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In situ effects of biochar on aggregation, water retention and porosity in light-textured tropical soils

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ABSTRACT

Biochar (BC) has been reported to improve soil physical properties mainly in laboratory and greenhouse pot experiments. Here we study, under field conditions, the effect of BC and its particle sizes on soil aggregate stability, bulk density (BD), water retention, and pore size distribution in two experiments in Zambia. A) Farmer practice experiment in sandy loam with maize cob BC in conservation farming planting basins under maize and soybeans crops. B) Maize cob and rice husk BC particle size experiments ($\leq$0.5, 0.5–1 and 1–5 mm particle sizes) in loamy sand and sand. In the farmer practice experiment, BC increased aggregate stability by 7–9% and 17–20% per percent BC added under maize and soybeans crops respectively ($p < 0.05$) after two growing seasons. Total porosity and available water capacity (AWC) increased by 2 and 3% respectively per percent BC added ($p < 0.05$) under both crops, whereas BD decreased by 3–5% per percent BC added ($p \leq 0.01$). In the maize cob BC particle size experiment after one growing season, dose was a more important factor than particle size across the soils tested. Particle size of BC was more important in loamy sand than in sand, with $\leq$0.5 and 1–5 mm sizes producing the strongest effects on the measured properties. For example, BD decreased while total porosity increased ($p < 0.01$) for all BC particle sizes in sand whereas only 1–5 mm BC significantly decreased BD and increased total porosity in loamy sand ($p < 0.05$). However, AWC was significantly increased by only $\leq$0.5 and 1–5 mm BCs by 7–9% per percent BC added in both loamy sand and sand. Rice husk BC effect after one year followed similar pattern as maize cob BC but less effective in affecting soil physical properties. Overall, reduced density of soil due to BC-induced soil aggregation may aid root growth and with more water available, can increase crop growth and yields.

1. Introduction

Biochar (BC) is the charcoal product from pyrolysis of biomass and has been reported to increase crop production when applied to soils (Glaser et al., 2002). Increase in crop production has been attributed to BCs' inherent properties such as high pH, high cation exchange capacities (CEC), high specific surface area and its effects on soil properties (Steiner et al., 2007; Sun et al., 2014; Yamato et al., 2006). However, BC properties and the effect on crop production depend on feedstock, pyrolysis conditions and soil type (Jeffery et al., 2011).

The effects of BC on soil physical properties have received less attention than effects on soil chemical properties (Atkinson et al., 2010), despite the potential importance of improved physical properties in increasing crop production in light-textured soils (Cornelissen et al., 2013). One of the most important soil physical conditions supporting crop production is available water capacity (AWC), which is the difference between water content at −100 hPa matrix potential (field capacity—FC) and water content at −15000 hPa (permanent wilting point—PWP). Biochar has been shown to increase both soil water holding capacity and AWC (Basso et al., 2013; Cornelissen et al., 2013; Herath et al., 2013; Martinsen et al., 2014; Mukherjee and Lal, 2013). However, other studies found no effect of BC addition on water holding capacity (Carlsson et al., 2012). Most studies reporting increased water holding capacity involved FC measurements only, and without PWP data, it is difficult to quantify the increase in AWC. Indeed, an increase in PWP after BC addition (Carlsson et al., 2012; Herath et al., 2013) may cause an overall reduced effect on AWC despite increase in FC (Herath et al., 2013). In addition, most studies have been conducted as either laboratory incubations or pot trials in greenhouses. Reports from field studies are only now beginning to appear, e.g.,

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de Melo Carvalho et al. (2014) in which BC was found to increase AWC.

The increase in AWC upon BC addition in sandy and loamy soils (Mukherjee and Lal, 2013) are an indication of altered pore-size distribution (Sun et al., 2014). These increases could be a direct effect of BC due to its high porosity (Mukherjee and Lal, 2013) or an indirect effect due to soil aggregation. Recent incubation studies in the laboratory reported increased aggregate stability following BC addition (Awad et al., 2013; Herath et al., 2013; Liu et al., 2012; Ouyang et al., 2013; Soinne et al., 2014; Sun and Lu, 2014). Even in studies where soil aggregation was not measured, the general increase in water holding capacity and decrease in bulk density (BD) (Mukherjee and Lal, 2013) are potential indicators for increased soil aggregation in loamy soils. The reasons for stimulation of soil aggregation can be attributed to BC surface characteristics, which result in direct binding of soil particles or firstly sorption of soil organic matter, which then binds soil particles (Brodowski et al., 2006; Joseph et al., 2010). This behavior causes occlusion of BC into aggregates (Brodowski et al., 2006). In addition, BC may increase root biomass (Bruun et al., 2014) and root activity causing an increase in aggregate stability (Reid and Goss, 1981). The effect of roots on aggregate stability may depend on crop type with monocotyledonous plants having stronger effect than dicotyledonous plants (Amézketa, 1999), even under the influence of BC. Improved aggregation of loamy soils by BC may therefore cause an increase in AWC.

Soils with a sand to loamy sand texture have inherently low AWC and high air capacity. Such soils, having physical conditions not conducive for crop production, are common in large parts of western Zambia, classified mainly as Arenosols and central Zambia, classified mainly as Acrisols. Effects of adverse physical soil properties on crop growth are exacerbated by the high inter-annual variation of rainfall and the general trend of declining rainfall amount in some areas of Zambia (Yatagai, 2011). In effect, inter-annual variation of rainfall is a major factor explaining the already low production and productivity of the Zambian agricultural sector (Goverment of Zambia, 2011) dominated by smallholder farmers who rely on rain fed agriculture. Biochar produced from crop wastes such as maize cobs which is widely available, has been shown to increase crop yields in these soils (Cornelissen et al., 2013; Martinsen et al., 2014), probably partly due to BC's potential to increase AWC, as shown only under laboratory conditions.

In this study, we hypothesize that BC will improve soil physical properties (increase aggregate stability and water retention and reduce bulk density) depending on the crop type. Biochar with fine particles will improve soil physical properties, e.g., water retention, more strongly than coarse BC particles due to better mixing with soil.

The objectives of the present study were to determine the effect of (i) BC from maize cobs on soil aggregate stability, water retention and pore size distribution under conservation farming planted with maize and soybeans. (ii) particle sizes of maize cob and rice husk BC on soil aggregate stability, water retention and pore size distribution under maize in conventional farming.

To this end, two sets of field experiments were conducted in Zambia. The first experiment involved locally produced maize cob BC applied following conservation farming practices (Cornelissen et al., 2013). The second experiment involved the application of locally produced maize cob and rice husk BC of different particle sizes mixed into the soil. Water retention curves, aggregate stability and BD were then determined on the samples taken from the field experiments. This study is one of the few investigating these parameters under field conditions, under various crops, and for various "real-world" BCs (i.e., not synthesized in the laboratory) of different particle sizes.

2. Materials and methods

2.1. Biochar production

The BCs whose properties are presented in Table 1 were produced in a slow pyrolysis (2–3 days) from two feedstocks: Maize cob, which is widely available throughout Zambia, was our primary feedstock for BC implementation (Cornelissen et al., 2013; Martinsen et al., 2014) and rice husk, which is available in western Zambia. The maize cobs were complete dry cobs after removing grains. Biochars were produced in two batches and the first batch was produced in 2011 from maize cob at a temperature of approximately 350 °C and a residence time of 2 days (during most of the residence time, temperature was 300–350 °C) in a brick kiln at Mkushi, Zambia. The second batch was produced in 2013 from maize cob and rice husk in a drum retort kiln at Chisamba, Zambia at a temperature of 350 °C and a retention time of 1 day. Details of other production conditions can be found in Sparrevik et al. (2015). Biochar from the first batch was used in the farmer practice

Table 1
Soil and biochar properties.

Properties	Mkushi soil Exp. A	Mkushi soil Exp. B	Kaoma soil Exp. B	Maize cob BC Exp. A	Rice husk BC, Exp. B			Maize cob BC, Exp. B		
					≤0.5 mm	0.5–1 mm	Unsorted	≤0.5 mm	1–5 mm	Unsorted
Sand (%)	64.4	75.1	85.4	–	–	–	–	–	–	–
Silt (%)	23.5	15.9	10.2	–	–	–	–	–	–	–
Clay (%)	12.2	9.0	4.4	–	–	–	–	–	–	–
Texture class	Sandy loam	Loamy sand	Sand	–	–	–	–	–	–	–
Total organic C (%)	0.67	0.74	0.62	81.1	39.3	42.8	47.8	44.8	60.1	53.8
Total nitrogen (%)	0.01	0.01	0.00	0.7	0.61	0.52	0.82	0.79	0.53	0.65
Total hydrogen (%)	0.10	0.27	0.05	3.0	2.33	2.41	2.37	2.09	2.63	2.36
H/C (molar ratio)	0.06	0.06	0.05	0.44	0.71	0.68	0.60	0.56	0.52	0.53
pH (H_2O)	6.4	5.8	5.8	9.7	8.3	8.3	8.3	9.0	8.6	8.8
CEC ($cmol_c\,kg^{-1}$)	2.7	1.7	2.8	21.1	–	–	14.0	–	–	22.2
K^+ ($cmol_c\,kg^{-1}$)	0.3	0.3	0.1	19.5	–	–	10.4	–	–	16.5
Ca^{2+} ($cmol_c\,kg^{-1}$)	1.4	1.1	1.2	0.9	–	–	2.4	–	–	4.3
Mg^{2+} ($cmol_c\,kg^{-1}$)	1.0	0.3	0.2	0.8	–	–	0.9	–	–	1.2
Bulk density ($g\,cm^{-3}$)	1.26	1.27	1.47	–	0.37	0.27	–	0.36	0.29	–
BET surface area ($m^2\,g^{-1}$)	–	–	–	–	2.4	2.3	–	10.5	4.9	–
Loss on ignition (%)	–	–	–	–	48.8	54.9	–	52.1	72.4	–

Exp. = Experiment.

experiment (Experiment A), whereas BC from second batch was used in maize cob and rice husk BC particle size experiments (Experiment B).

2.2. Experimental sites/set up

Field experiments were established on private farms in two districts of Mkushi and Kaoma in central and western Zambia respectively. The average annual rainfall of Mkushi and Kaoma is 1220 and 930 mm and average temperature is 20.4 °C and 20.8 °C respectively. The top soils in all the sites are light-textured, acidic and have low CEC (Table 1). The experimental set up is summarized in Table 2. There were two experiments: farmer practice experiment (Experiment A) and BC particle size experiment (Experiment B). Farmer practice experiment consisted of crushed maize cob BC applied in conservation farming while BC particle size experiment consisted of maize cob and rice husk BC, respectively, sieved into different particle sizes applied under conventional farming.

2.2.1. Farmer practice experiment (Experiment A)

This was established by applying crushed (unsorted) maize cob BC in sandy loam soil under conservation farming practice as described by Cornelissen et al. (2013). Briefly, conservation farming involved tilling about 10% of the total land by digging planting basins to conserve moisture and to minimize soil disturbance. Weeds in the rest of the land were managed through application of herbicide. The soil in the planting basins, of approximately $15 \times 20 \times 40$ cm size (~10 L) was dug and mixed with crushed maize cob BC at a rate of 0, 0.8 and 2.5 w/w%. Since the BC was concentrated in the planting basins, 0, 0.8 and 2.5 w/w% was equivalent to only 0, 2, and 6 ton ha^{-1} respectively. Fertilizer (140 kg ha^{-1} N:P:K:S—10:20:10:6 followed by 140 kg ha^{-1} top dressing with urea) was applied to all planting basins every season (i.e. November 2011–March 2012 and November 2012–March 2013). The experimental plot was divided into two, one part planted with maize and the other with soybeans. The layout consisted of nine rows planted with maize and nine rows planted with soybeans, with each row having 15 planting basins. Under maize crop, three neighboring rows each received 0, 0.8, 2.5 % BC and the same arrangement follows for soybeans. Further details of the set up can be found in Martinsen et al. (2014).

2.2.2. Biochar particle size experiment (Experiment B)

This was established in April 2013 under conventional farming by applying maize cob BC of three particle sizes prepared by crushing and dry sieving based on a split plot design (Table 2). The sites were uniform with respect to soils and divided into three blocks, each sub-divided into three main plots amended with BC of different particle sizes ($\leq$0.5, 0.5–1 and 1–5 mm). The main plots were divided into three sub-plots receiving BC at three doses (0, 1.7 and 3.4 w/w% for Kaoma sand and 0, 2 and 4 w/w% for Mkushi loamy sand). The same amounts of BC (0, 17.5, 35 ton ha^{-1}) were applied to the two sites but percentages differed due to differences in soil bulk density. The total number of sub-plots/experimental units at each site was 27. From each sub-plot, the top 7 cm of soil was removed and mixed with the required amount of BC in a bucket. The soil profile from 7 cm to approx. 30 cm was loosened using a hoe to remove the compacted layer before placing it back on top, the soil-BC mixture in the bucket. The sub-plot size was 0.5×0.5 m separated by vertical hard plastic sheet inserted approx. 10 cm into the soil and 10 cm remaining above the soil. Fertilizer at the recommended rate (see farmer practice experiment) was applied at the center of the sub-plots just before planting of maize (November 2013).

A small experiment was also established in April 2013 by applying rice husk BC of $\leq$0.5 and 0.5–1 mm particle sizes under conventional farming based on a completely randomized design. The experiment was established adjacent to, and using a similar approach as in the maize cob BC particle size experiment. Main findings are included only in the text of the result section. Experimental details (Description S1) and data (Table S1 and Fig. S1) are in the supplementary information.

2.3. Soil sampling

2.3.1. Farmer practice experiment

Soil was sampled in April 2013, two rainy seasons after application of BC, taking six undisturbed core ring samples and six disturbed samples randomly from each treatment. The samples were taken only from the planting basins with crops within the top 15 cm of soil, just prior to harvest in the second season.

2.3.2. Biochar particle size experiments

In April 2014, one year after BC application, we sampled the top soil from each of the sub-plots. Two undisturbed core ring samples and two disturbed samples were taken from each sub-plot.

2.4. Aggregate stability determination

Aggregate stability was assessed for disturbed soil samples from Mkushi (Experiments A and B—in maize cob BC experiments). Air-dry soil samples from the field were sieved in a shaker fitted with stacked sieves (20, 6, 2 and 0.6 mm). The stability of aggregates were tested for sizes 2–6 and 0.6–2 mm using the rainfall simulation method (Marti, 1984). The 2–6 and 0.6–2 mm

Table 2
Summary of experimental set up.

Distinguishing feature	Farmer practice - Experiment A	BC particle size - Experiment B[a]	
District	Mkushi	Mkushi	Kaoma
Site coordinate	S13 45.684, E29 03.349	S13 44.839, E29 05.972	S14 50.245, E25 02.150
Farming practice	Conservation farming	Conventional farming	Conventional farming
Soil type	Sandy loam Acrisol	Loamy sand Acrisol	Sand, Arenosol
BC type	Maize cob BC	Maize cob BC	Maize cob BC
BC particle size	Unsorted	$\leq$0.5, 0.5–1 & 1–5 mm	$\leq$0.5, 0.5–1 & 1–5 mm
BC dose[b] (%w/w)	0, 0.8 & 2.5%	0, 2 & 4%	0, 1.7 & 3.4%
BC application depth	15 cm	7 cm	7 cm
BC application time	October 2011	April 2013	April 2013
Soil sampling time	April 2013	April 2014	April 2014
Crop planted	Maize and soybeans	Maize	Maize

[a] Details about rice husk BC of different particle sizes are in the supplementary information.

[b] For BC particle size experiment, same amounts of BC were applied in Mkushi and Kaoma. Differences in percent BC are due to differences in bulk density of Mkushi (1.27 g cm^{-3}) and Kaoma (1.47 g cm^{-3}) soil. 0, 17.5 and 35 ton ha^{-1} BC correspond to 0, 2 and 4% BC in Mkushi and 0, 1.7 and 3.4% BC in Kaoma.

aggregates were air-dried for one week by spreading the soil on trays in the laboratory. Twenty grams of the air-dry soil aggregates were spread on the pre-wetted 0.5 mm sieves just before rainfall simulation. Pre-wetting of sieves moistened the soil and minimized slaking of aggregates. Eight sieves with moistened aggregates were placed on a circular rotating platform, 32 cm under the rain nozzles for each round. The water pressure for rain simulation was set at 1 atm. producing rain with intensity of approx. 350 mm hr^{-1} and the simulation was allowed to run for 2 min. Despite the high rainfall intensity, this method has been found to give results consistent with the more commonly used wet sieving (Grønsten and Børresen, 2009). Soil that remained in the sieves, providing a measure of stable aggregates, were removed and air-dried for 10 days before weighing. The soil weight was corrected for coarse sand and BC particles (>0.5 mm). This was done by immersing the 0.5 mm sieve having air-dry soil, that were retained in the sieve during rainfall simulation, in sodium hexametaphosphate solution (5 g l^{-1}) and washing out the fine soil particles less than 0.5 mm. The coarse fraction of sand and BC was also air-dried for 1 week. Stable aggregates (%) were calculated using a formula adapted from (Kemper and Koch, 1966):

$$\text{Stable aggregates} = \frac{\text{Dry wt soil after simulation} - \text{Dry wt coarse fraction sand \& BC}}{\text{20g dry soil} - \text{Dry wt coarse fraction sand \& BC}} \times 100 \quad (1)$$

2.5. Soil water retention and pore size distribution

Water retention and pore size distribution was determined for undisturbed soil cores of 100 cm^3 (~3.7 cm height, ~5.8 cm diameter) collected by driving steel rings into the soil vertically at a depth of ~0–5 cm. The rings were closed after cutting off with a knife both ends of the soil in the rings before transporting to the laboratory.

Standard laboratory procedure was used to measure water retention of initially saturated samples by applying various pressures to drain the soil. A sand box (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands) was used to determine water retention at high matrix potentials of −10, −30, −50 and −70 hPa, by measuring the weight of the samples when in equilibrium at each of the matrix potentials. For −100 and −1000 hPa, water retention was determined on the same undisturbed core samples using pressure plates (Soil moisture Equipment, Santa Barbara, CA). Positive pressure was applied on the samples for approximately one week until no water was coming out from the device for two days before taking the weight of the samples. After −1000 hPa matrix potential, the samples in the core rings were oven-dried for two days at 105 °C to determine water content at this potential and other higher potentials. The determined soil dry weight also allowed calculation of BD. The oven dry samples were then crushed and passed through a 2 mm sieve. Sub-samples were taken and water-saturated in small PVC rings placed on −15000 hPa pressure plate to determine PWP. Upon equilibration of the samples for 10 days at 15-bar pressure, soil weight was taken, and oven-dried to determine the water content.

The gravimetric water contents at all the measured pressures were converted to volumetric water contents using the measured BD. The volumetric water contents (θ) and matrix potential (h) were fitted to the van Genuchten (1980) model.

$$\theta = \theta_r + (\theta_s - \theta_r)\left[1 + (\alpha|h|)^n\right]^{-m} \quad (2)$$

Where, θ_r and θ_s are the residual and saturated ($h = 0$ hPa) volumetric water content respectively. Both θ_r and θ_s were included in the optimization of van Genuchten parameters i.e. not fixed to measured PWP and total porosity, respectively. α is related to the inverse of the air entry matrix potential, n is a measure of the pore-size distribution, and m is derived from parameter n where;

$$m = 1 - \frac{1}{n} \quad (3)$$

Soil volume in the core rings decreased as the saturated soil was drained in the sand box, especially for loamy sand from Mkushi (Experiment B). The decrease in the soil height in the core ring was measured using a ruler after equilibration at −100 hPa matrix potential and the decrease in soil volume was calculated. The water retention data generally fitted well to Eq. (2) except at high matrix potential (at saturation and −10 hPa; not shown) probably because of soil volume shrinkage. Agronomic important water retention points of FC, PWP and AWC were determined based on modelled water contents. FC and PWP are water contents at matrix potentials of −100 and −15000 hPa, respectively whereas AWC is the difference between FC and PWP. In addition, the air content of the soil at FC, commonly referred to as air capacity was measured using an air pycnometer (Torstensson and Eriksson, 1936). The presented total porosity was determined by summing up air capacity and FC.

Pore size distribution was calculated using a capillary model (Eq. (4)) based on the water content retained at all matrix potentials between −1 and −16000 hPa modelled using Eq. (2). The capillary model (Eq. (4)) assumes that all pores are cylindrical with radius r.

$$h = \frac{2\gamma.\cos\theta}{\rho g r} \quad (4)$$

where, h = matrix potential (hPa), γ = water surface tension (0.0728 N m^{-1} at 20 °C), ρ = density of the water (1000 Kg m^{-3}), g = gravitational constant (9.81 m s^{-2}) and θ = contact angle between water and solid ~0, r = pore radius (µm);

$$r \approx \frac{15}{h} \times 10^2 \quad (5)$$

2.6. Other lab analysis of soil and biochar

Soil texture was determined for Kaoma and Mkushi soils using the Pipette method. Total organic carbon, total nitrogen and total hydrogen content was determined on soil samples, on BCs after acidification to remove carbonates and on soil aggregates of sizes of 0.6–2 and 2–6 mm. The samples were milled and analyzed, using CHN analyzer (CHN-1000, LECO USA). Biochar carbon of soil aggregates was estimated by subtracting organic carbon content of aggregates of reference soil from organic carbon content of aggregates of BC amended soil. We did not expect either increase or decrease in soil carbon content after 18 months of BC amendment to affect strongly the obtained ‘BC carbon’. Any increase in soil carbon would be negligible with respect to added BC carbon given the known slow build-up of soil organic carbon. Also, a decrease in soil organic carbon due to BC would be small, e.g., Luo et al. (2011) where only ~3% of the soil organic carbon was lost and mainly at the start of incubation, in very acidic and neutral pH low-carbon soils. Density of BC was determined by averaging five values of density derived from weighing five 10 cm^{-3} cups filled with BC. pH was measured in water at a ratio of 1:2.5 soil (BC):water on volume basis using a pH meter (Orion 2 Star, Thermo Fisher Scientific, Fort Collins, CO, US) after overnight sedimentation and shaking. Base cations were determined after extracting the soils and BCs with ammonium acetate pH 7 and ammonium nitrate respectively. Extractable acidity of the soil was determined by back titration of ammonium acetate extract using NaOH. CEC of the soils were determined by summing base cations and extractable acidity and CEC for BCs by summing base cations. Soil and BC characteristics are presented in Table 1.

2.7. Data analysis

All the data were analyzed using the statistical software R (R Core Team, 2014). For Experiment A, the dependent variables were BD, aggregate stability, PWP, FC, AWC, air capacity and total porosity, whereas the explanatory variables consisted of crop (categorical; maize and soybeans) and BC dose (continuous; %). The data were analyzed by analysis of covariance (ANCOVA). Experiment B for the maize cob BC particle size consisted of the same dependent variables as Experiment A and were analyzed separately for each site. These data were analyzed using mixed model ANCOVA (lme4 package in R). Biochar particle size (categorical; three levels) and dose (continuous; 0–4%) were included as explanatory variables (fixed effects) whereas block and its interaction with particle size were included as random effects. Regression coefficients of ANCOVA are tabulated, with their standard errors and R^2 included, whereas the overall water retention curves and pore size distribution are presented graphically.

The aggregate stability of the soils from planting basins (Experiment A) were also plotted against BC carbon of the aggregates as explanatory variable. This data fitted well to Michaelis–Menten model (drc package in R), a dose response model previously used for describing enzyme kinetics.

$$y = c + \frac{d - c}{1 + (e/x)} \tag{6}$$

where, y = response variable (percent stable aggregates), c = percent stable aggregates at zero BC addition, d = maximum percent stable aggregates, e = BC carbon at half d and x = explanatory variable (BC carbon). Three-parameter Michaelis–Menten model ($c \neq 0$) was fitted to the percent stable aggregates as a function of BC carbon to determine how this factor relates to aggregate stability.

3. Results

3.1. Effect of biochar on soil aggregate stability

Biochar produced from maize cobs increased aggregate stability of the sandy loam soil in Mkushi (Experiment A, Table 3). The increase in stable aggregates under soybeans was 4.6 ± 1.9 and 6.8 ± 1.9% for the 0.6–2 and 2–6 mm aggregates, respectively, for each percent BC added. Under maize, stable aggregates increased by 2.6 ± 1.9 and 2.9 ± 1.9% for the 0.6–2 and 2–6 mm aggregates, respectively, for each percent BC added. The increase in the stability of aggregates due to BC was higher under soybeans than under maize crop but significant only for 2–6 mm soil aggregates (p = 0.05). In the absence of BC, soils under maize had higher aggregate stability than soil under soybeans (Table 3). The effect of different size fractions of maize cob BC (Experiment B) on soil aggregate stability in loamy sand at Mkushi was significant for the 0.5–1 mm BC particle size fraction on 0.6–2 mm aggregates only (Table 4). In both Experiments A and B, the 2–6 mm soil aggregates had higher stability than the smaller 0.6–2 mm soil aggregates irrespective of BC rate or particle size fraction.

The relationship between BC carbon and the stability of the 0.6–2 and 2–6 mm soil aggregates (Experiment A) was well described by the three-parameter Michaelis–Menten equation (Eq. (6)) (Fig. 1). Continuous BC carbon contents of the aggregates instead of BC doses, after merging the data of the two crop types as a factor, allowed fitting a non-linear Michaelis–Menten model as opposed to only three doses of BC under maize and soybeans fitted with a linear model. The increase in the stable aggregates with increasing BC carbon was steep at relatively low BC carbon (≤0.4%) of the aggregates. Stable 2–6 and 0.6–2 mm soil aggregates increased from 35 and 25% respectively at zero BC addition, which was greater than half of the maximum observed stability at high BC contents. The increase in stable aggregates with increasing BC carbon leveled off at a maximum of 51.4 and 41.3% for 2–6 mm and 0.6–2 mm aggregates, respectively (Fig. 1). Unlike in Experiment A, the stable aggregates of Experiment B at Mkushi increased linearly with increasing organic carbon in the aggregates (Fig. S2).

Table 3
Regression parameters (±SE) of soil quality indicators versus dose of maize cob BC in planting basins of sandy loams at Mkushi (Experiment A).[a]

Soil quality indicators	Crop	Intercept (0% BC)	Slope (change per percent BC added)	R^2
Aggregate stability 0.6–2 mm aggregates	Maize	30.2 (2.0)	2.6 (1.3)	0.33
	Soybeans	27.2 (2.8)	4.6 (1.9)*	
Aggregate stability 2–6 mm aggregates	Maize	42.6 (2.1)**	2.9 (1.4)*	0.52
	Soybeans	34.0 (2.9)**	6.8 (1.9)**	
Bulk density (g cm^{-3})	Maize	1.26 (0.04)	-0.06 (0.02)**	0.35
	Soybeans	1.29 (0.04)	-0.04 (0.03)**	
Field capacity (vol.%)	Maize	22.4 (0.5)	0.5 (0.2)*	0.20
	Soybeans	21.5 (0.5)	0.5 (0.2)*	
Permanent wilting point (vol.%)	Maize	5.5 (0.3)	0.0 (0.2)	0.01
	Soybeans	5.7 (0.3)	0.0 (0.2)	
Available water capacity (vol.%)	Maize	16.8 (0.4)	0.5 (0.2)*	0.23
	Soybeans	15.7 (0.5)*	0.5 (0.2)*	
Total porosity (vol.%)	Maize	54.3 (0.8)	1.2 (0.4)**	0.22
	Soybeans	53.2 (0.9)	1.2 (0.4)**	

Star in the slope column indicates significant difference from zero and star in the intercept column indicates significant difference between maize and soybeans for a given soil quality indicator.

[*] $p < 0.05$.

[**] $p < 0.01$.

[a] Basic soil and BC properties are in Table 1.

Table 4
Regression parameters (±SE) of soil quality indicators versus dose of maize cob BC of different particle sizes in loamy sands at Mkushi and sand at Kaoma (experiment B).[a]

Soil quality indicator	Site	BC sizes	Intercept (0% BC)	Slope (change per percent BC added)
Aggregate stability 0.6–2 mm aggregates	Mkushi	1–5 mm	25.8 (3.7)	0.3 (1.7)
		0.5–1 mm	18.8 (3.2)	3.0 (1.4)*
		≤0.5 mm	20.9 (3.7)	0.1 (1.7)
Aggregate stability 0.6–2 mm aggregates	Mkushi	1-5 mm	42.4 (5.2)*	−1.7 (2.4)
		0.5–1 mm	29.4 (3.8)	1.4 (1.9)
		≤0.5 mm	30.0 (5.2)	1.4 (2.4)
Bulk density (g cm^{-3})	Mkushi	1–5 mm	1.29 (0.03)	−0.03 (0.010)**
		0.5–1 mm	1.25 (0.05)	0.00 (0.017)
		≤0.5 mm	1.27 (0.05)	−0.02 (0.015)
	Kaoma	1–5 mm	1.41 (0.03)	−0.03 (0.008)**
		0.5–1 mm	1.45 (0.04)	−0.04 (0.011)**
		≤0.5 mm	1.52 (0.04)	−0.03 (0.011)**
Field capacity (vol.%)	Mkushi	1–5 mm	14.5 (0.3)	1.0 (0.08)***
		0.5–1 mm	15.2 (0.5)	0.2 (0.14)
		≤0.5 mm	14.3 (0.5)	0.8 (0.12)***
	Kaoma	1–5 mm	13.9 (0.6)	1.2 (0.21)***
		0.5–1 mm	14.6 (0.9)	0.6 (0.30)
		≤0.5 mm	13.9 (0.9)	1.0 (0.33)***
Permanent wilting point (vol.%)	Mkushi	1–5 mm	3.8 (0.2)	0.06 (0.07)
		0.5–1 mm	3.8 (0.3)	0.10 (0.11)
		≤0.5 mm	3.9 (0.3)	0.15 (0.09)
	Kaoma	1–5 mm	2.1 (0.2)	0.34 (0.11)**
		0.5–1 mm	2.2 (0.4)	0.26 (0.17)
		≤0.5 mm	2.9 (0.4)	−0.01 (0.15)
Available water capacity (vol.%)	Mkushi	1–5 mm	10.7 (0.4)	0.9 (0.11)***
		0.5–1 mm	11.4 (0.6)	0.1 (0.13)
		≤0.5 mm	10.4 (0.6)	0.7 (0.16)***
	Kaoma	1–5 mm	11.8 (0.7)	0.8 (0.20)***
		0.5–1 mm	12.4 (0.9)	0.3 (0.28)
		≤0.5 mm	11.0 (0.9)	1.0 (0.31)***
Total porosity (vol.%)	Mkushi	1–5 mm	50.6 (1.6)	1.4 (0.50)*
		0.5–1 mm	51.9 (2.3)	0.1 (0.82)
		≤0.5 mm	51.1 (2.3)	0.7 (0.70)
	Kaoma	1–5 mm	46.9 (1.2)	1.2 (0.34)**
		0.5–1 mm	45.6 (1.8)	1.5 (0.53)**
		≤0.5 mm	42.0 (1.7)	1.4 (0.47)**

The star in the slope column indicate a significant difference from zero.
* $p < 0.05$.
** $p < 0.01$.
*** $p < 0.001$.
[a] Basic soil and BC properties are in Table 1.

The association of BC particles of different sizes with either 0.6–2 or 2–6 mm soil aggregates differed in Experiment B (Fig. S3). Biochar particle sizes of ≤0.5 mm had an equal distribution between 0.6–2 and 2–6 mm soil aggregates. By contrast, 0.5–1 mm BC particles were mainly associated with 0.6–2 mm soil aggregates, whereas coarse 1–5 mm BC particles sizes as expected, were more (two times) strongly associated with 2–6 mm soil aggregates. The organic carbon of aggregates of the reference soil did not significantly differ between the aggregate sizes analyzed.

3.2. Effect of biochar on soil bulk density

In the planting basins at Mkushi (Experiment A), maize cob BC significantly decreased BD of the sandy loams ($p < 0.01$) by 0.04–0.06 g cm^{-3} per percent BC applied (Table 3) under both maize and soybeans crops. The decrease in BD was more associated with increase in macro-pores (Fig. 2). In the loamy sands at Mkushi (Experiment B), only maize cob BC with particle size of 1–5 mm and not the smaller size fractions of ≤0.5 and 0.5–1 mm significantly decreased the BD (0.03 g cm^{-3} decrease per percent BC added, Table 4). Similarly, fine rice husk BC with size of ≤0.5 mm did not significantly reduce the BD (Table S1). In the more coarse textured sand at Kaoma, BC application rate, but not particle size, affected BD causing a significant decrease of ~0.03 g cm^{-3} per percent BC applied (Table 4 and S1).

3.3. Effect of biochar on pore size distribution of soil

Biochar altered pore size distribution of soils in the planting basins of the sandy loams at Mkushi (Experiment A), with greater alterations at the largest BC application rate (2.5%; Fig. S4). Under maize, this occurred via an increase in the proportion of pores with a radius >1 μm whereas under soybeans the alteration of pore size distribution was not as strong as under maize even though the pattern was similar.

In Experiment B, the addition of fine (≤0.5 mm) and coarse (1–5 mm) maize cob BC in the Kaoma sand decreased the proportion of pores with radius 10–100 μm, while the proportion of the bigger or smaller pore sizes increased (Fig. 3). The intermediate BC particle size fraction of 0.5–1 mm had the smallest effect in altering the pore size distribution. For the loamy sand at Mkushi (Fig. S5), smaller BC particle sizes increased the proportion of pores with

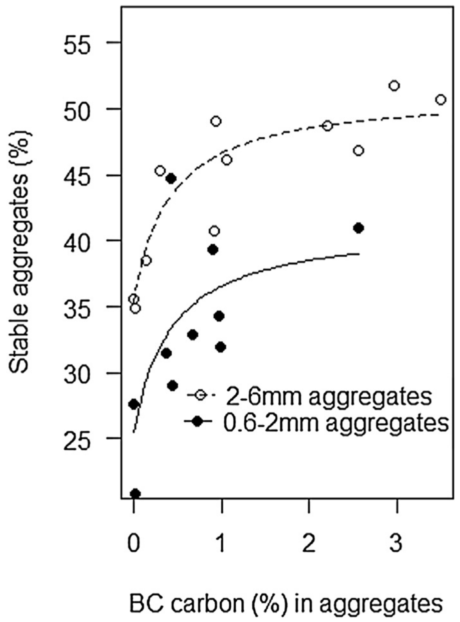

Fig. 1. Stable aggregates plotted against BC carbon in aggregates of BC amended soils from Experiment A in Mkushi, Zambia. The figure shows a fitted three-parameter Michaelis–Menten model (Eq. (6)), which estimates stable aggregate (c) at zero BC, maximum stable aggregates achievable (d) and BC carbon at half d (e). For 0.6–2 mm aggregates, c and $d = 25.5 \pm 1.9$ and 41.3 ± 4.9, respectively, and for 2–6 mm aggregates c and $d = 35.4 \pm 2.2$ and 51.4 ± 3.7, respectively ($p < 0.001$). Parameter $e = 0.4 \pm 0.4$ ($p > 0.05$) for both aggregate sizes tested. All parameters are ±SE.

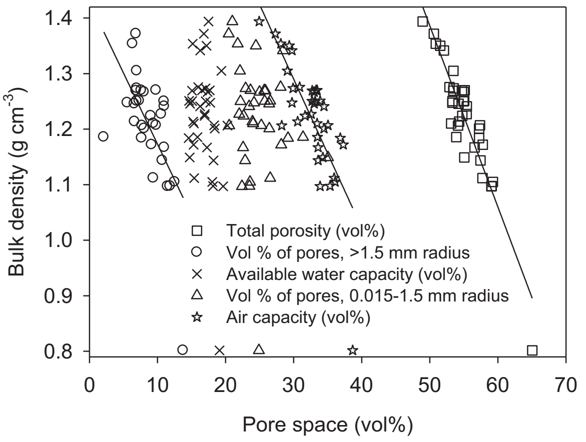

Fig. 2. Relationship of the bulk density and various components of the pore space in planting basins of Experiment A. Basic soil and BC properties are in Table 1.

radius 10–100 μm whereas coarse particle sizes of 1–5 mm followed a trend similar to that of the Kaoma soil.

Rice husk BC increased the proportion of the pores with radius 10–100 μm in the two soils, except for the ≤0.5 mm BC size fraction at Kaoma (Fig. S1). Generally, rice husk BC followed a similar pattern as maize cob BC of similar sizes in similar soils and at the same doses.

3.4. Available water capacity, air capacity and total porosity

In the planting basins at Mkushi (Experiment A), maize cob BC significantly ($p < 0.05$) increased AWC by 3% for each percent BC applied under both maize and soybeans ($p < 0.05$). In reference plots, the AWC was smaller under soybeans compared to maize ($p < 0.05$). There was also significant ($p < 0.05$) increase in FC and a non-significant effect on PWP (Table 3). Similarly, for Experiment B with controlled maize cob BC particle sizes, AWC increased for each of the size fractions, except for the intermediate (0.5–1 mm) BC particle sizes. The increase was between 7 and 9% per percent BC applied to both Mkushi and Kaoma soils ($p < 0.001$). There was also a significant increase in FC whereas PWP was not affected significantly (except BC of 1–5 mm particle size in Kaoma) for the soils at both Kaoma and Mkushi (Table 4). Rice husk BC had no significant effect on AWC in both Kaoma and Mkushi (Table S1).

The air capacity of the soil in the planting basins was 32% under soybeans and maize and was not affected by BC (Data not shown). On the other hand, BC significantly ($p < 0.01$) increased soil total porosity in the planting basins by 2% per percent BC applied (Table 3), but there was no difference between crops. Similarly, in Experiment B, there was no effect of BC on air capacity at both Kaoma (30%) and Mkushi (36%) (data not shown), whereas there was an increase in total porosity for all BC particle sizes in Kaoma soil ($p < 0.01$) and for the coarse 1–5 mm BC fraction in Mkushi ($p < 0.05$) (Table 4). Rice husk BC on the other hand increased both air capacity and total porosity (Table S1).

3.5. Soil shrinkage in core rings during water retention analysis

The soil volume in core rings decreased by 10–20% for samples taken from Experiment B at Mkushi during drainage of the saturated loamy sand soil in a water retention analysis as matrix potential decreased from zero to −100 hPa (Fig. 4). This effect depended on BC particle size and dosage (Fig. 4B). Consistent decrease in the soil volume with increasing dosage occurred in samples from 1–5 mm BC amended plots. Rice husk BC also caused an increase in shrinkage of Mkushi soil (Fig. 4C). The increase in soil volume shrinkage correlated positively with increase in soil porosity brought about by BC addition (Fig. 4A). The shrinkage was most influenced by porosity filled with water at matrix potential more than −10 hPa i.e. porosity composed of large pores with radius >150 μm (Fig. 4A).

4. Discussion

In this study, BC application changed the soil physical properties positively from an agronomic perspective. The changes in these properties, including increased soil aggregate stability and AWC in addition to reduced BD, are in line with results previously reported for soil incubated in the laboratory and greenhouse pot experiments (Mukherjee and Lal, 2013). The increase in aggregate stability may indicate that BC aids soil aggregation, which could at least partly be responsible for the increase in soil water retention and alteration of pore size distribution especially in the aggregated loamy soil at Mkushi. Besides soil aggregation, the high specific surface area (Table 1) and porosity of BCs compared to soil (Mukherjee and Lal, 2013) could have contributed to increase in water retention, particularly in the Kaoma sand (Table 4). From an agronomic perspective, the increase in AWC, generally low for the type of soils investigated in this study, is of major importance. Yields of maize crop significantly increased after application of maize cob BC in an earlier experiment established adjacent to the site of the current study at Kaoma (Martinsen et al., 2014). Low AWC with values less than 15% (v/v) and high air capacity (Section 3.4,Tables 3 and 4 and S1) render soil 'droughty or potentially droughty' (Reynolds et al., 2007). The effect of BC in increasing AWC under field conditions could also contribute to addressing the problem of uncertain rainfall patterns in Zambia (Yatagai, 2011). The increase in AWC due to maize cob BC addition in this study was more than that under laboratory condition for soils taken from the same sites at Kaoma and Mkushi (~2.5% versus 3–9% increase per percent BC added in this study) reported by

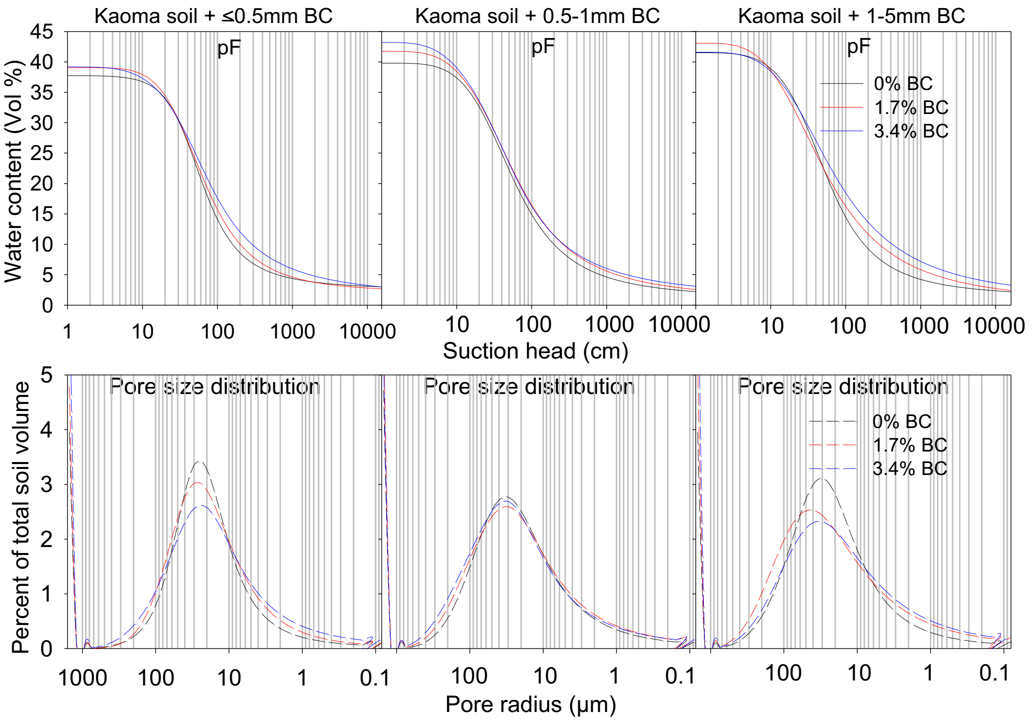

Fig. 3. Water retention curves fitted to van Genuchten equation and pore size distribution of sandy soils at Kaoma amended with maize cob BC of different particle sizes (Experiment B). Basic soil and BC properties are in Table 1.

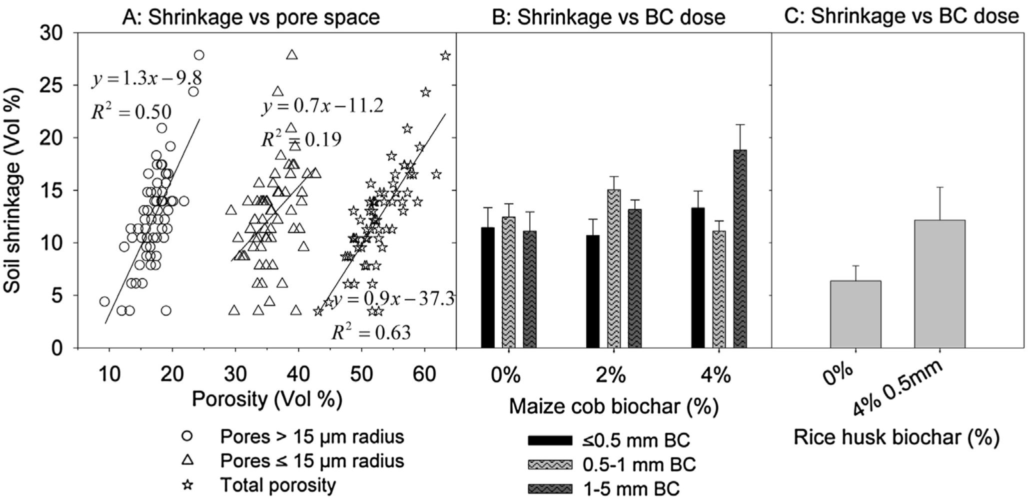

Fig. 4. Shrinkage of loamy sand at Mkushi (Experiment B) in the core rings during water retention study as a function of soil porosity. Basic soil and BC properties are in Table 1.

Martinsen et al. (2014). Maize cob BC addition to soils resulted in similar patterns but stronger net effect than rice husk BC on the soil physical properties, especially the hydraulic properties.

There was stronger increase in aggregate stability by BC under soybeans with slightly lower initial total organic carbon than under maize. In silt loam soils from New Zealand, Herath et al. (2013) also demonstrated that addition of corn stover and its corresponding BC increased aggregate stability. Stronger effects were also observed for soil with low initial total organic carbon (4%) than in soil with already high total organic carbon (10%). The increase in the stability of aggregates of Mkushi soils correlated positively with aggregate BC carbon, with strong responses at low BC carbon (Fig. 1). An optimal amount of BC carbon in aggregates occurred above which there was negligible increase in aggregate stability and this coincided with as low as 1–2% BC application rate (Fig. 1) in sandy loam soil of Experiment A. At these optimal BC carbon contents, the fraction of stable aggregates of soil increased from 25 to 35% and from 35 to 45% for 0.6–2 and 2-6 mm aggregates, respectively. This low BC carbon, which can potentially occur at low dose of BC, whilst producing a significant impact on the soil, is important given the potential difficulty in acquiring the large amount of BC for application to agricultural soil. Half the maximum stable aggregates occurred in the soil at its native state of total organic carbon and clay without BC addition (insignificant BC carbon = 0.4%, $p > 0.05$ at half the maximum stable aggregates based on Michaelis–Menten model). Probably, the native soil organic matter and the clay-size fraction (kaolinites, iron and aluminum oxides) in Mkushi soils contributed to binding of soil particles forming aggregates. The role of soil organic matter (Oades, 1984) and clay (Martin et al., 1955) in building soil aggregates are a rather well known phenomena.

The interaction between crop and BC addition on aggregate stability observed in this study (Experiment A) indicates an indirect effect of BC on soil aggregate stability. The application of BC in Experiment A enhanced root growth (Abiven et al., 2015) leading to increased root activity (e.g., releasing root exudates and moving soil particles aiding aggregate formation) in the planting basins. Root activity, together with the direct effect of BC acting as a binding agent of soil particles (Brodowski et al., 2006), could be responsible for the increase in aggregate stability relative to the reference plots. The higher root biomass of maize compared to soybeans (monocot vs dicot) (Amézketa, 1999) was probably the reason for higher organic carbon under maize than soybeans (Fig. S6). Organic carbon in the absence of BC was consistently higher for both 0.6–2 and 2–6 mm aggregates under maize than under soybeans (2–6 mm aggregates had 0.72% C under maize vs 0.53% under soybeans; 0.6–2 mm aggregates had 0.88% C under maize vs 0.56% under soybeans). Therefore, the higher aggregate stability under maize in the absence of BC compared to soybeans was most likely caused by higher root activity and organic matter e.g. root exudates as previously reviewed by Amézketa (1999). The difference in the stability of soil aggregates between maize and soybeans are also in accordance with the known effect of different plant species on aggregate stability e.g. Blanco-Canqui and Lal (2004); Reid and Goss (1981); Tisdall and Oades (1982).

The addition of BC to planting basins in sandy loams caused a reduction in soil BD, which was associated with an increase in soil porosity, particularly of the volume of macro-pores with radius >1.5 mm (Fig. 2) (Experiment A). This indicates that the build-up of soil macro-porosity, induced by BC was important, in addition to the direct weight dilution effect of BC on soil BD (Verheijen et al., 2009), which relates to BCs' light and porous nature. All BCs used in this study had a density of ~0.3 g cm^{-3} (Table 1) and weight dilution, assuming an increase in soil volume after BC addition, would result in a decrease in BD of 0.04 g cm^{-3} compared to the measured 0.05 g cm^{-3} per percent BC applied in Experiment A (maximum potential weight dilution contribution of 80%). Thus, minimum of 20% of the decrease in BD was due to increase in soil aggregation and not mere weight dilution. In fact, BD decreased with increasing stable aggregates (0.005 g cm^{-3} for every 1% increase in stable aggregates, data not shown). For the single-grained sandy soils at Kaoma (Experiment B), weight dilution was a more important factor than at Mkushi, contributing 0.05 g cm^{-3} compared to the measured 0.03 g cm^{-3} decrease in BD per percent BC applied (i.e. 160% contribution in decreasing BD; >100% means volume was not additive). In fact, in Kaoma sand, BC doses and not BC particle size played the main role in reducing BD, further pointing to the importance of a dilution effect in sandy soils. This is in contrast to the observations from the more loamy Mkushi soils (Experiments B), where both dose and BC particle size were important factors. Only coarse BC of 1–5 mm decreased BD in Mkushi, probably by creating packing voids forming weak pores.

The general lack of significant effects of BC on soil aggregate stability in BC particle size Experiment (B) (loamy sands at Mkushi) was probably caused by low stability of aggregates due to coarse texture. Only 0.5–1 mm BC in Experiment B at Mkushi resulted in a significant increase in stability of 0.6–2 mm soil aggregates (Table 4) probably because most of 0.5–1 mm BC was associated with 0.6–2 mm aggregates (Fig. S3). The low stability of soil pores in Experiment B caused structural collapse as shown by shrinkage of soil in core rings during the water retention study (Fig. 4). The tendency of increased soil shrinkage with BC addition is a potential indicator of initiation of soil structure build-up caused by BC. This collapse of soil structure in the core rings during water retention study makes it difficult to infer other soil properties (e.g., hydraulic conductivity) that rely on soil large pores from water retention curves without measuring them.

The reduced effect of 0.5–1 mm BC compared to smaller or larger BC particle sizes on soil hydraulic properties and pore size distribution (Table 4 and S1) of Experiment B was probably because 0.5–1 mm BC was within the sizes of soil particles dominating the sand and loamy sand soils. This would then result in minimal changes in the pore sizes of the soils.

5. Conclusions

In this work, we have demonstrated that BC can improve the physical condition of light-textured soils important for crop growth. Biochar increased soil aggregate stability, porosity and AWC and reduced soil bulk density. The fact that 'low dose' of BC of 1–2% impact soil properties (Experiment A) is important because large quantities of BC can be difficult to obtain. However, BC impact depends on soil texture (compare Experiments A & B in Mkushi, which was for two and one season, respectively): coarser textured loamy soils require more BC and time to produce any significant increase in aggregate stability. The BC particle size experiment (Experiment B) showed that the addition of larger particle size BCs, e.g. 1–5 mm, might result in equally strong positive effects on soil physical properties as powdery BC. Coarse BC eliminates the necessity of thorough crushing, and reduces dust formation during BC application. Maize cob BC additions resulted in stronger effects than rice husk BC on soil physical properties. Reduced density of soil due to BC-induced soil aggregation may aid root growth and with more water available, can increase crop growth and yields. Biochar application to highly weathered and sandy soils will therefore increase the soils' resilience against drought.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.still.2015.08.002.

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