Soil & Tillage Research 170 (2017) 114–121

Contents lists available at ScienceDirect

Soil & Tillage Research

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

Effect of biochar on crust formation, penetration resistance and hydraulic properties of two coarse-textured tropical soils

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ARTICLE INFO

Keywords:
Biochar particle size
Soil hydraulic properties
Penetration resistance

ABSTRACT

Biochar (BC) has been reported to improve a number of soil structural and hydraulic properties but detailed studies are scant on how BC affects crust formation, penetration resistance, water repellency and saturated hydraulic conductivity (K_{sat}). The objective of this study was to quantify the effect of maize cob BC of three different particle sizes on soil crusting (penetration resistance), water repellency, and K_{sat} of loamy fine sand and sandy loam in Zambia. The BC particle sizes were < 0.5 and 1–5 mm applied at 17.5 and 35 t ha^{-1} in the two soils and intermediate size of 0.5–1 mm applied at lower rates (17.5 and 28 t ha^{-1} in the loamy fine sand and 13.3 and 26.7 t ha^{-1} in the sandy loam). Water repellency included both water drop penetration time (WDPT) and minimum molarity of the ethanol droplet at which rapid infiltration into the soil occurs. The BC was produced by slow pyrolysis of corn cobs at a temperature of 350 °C. Biochar, added homogeneously to the upper 7 cm of the soil, reduced the penetration resistance of surface soil of sandy loam with both the crust intact (-2.1 ± 0.6 N cm^{-2} per percent BC added; $p = 0.001$ in March 2015 and slightly smaller in October 2014) and the crust removed (-2.9 ± 0.6 N cm^{-2} per percent BC added; $p = 0.0001$). This effect occurred irrespective of particle size of BC ($p > 0.05$). No effect of BC on penetration resistance was found in the loamy fine sand ($p > 0.05$). In dry sandy loam with moisture content < 1% v/v, the proportion of wettable crusted surface was significantly smaller (25%) than in moist soil (98%) with moisture content of ~ 10% v/v. Only fine BC of < 0.5 mm increased WDPT of the crusted surface of sandy loam ($p < 0.05$), reducing the proportion of wettable surface from 98 to 80% in moist soil and from 25 to 18% in dry soil. Coarser BCs, instead, increased the proportion of wettable crusted surface from 25% to 45% and 90% for 3% 0.5–1 mm BC and 4% 1–5 mm BC addition, respectively, in dry soil. Biochar significantly reduced K_{sat} ($p < 0.05$) in sandy loam below the crust by 0.17 ± 0.07 cm h^{-1} per percent BC added. However, no effect was found in loamy fine sand. Since BC amended sandy loam below the crust showed no water repellency, reduction in K_{sat} cannot be explained by water-repellent nature of BC. Instead, this may be due to clogging of soil pores by BC or to collapse of soil structure near water saturation.

1. Introduction

Biochar (BC), a biomass pyrolysis product, has received considerable attention as a soil amendment that can increase crop growth and yield (Glaser et al., 2001, 2002; Jeffery et al., 2011). To understand the mechanisms responsible for increased productivity, research has focused on BC's effect on soil chemical properties and crop nutrition rather than on soil physical properties (Atkinson et al., 2010; Lehmann et al., 2011; Mukherjee and Lal, 2013). Only recently, a number of studies have reported the effects of BC on soil aggregation, bulk density, water retention and saturated hydraulic conductivity (K_{sat}) (Ajayi et al., 2016; Castellini et al., 2015; de Melo Carvalho et al., 2014; Herath et al., 2013; Obia et al., 2016; Ouyang et al., 2013; Sun and Lu, 2014). Optimal soil physical characteristics are required for increased soil productivity. These include hydraulic properties, which determine water availability to crops and structural properties that aid root growth.

Studies of the effect of BC on K_{sat} of soil are inconclusive, as increase, decrease or no effect have been observed. Increased K_{sat} in response to the addition of BC was found in silty clay and sandy loam (Ajayi et al., 2016; Ajayi and Horn, 2016; Ouyang et al., 2013), in silt loam (Herath et al., 2013) and in clay rich soil (Barnes et al., 2014), all

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http://dx.doi.org/10.1016/j.still.2017.03.009
Received 17 July 2016; Received in revised form 10 February 2017; Accepted 19 March 2017
Available online 05 April 2017
0167-1987/

incubated in the laboratory, without plants. Increase in K_{sat} was also observed in field experiments in loamy (Asai et al., 2009) and sandy clay loam (Major et al., 2010) soils. The increase in K_{sat} of loamy soils could be linked to BC-induced increases in soil aggregation (Herath et al., 2013; Lei and Zhang, 2013; Obia et al., 2016; Ouyang et al., 2013). No effect of BC on K_{sat} has been observed in clay and fine loamy soils (Asai et al., 2009; Castellini et al., 2015; Laird et al., 2010) and in Dutch sandy soils (Jeffery et al., 2015), under both field and laboratory conditions. Biochar caused a decrease in K_{sat} in sand and organic soils in laboratory and greenhouse incubations (Ajayi et al., 2016; Barnes et al., 2014; Githinji, 2014; Uzoma et al., 2011). The decrease in K_{sat} may be due to the water repellent nature of BC (Briggs et al., 2012; Githinji, 2014; Verheijen et al., 2009) or due to infilling of large water conducting pores by BC (Ajayi et al., 2016). The water repellent nature of BC has been reported to decrease with increase in pyrolysis temperature, implying that some low temperature BCs could be very water repellent (Jeffery et al., 2015; Khanmohammadi et al., 2015; Kinney et al., 2012). At pyrolysis temperature of above 500 °C, certain BCs such as those from corn stover and apple wood can become non-repellent (Kinney et al., 2012). Recently, Yi et al. (2015) reported that the water repellency of poultry litter BC originated from surface coating by semi-volatile organic compounds while Kinney et al. (2012) found that water repellency of BC was due to alkyl groups on BC surfaces. How the water repellent nature of BC affects soil water repellency has only recently received attention (Abel et al., 2013; Ajayi et al., 2016; Eibisch et al., 2015; Herath et al., 2013; Page-Dumroese et al., 2015; Yi et al., 2015). In general, these studies, which were all conducted in the laboratory, show that BC had little effect on soil water repellency. Certain BCs may be non-repellent, and such BCs may reduce water repellency of hydrophobic soils (Hallin et al., 2015).

Soil water repellency is known to reduce water infiltration causing increase in soil erosion (Doerr et al., 2000), which can be exacerbated by soil crusting. Soil crusting may be assessed by measuring its strength in terms of a penetration resistance (Upadhyaya et al., 1995). Penetration resistance of the crust may indicate how easy it is for water to infiltrate the soil thereby directly affecting crop growth and yield. Soil crusting occurs primarily in soils with weak aggregates and high amounts of silt (Awadhwal and Thierstein, 1985). Increasing aggregate stability of soil, e.g. due to BC (Obia et al., 2016), could potentially reduce crust formation (Awadhwal and Thierstein, 1985 and references therein). Yet, the effect of BC on soil crusting in crust-prone soils has not yet been tested. Also the effect of BC on the penetration resistance of soil below the crust or in soils without crusting has received little attention (Busscher et al., 2010; Mukherjee et al., 2014), despite the fact that it relates directly to soil structural properties (Gao et al., 2016) that can influence plant root growth. In the laboratory, ground pecan shell BC reduced penetration resistance of bulk Norfolk loamy sand (Busscher et al., 2010). However, under field conditions, oak wood BC had no effect on the penetration resistance of bulk silt loam soil in the first year, and even increased the resistance in the second year (Mukherjee et al., 2014). Biochar has been reported to reduce bulk density and increase porosity in a range of soil types (Mukherjee and Lal, 2013), showing that BC could reduce penetration resistance of soil (Gao et al., 2016). In turn, reduction in the penetration resistance of bulk soil may reduce resistance to root growth in soils (Materechera and Mloza-Banda, 1997).

In situ studies are urgently needed to further explore the implication of the effect of BC addition on soil hydraulic properties in the field. This is all the more important in areas prone to drought, e.g. in Zambia where rainfall, the main source of agricultural water, is erratic and unreliable (Yatagai, 2011). Coarse-textured soils such as the ones studied here generally have low water retention (Obia et al., 2016) and can suffer more in case of drought. Use of BC of different particle sizes may aid the understanding of mechanisms behind BC effects on soil hydraulic properties. Barnes et al. (2014) proposed that BC affects soil hydraulic properties through the interstitial BC-soil particle space and through pores within the BC grains themselves. These proposed mechanisms may depend on the particle sizes of the BC, similar to the dependence of aggregate formation on particle size of the BC added (Obia et al., 2016).

The hypotheses of the present study were that

(i) BC, irrespective of particle size, reduces the penetration resistance for both crusted surface and bulk soil in aggregating sandy loam but not in loamy fine sand with single grain structure.
(ii) hydrophobic BC induces soil water repellency in BC-amended coarse-textured soils.
(iii) BC, irrespective of particle size, increases K_{sat} in sandy loam due to BC-induced soil aggregation. In loamy fine sand, finer BC reduces K_{sat} due to filling of inter particle space while coarse BC has no effect.

To investigate these hypotheses, three particle size fractions of hydrophobic maize cob BC (< 0.5, 0.5–1 and 1–5 mm, respectively) were applied and homogenized at two different application rates to the aggregating sandy loam at Mkushi, Zambia (crust-prone soil), and loamy fine sand at Kaoma, Zambia. After one and two years in the field, crusting and penetration resistance were assessed using a flat-tipped pocket penetrometer. Water repellency was quantified using water drop penetration time (WDPT) and the molarity of ethanol droplet (MED) test, and K_{sat} was measured using a tension disc infiltrometer.

2. Materials and methods

2.1. Biochar and experiments

The BCs were produced from dry maize cob after removing the grains in a slow pyrolysis for one day, using a drum retort kiln at Chisamba, Zambia at a temperature of 350 °C. Other BC production details can be found in Obia et al. (2016). Basic properties of the BC are presented in Table 1.

The experiments were established in April 2013 at Mkushi (S13 44.839, E29 05.972) and Kaoma (S14 50.245, E25 02.150) in Zambia, with the soils being classified as Acrisol and Arenosol, respectively. There is only one annual growing (wet) season in Zambia, which runs from November to March followed by a dry season from April to October. The experiments were organized in a split plot design, where maize cob BC of three particle size classes (< 0.5, 0.5–1 and 1–5 mm) was applied to small plots of 50 × 50 cm. The BC was applied at rates of 2% and 4% (w/w) at Mkushi and 1.7% and 3.4% (w/w) at Kaoma, to the top 7 cm of the soil in triplicates. There was an exception for 0.5–1 mm BC sizes, where lower rates of 1.5% and 3% were applied at Mkushi and 2.7% instead of 3.4% at Kaoma, due to shortage of this BC size fraction. Reference plots without BC application were included for each BC particle size at both sites in triplicate resulting in a total number of 27 plots per site. Reference and BC amended plots were treated in a similar way. The amounts of < 0.5 and 1–5 mm BC applied to the two sites were the same (i.e. 17.5 and 35 t ha^{-1}) but the resulting content of BC in the soils differed, because of differences in soil bulk density (Table 1). The doses and application depth of biochar in this study were of little practical relevance, but merely implemented to test specific hypotheses. The experimental plots were planted with maize in the first season (Nov 2013–Mar 2014) and under fallow prior to the first season and in the second season (Nov 2014–Mar 2015). Effects of BC on soil aggregation, porosity and soil water retention characteristics from the same experiment were reported in Obia et al. (2016). All measurements reported in the present study were conducted at the end of the two growing seasons (April 2014 and March 2015), except penetration resistance, which had one additional set of measurements conducted just before the beginning of the growing season (October 2014; Mkushi only). The main measurements are summarized in Table 2.

Table 1
Soil and biochar properties[a].

Properties	Kaoma soil	Mkushi soil	Maize cob BC		
			< 0.5 mm	1–5 mm	Unsorted
Sand (%)	85.4	75.1	–	–	–
Silt (%)	10.2	15.9	–	–	–
Clay (%)	4.4	9.0	–	–	–
Texture class	Loamy fine sand	Sandy loam	–	–	–
Total organic C (%)	0.62	0.74	44.8	60.1	53.8
Total nitrogen (%)	0.00	0.01	0.79	0.53	0.65
Total hydrogen (%)	0.05	0.27	2.09	2.63	2.36
H/C (mole ratio)	–	–	0.56	0.52	0.53
pH	5.8	5.8	9.0	8.6	8.8
CEC ($cmol_c\ kg^{-1}$)	2.79	1.73	–	–	22.19
K^+ ($cmol_c\ kg^{-1}$)	0.08	0.32	–	–	16.47
Ca^{2+} ($cmol_c\ kg^{-1}$)	1.20	1.09	–	–	4.30
Mg^{2+} ($cmol_c\ kg^{-1}$)	0.24	0.32	–	–	1.21
Bulk density ($g\ cm^{-3}$)	1.47	1.27	0.36	0.29	–
WDPT in seconds[b]	–	–	1386	594	3398
Loss on ignition (%)	–	–	52.1	72.4	–

[a] All soil measurements are from samples taken from within 0–7 cm depth interval. Maize cob BC of 0.5–1 mm were exhausted in the field and not characterized in the laboratory.
[b] The surface of 1–5 mm BC in the petri dish was rough due to the uniformly coarse particles resulting in water drops rolling off the particles. The unsorted BC consisted of all the particle sizes less than 5 mm.

2.2. Analyses of soil and biochar properties

The texture of the soil was determined using the Pipette method. Total organic carbon (TOC), total nitrogen and total hydrogen of soil and BC were determined using a CHN analyzer (CHN-1000, LECO USA). Loss on ignition of BC was determined by burning the sample at 550 °C in an oven (Carbolite Bamford, Sheffield, England). The pH of soil and BC was measured using an Orion 2 Star pH meter (Thermo Fisher Scientific, Fort Collins, CO) in 1:2.5 soil(BC):water mixture. To measure exchangeable base cations of soils and BC, samples were extracted using ammonium acetate (buffered at pH 7) and ammonium nitrate, respectively. Base cations in the extracts were determined using flame spectrophotometry (Perkin Elmer, AAS 3300). The cation exchange capacity (CEC), at pH 7, was computed as the sum of base cations for BCs and as the sum of base cations and exchangeable acidity for soils. Exchangeable acidity was determined by back titration of the ammonium acetate extract using sodium hydroxide (0.05 M NaOH). The density of BC was determined from the weight of BC in filled 10 cm^3 cups. Bulk density of the soils were derived from the oven dry weight of soil in 100 cm^3 core rings taken in April 2014 from the top 0–5 cm soil depth. Additionally, BC was characterized for hydrophobicity after placing and levelling dry BC in the petri dish. Water drop penetration time test was then conducted by placing ten drops of deionized water and time taken for complete infiltration registered. Average infiltration time for the ten drops (WDPT) can be found in Table 1.

2.3. Moisture content of the soil

The in situ soil moisture content (0–5 cm surface layer) was recorded with five replicates per plot, using hand-held time domain reflectometer (TDR) – SM150 (Delta-T Devices, Cambridge, England). Measurements were done on the same day as we measured water infiltration, water repellency and penetration resistance.

2.4. Penetration resistance of the soil

Measurements of penetration resistance were carried out at the end of the growing season in March 2015; 2 years after BC application at both sites. At Mkushi, one set of measurements was also conducted in October 2014 at the end of the dry season, just before the onset of the rains. A flat-tipped pocket penetrometer (Eijkelkamp, Giesbeek, The Netherlands) was used to quantify the penetration resistance of the soil. The penetrometer with diameter of 6.35 mm was gently pressed until the shaft was ~6 mm into the soil and the pressure reading on the penetrometer taken.

The penetration resistance of the soil at Mkushi in March 2015 was measured for both the crust (< 6 mm thick) and for the soft soil underneath. The penetration resistance of the soil underneath was done following careful removal of the crust with a knife. The penetration resistance of the Kaoma soil was measured at the soil surface only, since no crust was observed. Ten random measurements were carried out in each plot for both soil crust and for the soil underneath, totaling 540 measurements at Mkushi at each time point and 270 measurements at Kaoma.

2.5. Effect of biochar on soil water repellency

2.5.1. Water drop penetration time test in field and laboratory

Water drop penetration time (WDPT) provides a measure of stability or persistence of soil water repellency and is normally used to detect the existence of repellency (Dekker et al., 2009). Water drop penetration time was measured in the field at Mkushi and Kaoma according to Dekker et al. (2009). Measurements of WDPT were carried out in April 2014 and March 2015, one and two years after BC application, respectively. Ten drops of distilled water were placed on the soil surface within each of the 27 plots per site and the time for complete infiltration was recorded. For Mkushi soil, where surface crusting occurred, WDPT was also measured after removal of the crust. Measurement of WDPT at greater depth (down to 25 cm) was done on soil samples, obtained using a half cylindrical auger as previously described by Dekker et al. (2009).

In the laboratory, two core ring samples (100 cm^{-3}) per plot, taken

Table 2
Summary of measurements conducted[a].

Soil property	Measurement method	Site	Time of sampling or measurement	Number of measurements
Penetration resistance	Penetrometer	Kaoma	March 2015	10 per plot
		Mkushi	October 2014 & March 2015	10 per plot
Water repellency	WDPT – field & lab	Kaoma	April 2014 & March 2015	10 drops/plot – field 20 drop/plot – lab
	WDPT – field & lab	Mkushi	April 2014 & March 2015	10 drops/plot – field 20 drop/plot – lab
	MED test – field, on crusted surface only	Mkushi	March 2015	10 per plot
K_{sat} & sorptivity	Tension disc infiltrometer	Kaoma	April 2014 & March 2015	2 per plot
		Mkushi	April 2014 & March 2015	2 per plot
Moisture content	Hand-held TDR	Kaoma	April 2014 & March 2015	5 per plot
		Mkushi	April & October 2014, March 2015	5 per plot

[a] The experiment was set up in April 2013. Penetration resistance, K_{sat} and sorptivity were measured only in the field.

in April 2014, were used to test for repellency after oven drying at 105 °C. Five water drops were placed on each side of the two core ring samples, giving twenty water drops per plot.

The WDPT registered were classified according to Dekker and Jungerius (1990). The frequencies of occurrence of the different WDPT classes were grouped for each of the BC treatments.

2.5.2. Molarity of ethanol droplet (MED) test

The MED test was conducted, as previously described by Buczko et al. (2002), to assess the degree or severity of water repellency of the crusted soil surface at Mkushi. Ethanol breaks soil water repellency by reducing the surface tension of water. If the contact angle between a water drop and the soil surface is > 90°, then the soil is water repellent. Increasing ethanol concentration reduces the contact angle due to reduction of liquid surface tension. Here, we report the surface tension of droplet of ethanol solution at which drops penetrated soil at ≤5 s. The surface tension of the ethanol solution, σ_e in N m^{-1} was calculated according to Eq. (1) where surface tension is non-linearly related to the molarity M of ethanol (Roy and McGill, 2002).

$$\sigma_e = 0.06105 - 0.01475 * In(M + 0.5) \quad (1)$$

Surface tension of the ethanol solution was selected as variable of interest, because it is a fundamental property in the characterization of the degree of water repellency of the soil, due to its relationship with soil-air surface tension (Letey et al., 2000; Watson and Letey, 1970).

Only the crust of the Mkushi soil was included in the test, because only here the WDPT revealed water repellency, i.e., WDPT exceeded five seconds (see Results section). Solutions of ethanol ranging from 1 to 40% v/v (0.17–6.86 M) were prepared by dilution with distilled water and small drops were placed using a laboratory dropper on the crusted soil surface. Solutions with higher ethanol concentrations were used until drop penetration time was ≤5 s. Ten drops were placed on the soil crust at each ethanol concentration. The ethanol concentration at which at least eight drops infiltrated the soil at ≤5 s and the other two drops at ≤10 s or nine drops at ≤5 s and one drop at > 10 s was considered the concentration at which the soil water repellency was broken.

2.6. Measurement of K_{sat} and sorptivity of soil

Saturated hydraulic conductivity and sorptivity of soil were measured in the field using tension disc infiltrometers (Eijkelkamp, Giesbeek, The Netherlands) in April 2014 and March 2015, one and two years after BC application, respectively. Two sets of measurements were performed at each plot at two different tensions (high-tension, h_2 of 15 cm water column and low-tension, h_1 of 6 cm water column). The two measurements covered 25% of the plot surface area and gave representative K_{sat} for the plot. Water infiltration rate (cm^3 h^{-1}) was calculated by multiplying inner cross sectional area of the water supply tube with steady state reading – fall in height of water column (cm h^{-1}). Soil sorptivity, α, the ability of the soil to absorb water, was calculated from the combined equations of Wooding (1968) and Gardner (1958) in Eq. (2) at two suction pressures h_1 and h_2 as described in the manual of tension disc infiltrometer (Eijkelkamp).

$$\alpha = \frac{In[Q(h_2)/Q(h_1)]}{h_2 - h_1} \quad (2)$$

Where $Q(h_2)$ and $Q(h_1)$ were the water infiltration rates at high (h_2) and low (h_1) tensions respectively in cm^3 h^{-1}. With known α from Eq. (2), K_{sat} (cm h^{-1}) was calculated according to the combined Wooding's equation (Wooding, 1968) and Gardner's equation (Gardner, 1958) (Eq. (3)) using either the known $Q(h_1)$ and h_1 or $Q(h_2)$ and h_2.

$$Q(h_1) = \pi r^2 K_{sat} \exp(\alpha h_1)\left[1 + \frac{4}{\pi r \alpha}\right] \quad (3)$$

Where r (cm) is the radius of the disc in contact with soil. K_{sat} and sorptivity α were determined for two replicates per plot.

2.7. Statistical analysis

The data were analyzed using R software (R Core Team, 2014). Molarity of ethanol droplet test, K_{sat}, sorptivity and penetration resistance of the soil were analyzed using analysis of covariance (ANCOVA). Repeated measurements from each plot were averaged before fitting the data to linear model ANCOVA for each site separately. In fitting the model, MED test (expressed in terms of surface tension, N m^{-1}), K_{sat} (cm h^{-1}), sorptivity (cm^{-1}) and penetration resistance (N cm^{-2}) were the dependent variables and BC particle size (categorical) and BC dose (continuous) were the independent variables. Non-significant terms in the model were removed, where such removal did not significantly affect the explanatory power of the model, in order to obtain the minimal adequate model where all terms were significant. For WDPT, the data were categorized into repellency classes and presented graphically to show the proportion of repellency classes in the soil.

3. Results

3.1. Effect of biochar on penetration resistance of the crust and soil underneath

In both April 2014 and March 2015, at the end of the respective growing seasons, the sandy loam at Mkushi exhibited surface crusting, whereas the loamy fine sand at Kaoma did not. Despite the fragile nature of the crust, the soil surface layer with intact crust at Mkushi had a significantly ($p < 0.05$) larger penetration resistance (33.9 ± 1.0 N cm^{-2}, Fig. 1B) than the soil below the crust (27.9 ± 1.0 N cm^{-2}, Fig. 1C). The penetration resistance of the Kaoma loamy fine sand was smaller (16.7 ± 1.3 N cm^{-2}, Fig. 1D) than that of the Mkushi sandy loam at comparable (low) soil moisture contents in March 2015 (Table 3).

At Mkushi, maize cob BC content significantly decreased the penetration resistance of the soil surface layer with intact crust (−2.1 ± 0.6 N cm^{-2} per unit increase in percent BC; $p = 0.001$, Fig. 1B in March 2015). Likewise, BC content also reduced penetration resistance after crust removal in March 2015 (−2.9 ± 0.6 N cm^{-2} per unit increase in percent BC; $p < 0.0001$, Fig. 1C) and when there was no visible crust in October 2014 (−1.4 ± 0.5 N cm^{-2} per unit increase in percent BC; $p = 0.005$, Fig. 1A). There was no significant difference in the effect of BC content on penetration resistance between October 2014 and March 2015. BC particle size did not have a significant effect on the penetration resistance in Mkushi soil ($p > 0.05$). The penetration resistance in the Kaoma loamy fine sand was not significantly affected by BC content ($p = 0.77$, Fig. 1D).

3.2. Effect of biochar on soil water repellency – WDPT and MED test

In the field, the loamy fine sand at Kaoma, down to 25 cm depth, was non-repellent (WDPT generally within 1 s; Fig. 2), even when dry (e.g. March 2015, Table 3). Likewise, the sandy loam below the surface crust at Mkushi was non-repellent in both April 2014 and March 2015 (Fig. 2). The maize cob BC did not affect the non-repellent behavior of Kaoma soil and the soil below the crust at Mkushi, one and two years after application of BC to the upper 7 cm of the soil. Even in the laboratory, there was immediate infiltration of water drops (within 1 s) into the oven-dry BC-amended soil from both Mkushi (below the crust) and Kaoma (Fig. 2).

The crusted soil surface at Mkushi did show in situ water repellent behavior (Fig. 2). The water repellency of the crusted surface at Mkushi was greater during the drought in March 2015 (74% of surface was repellent) than during the wetter conditions in April 2014 (only 2% of surface was repellent) (Fig. 2). The soil moisture content was < 1% in

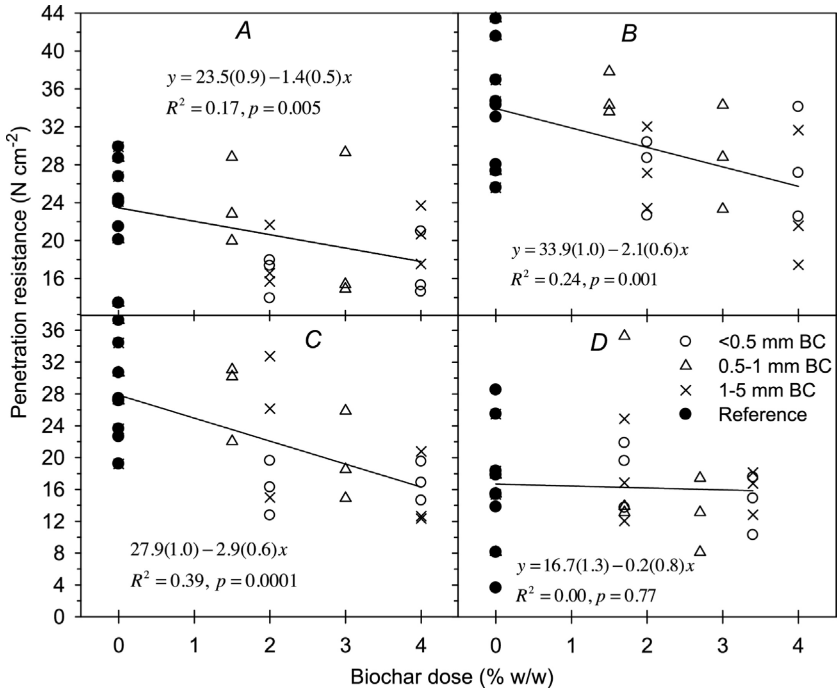

Fig. 1. Penetration resistance of soil amended with BC of different particle sizes. A = 0–6 mm Mkushi soil surface with no visible crust in October 2014, B = 0–6 mm Mkushi soil surface with crust intact in March 2015, C = 10–16 mm Mkushi soil layer underneath the crust in March 2015, D = 0–6 mm Kaoma soil surface layer in March 2015. Numbers between brackets in the regression equations are SEs. No significant difference was established between particle size classes ($p > 0.05$).

March 2015 compared to ~10% v/v in April 2014 (Table 3). In April 2014, under moist conditions, only addition of the finest BC fraction (< 0.5 mm) caused increased repellency of the crusted surface, decreasing wettability from 98% to 80% (Fig. 2). On the other hand, in March 2015 under dry conditions, the crusted surface at Mkushi showed more repellency although it was classified mainly as slightly water-repellent (60% of the surface with WDPT = 5–60 s; Fig. 2). The finest BC (< 0.5 mm) decreased the proportion of wettable surface from 26% of the crusted soil surface in the reference soil to 17% at 4% BC (Fig. 2). Addition of the coarser BC fractions (> 0.5 mm) on the other hand increased wettability e.g. proportion of wettable surface increased from 26% in reference plots to 90% at BC addition rates of 4% (1–5 mm size fraction; Fig. 2). Despite water-repellent behavior of crusted soil surfaces at Mkushi, there was no case where WDPT reached the "extremely water repellent" class of > 3600 s (Dekker and Jungerius, 1990). In the loamy fine sand at Kaoma, addition of hydrophobic maize cob BC (Table 1) did not affect the WDPT of the surface, which remained highly wettable (Fig. 2).

In the MED test, the average surface tension was between 0.030–0.072 N m^{-1} and it was not affected by BC addition ($p = 0.24$) (Fig. 3) in March 2015.

3.3. Effect of biochar on K_{sat} and sorptivity of the soil

In dry soils (March 2015), the average K_{sat} was smaller in the sandy loam at Mkushi (below the crust) than in the loamy fine sand at Kaoma (1.7 vs 5.2 cm h^{-1}, respectively). Both soils showed a general trend of decreasing K_{sat} with increasing doses of maize cob BC (Fig. 4), irrespective of BC particle size ($p > 0.05$). However, this trend was significant only for the sandy loam at Mkushi (−0.13 cm h^{-1} per percent BC added, $p = 0.02$), but not for the loamy fine sand at Kaoma ($p = 0.31$) (Fig. 4). K_{sat} was not significantly affected by the maize cob BC at the two sites when the soil was moist (April 2014; data not shown, $p = 0.62$ at Mkushi and $p = 0.15$ at Kaoma).

Both Mkushi and Kaoma soil had similar sorptivity (~0.08 cm^{-1}). Sorptivity showed a decreasing, albeit non-significant trend ($p > 0.05$), with increasing amount of maize cob BC applied (Fig. 4).

4. Discussion

4.1. Effect of biochar on penetration resistance of soil at and below the surface

In the sandy loam at Mkushi, the maize cob BC significantly reduced

Table 3
Soil moisture content and bulk density at the time of penetration resistance/water repellency measurement[a].

BC particle size	BC dose (w/w%)		Moisture (vol%) April 2014		Moisture (vol%) March 2015		Bulk density (g cm^{-3}) April 2014	
	Mkushi	Kaoma	Mkushi	Kaoma	Mkushi	Kaoma	Mkushi	Kaoma
Reference plot	0	0	11.2 ± 0.5	0.8 ± 0.3	0.7 ± 0.2	0.2 ± 0.1	1.27 ± 0.02	1.47 ± 0.02
< 0.5 mm	2	1.7	12.4 ± 0.7	0.1 ± 0.0	1.4 ± 0.8	0.1 ± 0.1	1.24 ± 0.01	1.46 ± 0.02
	4	3.4	11.8 ± 0.9	0.5 ± 0.3	0.5 ± 0.1	0.2 ± 0.1	1.21 ± 0.03	1.42 ± 0.01
0.5–1 mm	1.5	1.7	9.7 ± 0.4	1.3 ± 0.4	0.7 ± 0.6	0.2 ± 0.1	1.21 ± 0.02	1.37 ± 0.01
	3	2.7	9.5 ± 0.7	0.5 ± 0.2	0.8 ± 0.4	0.4 ± 0.1	1.27 ± 0.03	1.35 ± 0.05
1–5 mm	2	1.7	9.6 ± 0.3	0.2 ± 0.1	0.2 ± 0.2	0.1 ± 0.0	1.25 ± 0.01	1.35 ± 0.02
	4	3.4	9.2 ± 0.6	0.4 ± 0.2	0.0 ± 0.0	0.1 ± 0.0	1.15 ± 0.04	1.33 ± 0.01

[a] The moisture content in October 2014 during the measurement of penetration resistance was below detection limit of TDR. Numbers in the table are means ± standard error (n = 3 for treated plots and n = 9 for reference plots). All measurements are for the bulk soil from within 0–7 cm depth interval.

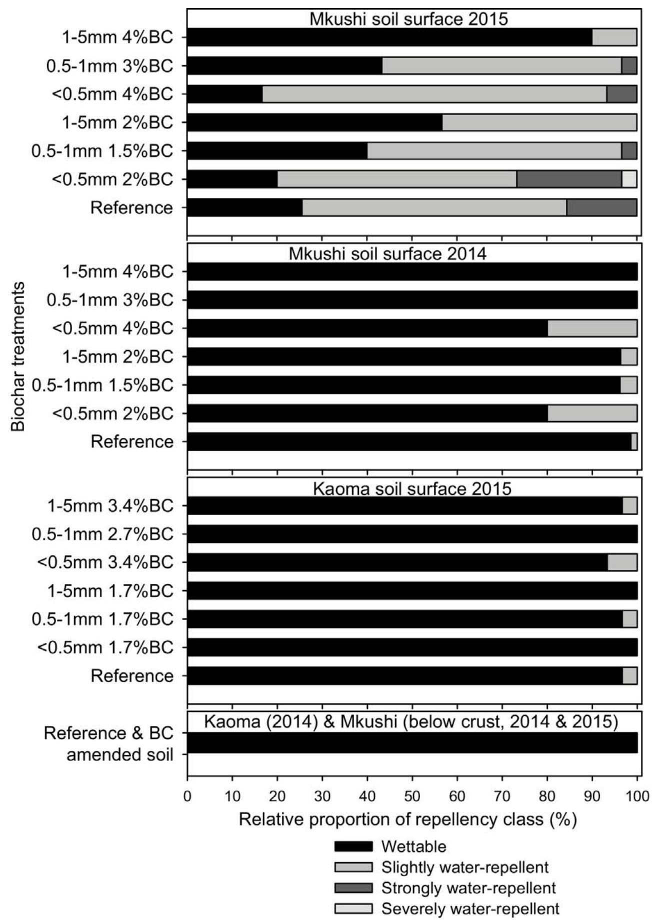

Fig. 2. Relative proportion of wettable and water repellent surface of a sandy loam soil (Mkushi) and a loamy fine sand (Kaoma) for various BC treatments (n = 90 for reference plot and n = 30 for BC treatments). The bottom panel of Kaoma and Mkushi (below crust, 2014 & 2015) represents measurements conducted both in the field and laboratory irrespective of moisture content: all 100% wettable. Water repellency classes according to Dekker and Jungerius (1990): WDPT < 5 s – wettable or non-water-repellent, 5 s < WDPT < 60 s – slightly water-repellent, 60 s < WDPT < 600 s – strongly water-repellent, 600 s < WDPT < 3600 s – severely water-repellent, WDPT > 3600 s – extremely water-repellent.

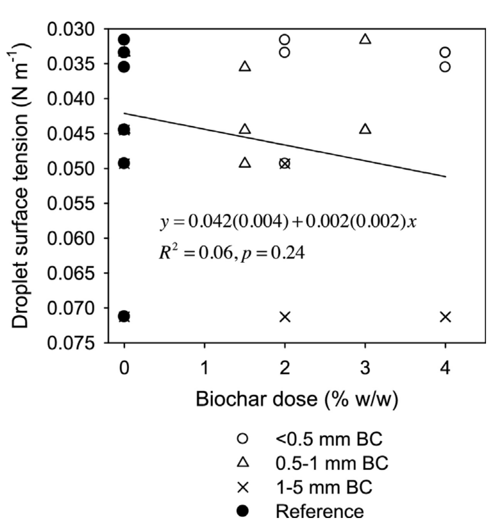

Fig. 3. Water repellency expressed as surface tension of drops of ethanol solution placed on the crusted surface of BC amended Mkushi soil measured in March 2015. Note the reversed y-axis; lower surface tension means higher alcohol concentration. Numbers between brackets in regression equations are the SEs. No significant difference was established between particle size classes ($p > 0.05$).

the penetration resistance of the surface soil irrespective of BC particle size (Fig. 1). In contrast, BC had no effect on the penetration resistance in the loamy fine sand at Kaoma. Thus, our hypothesis that BC irrespective of particles size reduces the penetration resistance for surface soil in aggregating sandy loam but not in loamy fine sand, without aggregation (Obia et al., 2016) was confirmed.

The difference in penetration resistance of surface soil with intact crust (Fig. 1B), and the bulk soil below the crust in the sandy loam (Fig. 1C), which represents the resistance of the crust alone, was relatively small (6 to 10 N cm^{-2}) and was not significantly affected by BC (Fig. 1B and C). This suggests that the addition of BC had no effect on the strength of the soil crust, which is important in triggering surface water run-off. Besides the crust, soil texture affected the penetration resistance, with loamy fine sand having a lower penetration resistance than sandy loam in the absence of BC (compare the intercept in Fig. 1C vs D), which is consistent with other studies e.g., Dexter et al. (2007).

Similar to our results, a significant decrease in penetration resistance has also been reported by Busscher et al. (2010) in sandy loam amended with up to 2% pecan BC under laboratory conditions. However, in their study the magnitude of decrease in penetration resistance per percent BC added was much higher (~10 N cm^{-2}) compared to our study (< 3 N cm^{-2}). Mukherjee et al. (2014) on the other hand observed no effect of BC on penetration resistance of silty clay loam but the application dose in their study was rather small at 0.5%.

4.2. Effect of biochar on soil water repellency and soil K_{sat}

The crusted soil surface in the sandy loam at Mkushi was water repellent, when dry (74% of the crusted surface with WDPT > 5 s in March 2015). The finest BC fraction increased the proportion of repellent surface, whereas coarse BCs reduced it (Fig. 2). Since BC affected the water repellency of the crust and not that of the bulk soil (Fig. 2), the changes in the repellency of the crust were probably not due to BCs' direct hydrophobic effect. Much of the hydrophobic compounds of BC may have been lost to percolating soil water (Yi et al., 2015). Such loss of hydrophobic compounds from BC may explain the lack of significant effect of BC on severity of water repellency of the crust measured using ethanol solution (Fig. 3).

The dark shiny appearance of the crusted surface observed in the field probably indicated previous surface growth of microorganisms, which may render the surface water repellent (Doerr et al., 2000 and references therein). Shiny-crusted surfaces were more frequently observed for plots amended with < 0.5 mm BC than for those with coarser BC. Biochar of < 0.5 mm sizes had higher pH, and smaller TOC and loss on ignition compared to the 1–5 mm fraction of BC (Table 1). Higher pH and smaller loss on ignition suggest greater alkalinity in < 0.5 mm BCs, which may have stimulated microbial growth. In a review by Warnock et al. (2007), BC was shown in a number of studies to increase the abundance of fungi, especially mycorrhizal fungi, which was linked to greater availability of nutrients introduced by BC. The coarser BC of 0.5–5 mm, which increased the wettability of the crust of the sandy loam (Fig. 2), had smaller amounts of inorganic constituents indicated by higher loss on ignition (Table 1); hence, the stimulation of microbial growth may have been less likely. The observed reduction in WDPT of the crusted soil surface amended with coarse BC (0.5–5 mm particle sizes; Fig. 2) on the other hand could be related to larger pores on the crusted surface due to inclusion of large BC particles.

The non-repellency of the coarse-textured soils other than on the crust (Fig. 2) at our sites is contrary to the common occurrence of repellency in this type of soils (Doerr et al., 2000). The water repellency in coarse-textured soils has been explained by their smaller surface areas, which require small amounts of hydrophobic organic compounds to coat the soil particles (Doerr et al., 2000). Our sites had little TOC (Table 1), which may translate into small amounts of hydrophobic

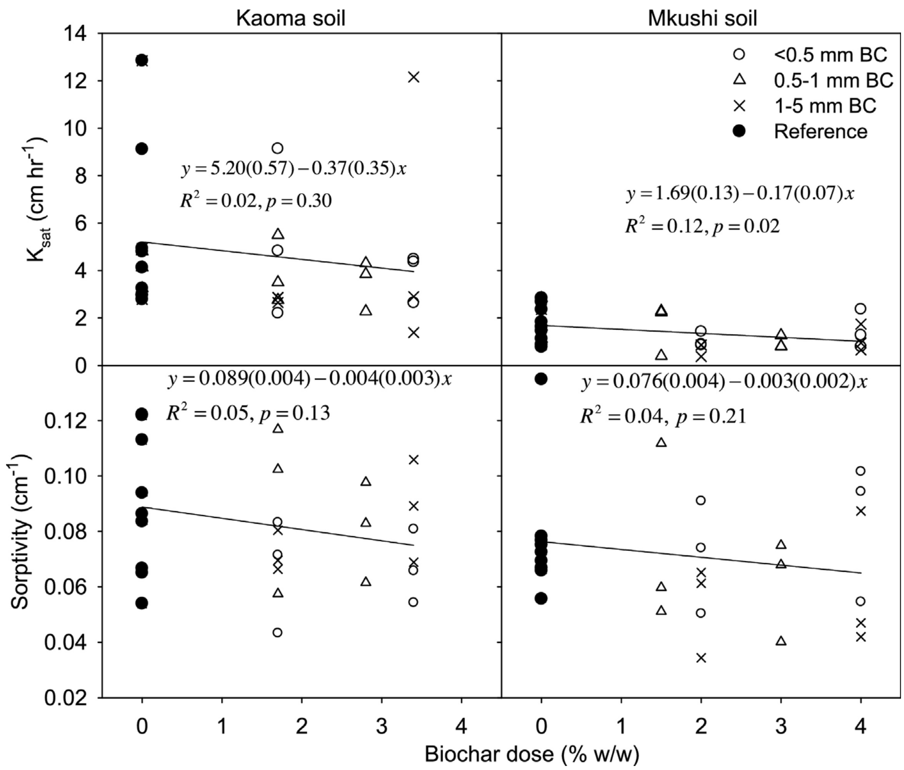

Fig. 4. Saturated hydraulic conductivity and sorptivity of loamy fine sand (Kaoma) and sandy loam soils (Mkushi, below the crust) amended with maize cob BC of different particle sizes, measured in March 2015. Numbers between brackets in the fitted regression equation are the SEs for either intercept or slope. No significant difference was established between particle size classes ($p > 0.05$).

organic compounds. The relatively high repellency of the crusted soil surface in Mkushi in March 2015 as compared to April 2014 (Fig. 2) may have been due to the dry state of the soil (Table 3), which is consistent with the known transient character of water repellency with changes in soil moisture content (Doerr and Thomas, 2000).

Unlike the crusted surface in sandy loam, the water repellency of the bulk soils was not affected by BC (Fig. 2). This is consistent with previous studies where mixing maize BC with sand (Abel et al., 2013) and silt loam (Herath et al., 2013) did not significantly affect their water repellency at varying moisture content, including oven-dried soils. The lack of water repellency in the oven-dry soil samples was less likely due to heat pre-treatment, as earlier reported by de Jonge et al. (1999), because even field measurements on dry soil below the crust showed a lack of water repellency. Therefore, our hypothesis, that the hydrophobicity of BC induces soil water repellency in coarse-textured soils, was rejected.

Saturated hydraulic conductivity decreased with increasing BC amounts in sandy loam irrespective of BC particle size (Fig. 4). Since BC had no effect on water repellency of the bulk soils (Fig. 2), the decrease in K_{sat} could not be attributed to the water repellency of BC, as suggested by Jeffery et al. (2015). Eibisch et al. (2015) also reported that the wettability characteristics of their digestate and woodchip BCs played no role in the observed increase in K_{sat} of loamy sand in their study. Thus, other mechanisms probably contributed to the observed decrease in K_{sat} of soils upon BC addition in the present study. This may include the filling of large water-conducting inter-particle soil pores (macro-pores > 30 μm diameter) by BC, which may be further aided by disintegration of BC in soil (Spokas et al., 2014). Filling of soil inter-particle space versus inclusion of BC into soil aggregates (Herath et al., 2013; Obia et al., 2016; Ouyang et al., 2013; Soinne et al., 2014) are potentially opposing mechanisms. Thus, the direction of the BC effect on K_{sat} is probably dependent on which of these mechanisms is dominant. For aggregating fine-textured soils, such as the ones studied by Major et al. (2010) and Asai et al. (2009), the increase in water flow rates may have been due to BC-induced soil aggregation. By contrast, in our study, the soils were coarse-textured, such that aggregation may not have been possible (loamy fine sand) or very slow (sandy loam). In our earlier work (Obia et al., 2016), we observed soil structural collapse upon draining saturated Mkushi soil amended with BC, indicating that structural development was slow and initially weak. Therefore, the filling of large water conducting soil pores directly by BC, or associated with structural collapse during infiltration could be the cause of BC-induced decrease in soil sorptivity and K_{sat} (Fig. 4). The hypothesis that BC increases K_{sat} in sandy loam due to BC-induced soil aggregation was not supported. Similarly, the hypothesis that finer BC reduces K_{sat} in loamy fine sand, due to filling of inter particle space, was not supported, as no significant effect was observed.

5. Conclusions and implications

Independent of its particle size, BC reduced the penetration resistance of sandy loam soils both with intact crust and after crust removal. By contrast, BC had no significant effect on penetration resistance in loamy fine sand. The reduction of penetration resistance in response to BC addition in sandy loam was attributed to BC-induced soil aggregation, which did not occur in loamy fine sand. The reduction of penetration resistance in sandy loam may aid growth of roots, which may translate into better crop growth.

Biochar affected water repellency of the crusted surface of sandy loam. This effect was related to BC particle size. Biochar with fine particle sizes promoted water repellency, whereas coarser BCs reduced water repellency. By contrast, there was no effect of BC on the water repellency of loamy fine sand and sandy loam soil below the crust indicating that the repellency of BC either did not affect soil water repellency or was lost in less than one year after BC application. This suggests that the reduction in K_{sat} of sandy loam due to BC, was not because of water-repellent behavior of BC per sé, but may be due to clogging of pores or to structural collapse. The coarse-textured soils studied here have a relatively high K_{sat} and the moderate reduction in K_{sat} in response to BC addition is not expected to have any detrimental effect on soil productivity. The indirect promotion of water repellency of surfaces of crusted soil by fine BC may limit water infiltration and promote soil erosion.

Acknowledgements

We are thankful for funding from the Norwegian Research Council (NFR) under FRIMUF project No. 204112 and NMBU PhD internal financing to the first author with co-funding from NFR FriPro project No. 217918, a stipend to Gerard Cornelissen. We are thankful to the Conservation Farming Unit, Lusaka, Zambia, Jeremy Selby (Mkushi) and Kebby Kasanga (Kaoma) for making their sites available for our research and the support during the experiments. We are also grateful to Edward Bwalya of Soil Science Department, University of Zambia for the help during infiltration measurement.

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.
Ajayi, A.E., Horn, R., 2016. Modification of chemical and hydrophysical properties of two texturally differentiated soils due to varying magnitudes of added biochar. Soil Tillage Res. 164, 34–44.
Ajayi, A.E., Holthusen, D., Horn, R., 2016. Changes in microstructural behaviour and hydraulic functions of biochar amended soils. Soil Tillage Res. 155, 166–175.
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. Field Crops Res. 111, 81–84.
Atkinson, C.J., Fitzgerald, J.D., Hipps, N.A., 2010. Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. Plant Soil 337, 1–18.
Awadhwal, N.K., Thierstein, G.E., 1985. Soil crust and its impact on crop establishment: a review. Soil Tillage Res. 5, 289–302.
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.
Briggs, C., Breiner, J.M., Graham, R.C., 2012. Physical and chemical properties of Pinus ponderosa charcoal: implications for soil modification. Soil Sci. 177 (4), 263–268.
Buczko, U., Bens, O., Fischer, H., Hüttl, R., 2002. Water repellency in sandy luvisols under different forest transformation stages in northeast Germany. Geoderma 109, 1–18.
Busscher, W.J., Novak, J.M., Evans, D.E., Watts, D.W., Niandou, M.A.S., Ahmedna, M., 2010. Influence of pecan biochar on physical properties of a Norfolk loamy sand. Soil Sci. 175, 10–14.
Castellini, M., Giglio, L., Niedda, M., Palumbo, A.D., Ventrella, D., 2015. Impact of biochar addition on the physical and hydraulic properties of a clay soil. Soil Tillage Res. 154, 1–13.
de Jonge, L.W., Jacobsen, O.H., Moldrup, P., 1999. Soil water repellency: effects of water content, temperature, and particle size. Soil Sci. Soc. Am. J. 63, 437–442.
de Melo Carvalho, M.T., de Holanda Nunes Maia, A., Madari, B.E., Bastiaans, L., van Oort, P.A.J., Heinemann, A.B., Soler da Silva, M.A., Petter, F.A., Marimon Jr, B.H., Meinke, H., 2014. Biochar increases plant-available water in a sandy loam soil under an aerobic rice crop system. Solid Earth 5, 939–952.
Dekker, L., Jungerius, P., 1990. Water repellency in the dunes with special reference to The Netherlands. Catena Suppl. 173–183.
Dekker, L.W., Ritsema, C.J., Oostindie, K., Moore, D., Wesseling, J.G., 2009. Methods for determining soil water repellency on field-moist samples. Water Resour. Res. 45. http://dx.doi.org/10.1029/2008wr007070.
Dexter, A.R., Czyż, E.A., Gaţe, O.P., 2007. A method for prediction of soil penetration resistance. Soil Tillage Res. 93, 412–419.
Doerr, S.H., Thomas, A.D., 2000. The role of soil moisture in controlling water repellency: new evidence from forest soils in Portugal. J. Hydrol. 231–232, 134–147.
Doerr, S.H., Shakesby, R.A., Walsh, R.P.D., 2000. Soil water repellency: its causes, characteristics and hydro-geomorphological significance. Earth-Sci. Rev. 51, 33–65.
Eibisch, N., Durner, W., Bechtold, M., Fuß, R., Mikutta, R., Woche, S.K., Helfrich, M., 2015. Does water repellency of pyrochars and hydrochars counter their positive effects on soil hydraulic properties? Geoderma 245–246, 31–39.
Gao, W., Whalley, W.R., Tian, Z., Liu, J., Ren, T., 2016. A simple model to predict soil penetrometer resistance as a function of density, drying and depth in the field. Soil Tillage Res. 155, 190–198.
Gardner, W.R., 1958. Some steady-state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. Soil Sci. 85, 228–232.
Githinji, L., 2014. Effect of biochar application rate on soil physical and hydraulic properties of a sandy loam. Arch. Agron. Soil Sci. 60, 457–470.
Glaser, B., Haumaier, L., Guggenberger, G., Zech, W., 2001. The'Terra Preta'phenomenon: a model for sustainable agriculture in the humid tropics. Naturwissenschaften 88, 37–41.
Glaser, B., Lehmann, J., Zech, W., 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal – a review. Biol. Fertil. Soils 35, 219–230.
Hallin, I.L., Douglas, P., Doerr, S.H., Bryant, R., 2015. The effect of addition of a wettable biochar on soil water repellency. Eur. J. Soil Sci. 66, 1063–1073.
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.
Jeffery, S., Verheijen, F.G.A., van der Velde, M., Bastos, A.C., 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agric. Ecosyst. Environ. 144, 175–187.
Jeffery, S., Meinders, M.B.J., Stoof, C.R., Bezemer, T.M., van de Voorde, T.F.J., Mommer, L., van Groenigen, J.W., 2015. Biochar application does not improve the soil hydrological function of a sandy soil. Geoderma 251–252, 47–54.
Khanmohammadi, Z., Afyuni, M., Mosaddeghi, M.R., 2015. Effect of pyrolysis temperature on chemical and physical properties of sewage sludge biochar. Waste Manage. Res. 33, 275–283.
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.
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.
Lehmann, J., Rillig, M.C., Thies, J., Masiello, C.A., Hockaday, W.C., Crowley, D., 2011. Biochar effects on soil biota – a review. Soil Biol. Biochem. 43, 1812–1836.
Lei, O., Zhang, R., 2013. Effects of biochars derived from different feedstocks and pyrolysis temperatures on soil physical and hydraulic properties. J. Soil Sediments 13, 1561–1572.
Letey, J., Carrillo, M.L.K., Pang, X.P., 2000. Approaches to characterize the degree of water repellency. J. Hydrol. 231–232, 61–65.
Major, J., Lehmann, J., Rondon, M., Goodale, C., 2010. Fate of soil-applied black carbon: downward migration, leaching and soil respiration. Global Change Biol. 16, 1366–1379.
Materechera, S.A., Mloza-Banda, H.R., 1997. Soil penetration resistance, root growth and yield of maize as influenced by tillage system on ridges in Malawi. Soil Tillage Res. 41, 13–24.
Mukherjee, A., Lal, R., 2013. Biochar impacts on soil physical properties and greenhouse gas emissions. Agronomy 3, 313–339.
Mukherjee, A., Lal, R., Zimmerman, A.R., 2014. Impacts of 1.5-year field aging on biochar, humic acid, and water treatment residual amended soil. Soil Sci. 179, 333–339.
Obia, A., Mulder, J., Martinsen, V., Cornelissen, G., Børresen, T., 2016. In situ effects of biochar on aggregation, water retention and porosity in light-textured tropical soils. Soil Tillage Res. 155, 35–44.
Ouyang, L., Wang, F., Tang, J., Yu, L., Zhang, R., 2013. Effects of biochar amendment on soil aggregates and hydraulic properties. J. Soil Sci. Plant Nutr. 13, 991–1002.
Page-Dumroese, D.S., Robichaud, P.R., Brown, R.E., Tirocke, J.M., 2015. Water repellency of two forest soils after biochar addition. Trans. ASABE 58, 335–342.
R Core Team, 2014. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.
Roy, J.L., McGill, W.B., 2002. Assessing soil water repellency using the molarity of ethanol droplet (MED) test. Soil Sci. 167, 83–97.
Soinne, H., Hovi, J., Tammeorg, P., Turtola, E., 2014. Effect of biochar on phosphorus sorption and clay soil aggregate stability. Geoderma 219–220, 162–167.
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.
Sun, F., Lu, S., 2014. Biochars improve aggregate stability, water retention, and pore-space properties of clayey soil. J. Plant Nutr. Soil Sci. 177, 26–33.
Upadhyaya, S., Sakai, K., Glancey, J., 1995. Instrumentation for in-field measurement of soil crust strength. Trans. ASAE 38, 39–44.
Uzoma, K.C., Inoue, M., Andry, H., Fujimaki, H., Zahoor, A., Nishihara, E., 2011. Effect of cow manure biochar on maize productivity under sandy soil condition. Soil Use Manage. 27, 205–212.
Verheijen, F.G.A., Jeffery, S., Bastos, A.C., van der Velde, M., Diafas, I., 2009. Biochar Application to Soils: A Critical Scientific Review of Effects on Soil Properties, Processes and Functions. EUR 24099 EN, Office for the Official Publications of the European Communities, Luxembourg (149 pp.).
Warnock, D.D., Lehmann, J., Kuyper, T.W., Rillig, M.C., 2007. Mycorrhizal responses to biochar in soil – concepts and mechanisms. Plant Soil 300, 9–20.
Watson, C., Letey, J., 1970. Indices for characterizing soil-water repellency based upon contact angle-surface tension relationships. Soil Sci. Soc. Am. J. 34, 841–844.
Wooding, R., 1968. Steady infiltration from a shallow circular pond. Water Resour. Res. 4, 1259–1273.
Yatagai, A., 2011. Interannual variation of seasonal rain fall in South Zambia. In: Umetsu, C. (Ed.), Vulnerability and Resilience of Social-Ecological Systems. Research Institute For Humanity And Nature, Kyoto, pp. 206–212.
Yi, S., Witt, B., Chiu, P., Guo, M., Imhoff, P., 2015. The origin and reversible nature of poultry litter biochar hydrophobicity. J. Environ. Qual. 44, 963–971.