils in the Southern Piedmont of Georgia, USA: field evaluation and relation to horizon and landscape properties. Catena 73, 174–179.
Yu, X.Y., Ying, G.G., Kookana, R.S., 2006. Sorption and desorption behaviors of diuron in soils amended with charcoal. J. Agric. Food Chem. 54, 8545–8550.
Zimmerman, A.R., 2010. Abiotic and microbial oxidation of laboratory-produced black carbon (biochar). Environ. Sci. Technol. 44, 1295–1301.