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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 (≤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 ≤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 ≤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 small-holder 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.