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

Alfred Obia[a,b,*], Trond Børresen[a], Vegard Martinsen[a], Gerard Cornelissen[b,a], Jan Mulder[a]

[a] Faculty of Environmental Sciences and Natural Resource Management (MINA), Norwegian University of Life Sciences (NMBU), P.O. Box 5003, NO-1432 Aas, Norway
[b] Norwegian Geotechnical Institute (NGI), Department of Environmental Engineering, P.O. Box 3930, Ullevaal Stadion, NO-0806 Oslo, Norway

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

* Corresponding author at: Faculty of Environmental Sciences and Natural Resource Management (MINA), Norwegian University of Life Sciences (NMBU), P.O. Box 5003, NO-1432 Aas, Norway.
E-mail addresses: alfred.obia@nmbu.no, alfred.obia@ngi.no (A. Obia).

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

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.