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Effect of biochar on soil physical properties in two contrasting soils: An Alfisol and an Andisol

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ABSTRACT

Improving soil physical properties by means of biochar application has been proposed in recent publications. The objective of this study was to investigate to what extent the addition of corn stover (CS) and biochars produced from the pyrolysis of corn stover feedstock (CS) at 350 and 550 °C temperatures (CS-350, CS-550) affected aggregate stability, volumetric water content (θ_V), bulk density, saturated hydraulic conductivity (Ks) and soil water repellency of specific soils. Organic amendments (CS, CS-350, CS-550) were incorporated into a Typic Fragiaqualf (TK) and a Typic Hapludand (EG) soils at the rate of 7.18 t C ha^{-1}, which corresponded to 17.3, 11.3 and 10.0 t biochar ha^{-1} for the CS, CS-350 and CS-550 treatments, respectively. After 295 d of incubation (T295), soils were sampled as (i) undisturbed samples for bulk density and Ks; and (ii) mildly disturbed samples for θ_V (at −15, −1, −0.3, −0.1, −0.08, −0.06, −0.04, and −0.02 bar), aggregate stability and soil water repellency. The θ_V at time 0 (T0) was also determined at −15, −1 and −0.3 matric potentials for the different treatments. Biochar application significantly increased ($P < 0.05$) aggregate stability of both soils, the effect of CS-550 biochar being more prominent in the TK soil than that in the EG soil, and the reverse pattern being observed for the CS-350 biochar. Biochar application increased the θ_V at each matric potential although the effect was not always significant ($P < 0.05$) and was generally more evident in the TK soil than that in the EG soil, at both T0 and T295. Biochar addition significantly ($P < 0.05$) increased the macroporosity (e.g., increase in θ_V at −0.08 to 0 bar) in the TK soil and also the mesoporosity in the EG soil (e.g., increase in θ_V from −1 to −0.1 bar). Both biochars significantly increased ($P < 0.05$) the Ks of the TK soil, but only CS-350 biochar significantly increased ($P < 0.05$) the Ks in the EG soil. Biochar was not found to increase the water repellency of these soils. Overall results suggest that these biochars may facilitate drainage in the poorly drained TK soil. However, the present results are biochar-, dose- and soil-specific. More research is needed to determine changes produced in other biochar, dose and soil combination, especially under field conditions.

1. Introduction

Production of biochar from the pyrolysis of forest and crop residue has the potential to sequester atmospheric CO_2 into more stable soil C pools (Lehmann et al., 2009; Liang et al., 2010; Zimmerman, 2010). Agronomic benefits are mainly derived from the fertilizer value of biochar and its effects on the improvement of soil physical conditions, in particular, the soil water holding capacity and soil drainage characteristics. There is however a number of logistic and financial constraints limiting the immediate adoption of biochar as a greenhouse gas (GHG) mitigation strategy. Among these is the lack of sound economic evidence for its true agronomic value. When carbon dioxide credit values are low, a high agronomic value is important to offset the cost of biochar production. Obtaining an agronomic value is complicated because beneficial effects are dependent on the interaction between the different types of biochar and pedoclimatic conditions of the area where they are deployed. Therefore, a mechanistic understanding of these interactions is needed.

The use of biochar as a means to ameliorate soil physical properties and, particularly, the soil water holding capacity, has emerged after identifying its general high porosity (Hina et al., 2010; Liang et al.,

Abbreviations: CS, corn stover feedstock; CS-350, corn stover biochar produced at 350 °C; CS-550, corn stover biochar produced at 550 °C; TK, Typic Fragiaqualf/Tokomaru soil; EG, Typic Hapludand/Egmont soil; OC, organic carbon (soil); C_{org}, organic carbon (biochar/feedstock); θ_V, volumetric water content; Ks, saturated hydraulic conductivity; T295, after 295 d; T0, at time zero; GHG, greenhouse gas; AWC, available water content; RAWC, readily available water content; TPV, total soil pore volume; MWD, mean weight diameter; WDPT, water droplet penetration test; MED, molarity of ethanol droplet; SEM, scanning electron microscopy.

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2006) and large inner surface area (Kishimoto and Sugiura, 1985; Van Zwieten et al., 2009). The porosity of biochar depends on (i) the temperature of pyrolysis – increasing with increasing temperature up to ~750 °C (Schimmelpfennig and Glaser, 2011) – and (ii) the type of feedstock used (Calvelo Pereira et al., 2011; Hina et al., 2010). Pore sizes in biochar have been reported to range from <2 nm to >50 nm, with an increase in the small diameter pore fraction as temperature of pyrolysis increases (Downie et al., 2009). However, a high porosity in charcoal particles does not necessarily increase the amount of plant-available water in soil, as pore sizes <200 nm tend to retain water at greater water potential than that generated by plants (Lal and Shukla, 2004). Biochar–soil interactions through aggregation (Brodowski et al., 2006) and soil texture (Tryon, 1948) may in turn affect the soil moisture retention pattern of the biochar-amended soil as well as soil drainage. While microporosity and mesoporosity are primarily important to retain both available water content (AWC) and readily available water content (RAWC) of a soil, macroporosity influences on the hydraulic conductivity and aeration of soil.

Application of charred material to soil has been shown to have a clear effect on AWC and/or water holding capacity at field capacity (Chan et al., 2007; Glaser et al., 2002; Kammann et al., 2011; Tryon, 1948), although most experiments carried out to date on the effect of biochar on soil physical properties have used high rates of this amendment — 100 and 200 t ha^{-1} (Kammann et al., 2011); 50 and 100 t ha^{-1} (Chan et al., 2007); ~70 t ha^{-1} (Tryon, 1948), — which are not practically feasible at the farmer level. Studies using lower rates have only measured the water holding capacity at specific soil water potential and/or shortly after application to soil (Agusalim et al., 2010; Karhu et al., 2011; Laird et al., 2010). Moreover, the question arises whether the same level of soil physical improvement can be achieved by incorporation of the feedstock given the cost of biochar manufacture. Feedstocks such as manures and corn stover residues are prone to decompose rapidly (Torn et al., 2005; Weerakkody and Parkinson, 2006) and need to be applied in large quantity (between 50 and 200 Mg ha^{-1}) if significant undecomposed residues are to increase soil carbon, which is not affordable at a farm scale (Piccolo et al., 1996). Given the high stability of biochar in soils (Lehmann et al., 2009; Liang et al., 2010), long-term effects are expected in the context of soil water holding capacity and other physical properties if these are proven to occur. The effects of biochar on other soil physical properties, such as penetration resistance, hydraulic conductivity, bulk density, and soil structure, have not been fully evaluated in field conditions (Agusalim et al., 2010; Asai et al., 2009; Busscher et al., 2010; Chan et al., 2007; Glaser et al., 2002; Laird et al., 2010; Peng et al., 2011).

Under this context, we hypothesised that soil application of biochar could improve the water holding capacity (including AWC and RAWC) and drainage facility of soil. The objective of this study was to determine whether the addition of biochar produced from the pyrolysis of corn stover at two temperatures (350 and 550 °C) affects the volumetric water content (θ_V), aggregate stability, bulk density, saturated hydraulic conductivity (Ks), and water repellency of two contrasting soils. These were chosen as they have distinct organic carbon (OC) content, mineralogy and, consequently, distinct soil physical conditions.

2. Materials and methods

2.1. Biomass used and carbonisation process

Corn stover (*Zea mays*) (CS), with a cellulose, hemicellulose and lignin content of 38.3, 35.7 and 9.6%, respectively, was used as feedstock. The feedstock was first cut into pieces of 2.5-cm size with an electronic chipper, and thereafter cut to 5 mm using a cross-cutting mill. The material was dried for 24 h at 60 °C before pyrolysis. Two hundred grams of CS were pyrolysed at highest heating temperatures of 350 and 550 °C with an average heating rate of 36 and 51 °C min^{-1}, respectively, using a gas-fired, stainless steel, rotating drum kiln. When the desired temperature was reached, the kiln was allowed to cool to room temperature. The carbonised material was stored in sealed plastic bags until used. The two biochars produced were referred to as CS-350 and CS-550, respectively. The yield, biochar chemical composition, and recovery of C, N and S are reported in Table 1.

2.2. Particle-size distribution of biochar

Particle-size distribution of biochars was determined by dry sieving the samples using a sieve shaker (Endecott Test Sieve Shaker, Watson Victor Ltd.). Seven different fractions were obtained using 2.00, 1.00, 0.50, 0.25, 0.15, and 0.05 mm sieves (Fig. 1). Three consecutive shakings were conducted, as it was observed that the weight of different fractions remained unchanged thereafter. The first shaking was continued for 3 min; the other two shakings were only done for 2 min.

2.3. BET surface area and scanning electron microscope (SEM)

Measurements of N_2 gas adsorption for BET surface area determination of biochars were undertaken with a Micromeritics ASAP 2020 volumetric adsorption system. The surface physical morphology of the biochars at time 0 (T0) and after 295 d of incubation (T295, biochar particles separated from incubated soil) was examined by Quanta 200 equipment (FEI, Eindhoven, The Netherlands) after coating the particles with gold using a Bal Tec SCD 500 cool sputting device (Balzers Union, Wallruf, Germany).

2.4. Soil collection

Soil cores (0–10 cm) were taken from sampling areas of ~3 m^2 at two different sites: Manawatu (Tokomaru Silt Loam; TK soil) (40°17′ S, 175°24′ E, 24 m above sea level), and Hawera (Egmont Silt Loam; EG soil) (39°37′ N, 74°21′ E, 66 m above sea level) in New Zealand. The two soils are classified as Typic Fragiaqualf and Typic Hapludand (Soil Survey Staff, 2006), respectively. Both sites have been under permanent pasture for at least 50 years (Parfitt et al., 1984; Roberts and Thompson, 1984). The basic properties of these soils are given in Table 2. Soils were then thoroughly mixed, sieved to 5 mm, and stored in the cold room (temperature <4 °C) until used.

Table 1
Elemental analysis of feedstock and biochars and yield of biochar.

Sample	Chemical composition (%)						Biochar yield (%)	Atomic ratio (d.a.f.)[b]		Recovery (%)		
	C	N	H	O[a]	S	Ash		(H/C)	(O/C)	C	N	S
CS feedstock	41.4	0.83	6.08	40.66	0.13	10.9	n.a.	1.98	0.74	n.a.	n.a.	n.a.
CS-350	63.5	0.71	3.77	21.62	0.44	9.8	35.0	0.64	0.26	67.0	28.6	120.9
CS-550	71.8	0.76	2.92	13.55	0.12	11.5	27.0	0.45	0.14	56.6	21.0	25.0

n.a. — not analysed.
[a] Estimated by difference as O = 100 − (C + H + N + S + Ash).
[b] Dry ash free basis.