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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.

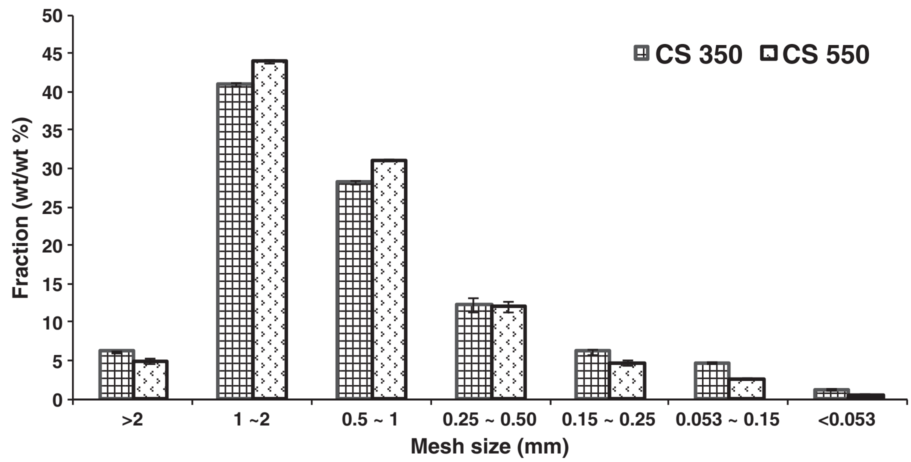

Fig. 1. Particle size distribution of CS-350 and CS-550 biochars.

2.5. Sample preparation, incubation and sampling

Biochars and fresh CS were incorporated into soils at a rate of 7.18 t C ha^{-1}, which corresponds to the following application rates: 17.3, 11.3, and 10.0 t ha^{-1} of CS, CS-350, and CS-550 amendments, respectively. This was achieved by adding 1.73, 1.13, and 1.00 g 100 g^{-1}, respectively, for the TK soil, and 2.30, 1.50, and 1.33 g 100 g^{-1}, respectively, for the EG soil (oven dry wt/wt basis), based on the initial bulk densities of the soils. A control, without organic amendment, was also prepared for each soil. The amendments were evenly mixed with soils and the mixtures were packed into PVC columns (15 cm in diameter and 10 cm in height) based on pre-calculated bulk densities, which included the contribution of the amendments to the final bulk density. Treatments were run in triplicates ($n = 3$) and identified as follows: (i) control treatments (TK-Ctr, EG-Ctr), (ii) fresh corn stover (TK-CS, EG-CS), (iii) low-temperature biochar (TK-350, EG-350), and (iv) high-temperature biochar (TK-550, EG-550). Soil water content was returned to 70% field capacity (w/w) every 2 d throughout the experiment. The soil columns were stored in a chamber provided with an open plastic container of 2 L of water to maintain the moisture of the atmosphere and thus minimising water evaporation from soils, while allowing air circulation. The average room temperature was ~20 °C (Herath, 2012). After 295 d of incubation, undisturbed ring samples (5 cm in height × 4.8 cm in diameter) were taken for the determination of Ks and bulk density. Samples also were taken for the determination of soil WHC, aggregate stability, and soil water repellency.

2.6. Determination of soil physical properties

2.6.1. Aggregate stability

Aggregate stability at T295 was determined according to Le Bissonnais's (1996) method. Air-dried samples were forced through 4.75 and 3 mm sieves, sequentially, and the 3–4.75 mm size aggregates were selected for the analysis. Three different procedures were applied by simulating conditions at the laboratory level following Le Bissonnais (1996) using five replicates in each: (i) procedure I (fast wetting) simulated a heavy rain storm in summer; (ii) procedure II (slow wetting) corresponded to a field condition of wetting under gentle rain; and (iii) procedure III, where samples were exposed to a mechanical breakdown by shaking after pre-wetting. At the end of all procedures, dry sieving was carried out using a column of six sieves: 2, 1, 0.5, 0.2, 0.1 and 0.05 mm. The mean weight diameter (MWD), which represents the aggregate stability, was calculated as follows:

$$MWD = \sum_{i=1}^{n} X_i W_i \quad (1)$$

where *Xi* the mean diameter of each size fraction (mm) and *Wi* the proportion of the total sample mass in the corresponding size fraction.

2.6.2. Soil water holding capacity measurements

Moisture contents of the samples at T295 were measured at different matric potentials (−15, −1, −0.3, −0.1, −0.08, −0.06, −0.04, and −0.02 bar). At T0, they were measured at −15, −1, and −0.3 bar matric potentials. Haines' apparatus was used to determine the moisture contents from −0.08 to 0 bar pressures, while suction plate was used for −0.1 bar matric potential. Five- and 15-bar pressure plate apparatus were used to measure the water contents at −0.3 and −1 bar, and −15 bar, respectively (Dane and Hopmans, 2002). Gravimetric analysis was undertaken to determine the moisture contents and these were converted to volumetric basis using the corresponding bulk density values. Total porosity was estimated as (i) the volume equivalent to the moisture content at saturation using slightly disturbed samples, and (ii) as the volume equivalent calculated using a soil particle density of 2.65 g cm^{-3}. Both estimations provided similar values and only the former are reported.

2.6.3. Saturated hydraulic conductivity and bulk density

Saturated hydraulic conductivity was measured using a constant head permeameter (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands). The bulk density of each undisturbed sample (5 cm in height × 4.8 cm in diameter) was also measured.

2.6.4. Soil water repellency

The water droplet penetration test (WDPT) was conducted to quantify the persistence of soil water repellency and the molarity of ethanol droplet (MED) test to determine the degree of water repellency. For the potential WDPT, samples were prepared as described by Kawamoto et al. (2007). Thereafter, the time taken from the initial contact of the water droplet until complete penetration into the soil layer was recorded (Dekker and Jungerius, 1990; Täumer et al., 2005). For the MED test, soil samples were prepared similarly to the WDPT. Once the suitable molarity – for which the ethanol drops did not penetrate within 10 s – was identified, the contact angle was

Table 2
Basic properties of the TK and EG soils.

Soil	Texture	Bulk density (g cm^{-3})	OC[a] (g C kg^{-1} soil)	Total N (%)	pH–H_2O
Typic Fragiaqualf	Silt loam	1.13	41.7	0.32	5.7
Typic Hapludand	Silt loam	0.75	102.0	0.64	5.8

[a] OC — organic carbon (total C content).

calculated using the average value of the detected and the immediate high molarities (Deurer and Müller, 2010).

2.7. Statistical analysis

The statistical differences between the treatments under study were determined by analysis of variance (ANOVA) using SPSS software (General Linear Model, Multivariate) with version 16.0 (SPSS Inc., Chicago, USA). Post hoc analysis were computed using Duncan test at $P = 0.05$.

3. Results

3.1. Pyrolysis yield and biochar characteristics

Yield of CS-350 biochar (i.e., the mass ratio of biochar recovered after pyrolysis and the initial feedstock) was 35.0%; that of CS-550 biochar was 27.0% (Table 1). As expected, biochar C content (635 and 718 g kg^{-1} C for CS-350 and CS-550, respectively) was high compared with the original feedstock (413 g kg^{-1}). Recovered C, which is the proportion of the original C retained in the biochar sample, decreased with the increase of pyrolysis temperature (67.0 and 56.6% for CS-350 and CS-550 biochars, respectively) (Table 1). As the amount of inorganic C was <0.9% (data not shown), total C was considered organic C (C_{org}). The elemental concentrations of H and O were always higher in the CS-350 biochar than in the CS-550 biochar. As such, the H/C_{org} and O/C_{org} atomic ratios decreased as temperature of pyrolysis increased (Table 1), as did the volatile fraction (from 31.2 to 18.5%). Conversely, the fixed C content increased with the increase of temperature from 57.2 to 67.4% for CS-350 and CS-550 biochars, respectively, as did the pH and the ash contents (Table 1).

The particle-size distribution of two biochars is reported in Fig. 1. Most particles were >0.25 mm in diameter, irrespective of pyrolysis temperature. This fraction corresponded to 88 and 92% for the CS-350 and the CS-550 biochars, respectively.

3.2. Aggregate stability

With few exceptions, biochar and fresh CS application significantly ($P < 0.05$) improved the aggregate stability of both soils (Fig. 2). In the TK soil, biochar amendment improved the aggregate stability (based on procedure I) by >17% compared with the control; based on procedures II and III, this increase was smaller, ranging from 4 to 16%. The effect of fresh CS application on aggregate stability of the TK soil was 14, 8 and 16% for procedures I, II and III, respectively. In the EG soil, increased aggregate stability due to biochar addition compared with the control was not as prominent as in the TK soil, with values ranging from 7 to 15%, while no effect was observed for the CS-550 treatment when following procedure II. Fresh CS only improved the aggregate stability of the EG soil in procedures II and III (by 6 and 10%, respectively).

3.3. Soil water holding capacity

3.3.1. Effect of biochar on soil water holding capacity at T0

Immediately after biochar application a significant increase ($P < 0.05$) in θ_V at −0.3, −1 and −15 bar was observed compared with the corresponding unamended controls (Table 3). Application of fresh CS showed a similar trend, although the effect was not always significant at $P < 0.05$. The increase of θ_V in the presence of biochars at −0.3 bar was 6% in the TK soil and 11–12% in the EG soil. At −15 bar, the increase of θ_V in fresh CS, CS-350 and CS-550 treatments was 15, 13 and 10% in the TK soil; in the EG soil this was only observed for the biochar treatments (6 and 10%, respectively). Temperature of pyrolysis did not affect the θ_V at the matric potentials tested, except at −1 bar pressure in the EG soil, with the soil amended with CS-350 biochar having a significantly ($P < 0.05$) greater water holding capacity than that amended with CS-550 (Table 3). The AWC was calculated as the difference between θ_V at −0.3 and −15 bar; the biochar amendments significantly increased ($P < 0.05$) the AWC in the EG soil, with values of 21 and 17% for the CS-350 and CS-550 biochar treatments, respectively. No significant effect ($P < 0.05$) of the organic amendments on AWC was observed in the TK soil. RAWC calculated as the difference in θ_V at −0.3 and −1 bar tended to decrease with the organic amendments, this decrease being significant ($P < 0.05$) in both soils for the fresh CS, and for CS-350 biochar in the EG soil.

3.3.2. Effect of biochar on soil water holding capacity after 295 d

After 295 d, all amendments increased the θ_V of both soils compared with the controls; however, this increase was only significant ($P < 0.05$) at a particular range of matric potentials (0 to −0.08 and −0.3 bar in the TK soil, and −0.08 to −1 bar in the EG soil; Table 4). At low tensions (>−0.1 bar), high-temperature biochar had a greater effect on increasing the θ_V than the low-temperature biochar, but the effect was only significant ($P < 0.05$) at saturation in the TK soil, and at −0.1 bar in the EG soil (Table 4). Incubation for 295 d increased θ_V at the three common matric potentials investigated (−0.3, −1 and −15 bar) for all the treatments with respect to T0 (Tables 3 and 4). However, that increase was only significant ($P < 0.05$) at −0.3 and −15 bar matric potentials.

At T295, biochar-amended soils tended to have greater water holding capacity than those amended with fresh CS, although these differences were only significant at $P < 0.05$ for the TK soil at saturation. The amendments had no significant effect ($P < 0.05$) on the AWC of both soils, but a general increasing trend was observed, especially in biochar-amended soils, compared with the controls. Differences

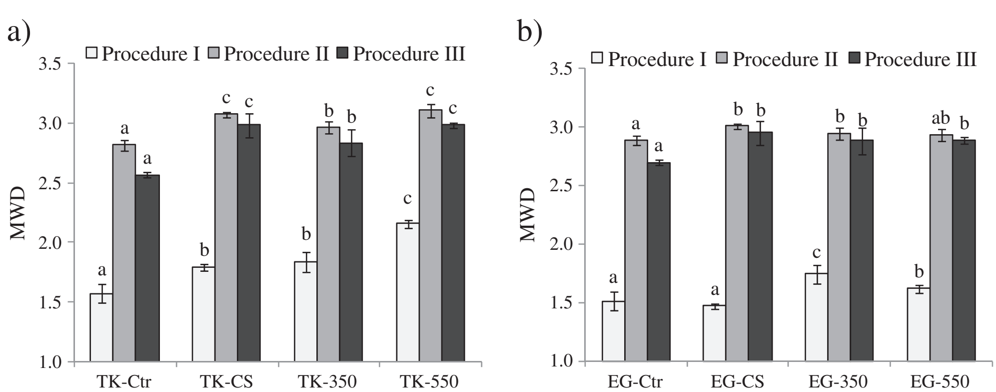

Fig. 2. Aggregate stability as given by MWD determined using the Le Bissonnais (1996) method for the (a) TK soil, and (b) EG soil at T295. Minimum significant (alpha = 0.05) differences between any two means of a specific procedure are based on the Duncan post hoc test, and different letters denote the significant differences between treatments when tested with a specific procedure in each soil.

Table 3
Mean ($n = 3$) volumetric soil moisture contents measured at different matric potentials, AWC and RAWC immediately after establishment (T0) of soil–feedstock and soil–char mixtures. Least significant (alpha = 0.05) differences between any two means are based on the Duncan post hoc test, and different letters denote the significant differences between treatments in each soil.

Treatment	−15 bar	−1 bar	−0.3 bar	AWC[a]	RAWC[b]
TK-Ctr	0.1300a	0.1767a	0.2200a	0.0867a	0.0433b
TK-CS	0.1500b	0.2100c	0.2200a	0.0700a	0.0100a
TK-350	0.1467b	0.2000b	0.2333b	0.0833a	0.0300b
TK-550	0.1433b	0.2033bc	0.2333b	0.0800a	0.0300b
EG-Ctr	0.2100a	0.2400a	0.3067a	0.0967a	0.0667b
EG-CS	0.2133a	0.2733b	0.3167a	0.1034a	0.0467a
EG-350	0.2233b	0.2900d	0.3400b	0.1167b	0.0500a
EG-550	0.2300b	0.2800c	0.3433b	0.1133b	0.0600b

[a] AWC — available water content.
[b] RAWC — readily available water content.

Table 5
Analysis of variance (ANOVA) for the effect of treatment and time on AWC and RAWC of the TK and EG soils. The signification of the ANOVA is given: ** — significant at $P \leq 0.01$; * — significant at $P \leq 0.05$; n.s. — not significant.

Source		DF[a]	AWC[b]	RAWC[c]
Model	TK soil	7	*	**
	EG soil	7	n.s.	n.s.
Treatment	TK soil	3	n.s.	n.s.
	EG soil	3	*	n.s.
Time	TK soil	1	*	**
	EG soil	1	n.s.	n.s.
Treatment × time	TK soil	3	n.s.	**
	EG soil	3	n.s.	n.s.

[a] DF — degree of freedom.
[b] AWC — available water content.
[c] RAWC — readily available water content.

were more evident for the RAWC in the TK soil, as the organic amendments significantly increased ($P < 0.05$) the RAWC by 133, 100, and 78% for the fresh CS, CS-350 and CS-550, respectively, compared to the control treatment at the same sampling time (Table 4). Compared to T0, AWC and RAWC significantly increased ($P < 0.05$) in the TK soil after 295 d, but not in the EG soil (Table 5). A significant ($P < 0.01$) interactive effect of treatment × time was observed in the RAWC of the TK soil (Table 5).

3.4. Effect of biochar on soil porosity

Total soil pore volume (TPV) was estimated based on the water content of the soil samples at saturation (0 bar) (Table 4). After 295 d, TPV of the TK soil significantly increased ($P < 0.05$) with the addition of organic amendments compared with the corresponding control soil (13, 10, and 19% for the fresh CS, CS-350, and CS-550, respectively). No significant ($P < 0.05$) differences in TPV were observed in the EG soil. The macropore volume – calculated based on θ_V data – significantly ($P < 0.05$) increased with the amendments in the TK soil (13, 7 and 20% for the TK-CS, TK-350 and TK-550, respectively), but not in the EG soil. No significant changes ($P < 0.05$) were observed in the meso- and micro-pore volume of these soils, although there was a general increasing trend for most of the amended treatments.

3.5. Hydraulic conductivity

Application of amendments had a significant ($P < 0.05$) effect on the hydraulic conductivity values at saturation (Ks) after 295 d of incubation (Fig. 3). In the TK soil, the lowest Ks value was observed in the TK-Ctr (2.8 10^{-5} m s^{-1}). TK-CS, TK-350 and TK-550 treatments had Ks values of 4.2 10^{-5}, 3.7 10^{-5}, and 6.7 10^{-5} m s^{-1} respectively, which corresponded to a Ks increase of 50, 32 and 139%, respectively. The effect of the amendments on the Ks of the EG soil was only significantly different ($P < 0.05$) for the CS-350 treatment, with a 41% increase.

3.6. Bulk density

Amended TK soils had significantly smaller ($P < 0.05$) bulk densities (0.93, 0.94, and 0.91 g cm^{-3} for the fresh CS, CS-350 and CS-550 amended soils) than the control (1.01 g cm^{-3}) (Fig. 4). Bulk densities of the EG soil treatments were not significantly different ($P < 0.05$) and values were always below 0.8 g cm^{-3}, as expected for an Andisol (Soil Survey Staff, 2006).

3.7. Soil water repellency

The two contrasting soils fall in either WDPT class 1 (TK soil) or 2 (EG soil) (Täumer et al., 2005) (Table 6). No changes in WDPT classes occurred as a result of biochar addition, the only exception being the EG-350 treatment, which fell into class 1. The results obtained with the MED test – used to determine the contact angle – showed a similar trend. The smallest contact angle was observed in the CS-350 biochar-amended TK and EG soils (92.5 and 92.9°, respectively), although only the latter was significantly different ($P < 0.05$) from the control. For the remaining treatments, contact angles ranged between 93.4 and 95.5° (Table 6).

4. Discussion

This research forms part of a long term study in which, the rates of decomposition of native soil organic matter as influenced by biochar and crop residue addition have been investigated (Herath, 2012). This paper reports the changes in soil physical properties that were observed on addition (T0) and 295 d (T295) after addition of the CS residue and biochars to two soils that have contrasting mineralogy. To place in context the changes in soil organic C that had occurred during the 295 d incubation we give the following brief description.

Table 4
Mean ($n = 3$) volumetric soil moisture contents measured at different matric potentials, AWC and RAWC after 295 d of incubation of soil–feedstock and soil–char mixtures (T295). Minimum significant (alpha = 0.05) differences between any two means are based on the Duncan post hoc test, and different letters denote the significant differences between treatments in each soil.

Treatment	−15 bar	−1 bar	−0.3 bar	−0.1 bar	−0.08 bar	−0.06 bar	−0.04 bar	−0.02 bar	0 bar	AWC[a]	RAWC[b]
TK-Ctr	0.1450a	0.1950a	0.2250a	0.3200a	0.3150a	0.3350a	0.3650a	0.4100a	0.5850a	0.0850a	0.0300a
TK-CS	0.1567a	0.1900a	0.2533b	0.3200a	0.3500b	0.3733ab	0.4267b	0.4833b	0.6600b	0.0967a	0.0700b
TK-350	0.1533a	0.2000a	0.2600b	0.3433a	0.3633b	0.3867b	0.4100b	0.4833b	0.6433b	0.1033a	0.0600b
TK-550	0.1567a	0.2067a	0.2600b	0.3533a	0.3733b	0.3967b	0.4200b	0.5000b	0.6933c	0.1033a	0.0533ab
EG-Ctr	0.2200a	0.2533a	0.3100a	0.3867ab	0.4267a	0.4800a	0.5033a	0.5833a	0.7133a	0.0900a	0.0600a
EG-CS	0.2333a	0.2667a	0.3200ab	0.3833a	0.4600b	0.5033a	0.5467a	0.6033a	0.7400a	0.0867a	0.0567a
EG-350	0.2400a	0.3000b	0.3600b	0.4133b	0.4533ab	0.4900a	0.5267a	0.5867a	0.7533a	0.1200a	0.0600a
EG-550	0.2433a	0.2767ab	0.3467ab	0.4167c	0.4567ab	0.4967a	0.5500a	0.6100a	0.7533a	0.1067a	0.0733a

[a] AWC — available water content.
[b] RAWC — readily available water content.

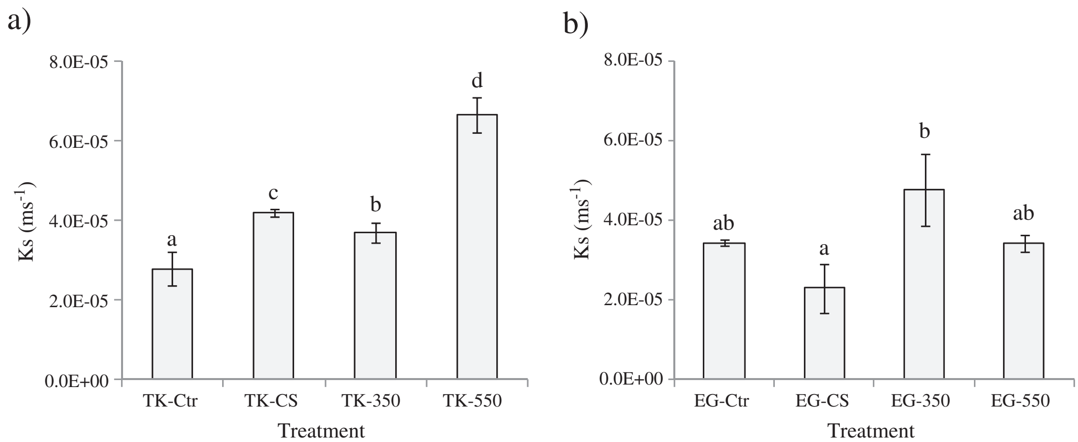

Fig. 3. Saturated hydraulic conductivity (Ks) determined for the (a) TK soil, and (b) EG soil at T295. Minimum significant (alpha = 0.05) differences between any two means are based on the Duncan post hoc test, and different letters denote the significant differences between treatments in each soil.

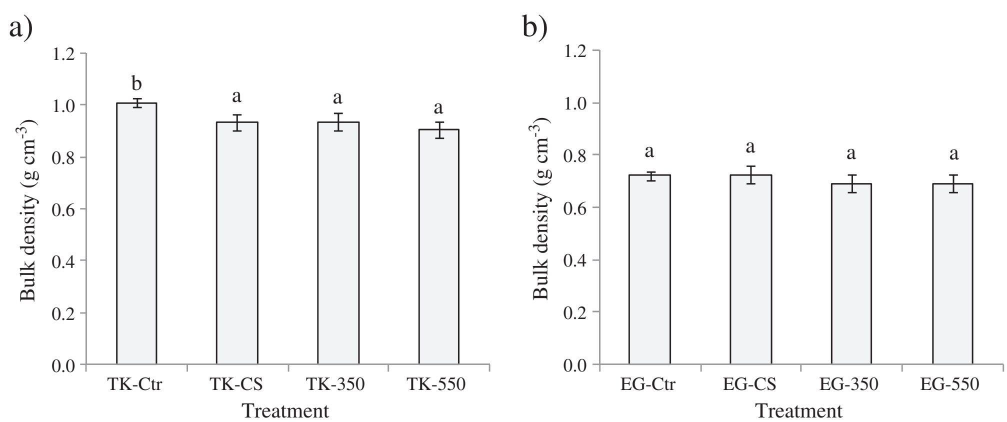

Fig. 4. Bulk density determined for the (a) TK soil, and (b) EG soil at T295. Minimum significant (alpha = 0.05) differences between any two means are based on the Duncan post hoc test, and different letters denote the significant differences between treatments in each soil.

The initial soil OC content was 41.7 and 102.0 g C kg^{-1} in the TK and EG soils, respectively (Table 2). The TK and EG soils received 5.6 and 6.3 g C kg^{-1}, respectively, as biochar or feedstock amendment. The decline in OC after 295 d of incubation ranged between 6.3 and 9.3%. Soil OC contents and pH values of the soils at T295 are reported in Table 7. Biochar addition to soils immediately increased soil pore volume per unit mass and this is discussed below under the section 'total soil porosity'.

Table 6
The persistence and the degree of water repellence determined for the fresh and charred CS amended soils from the incubation experiment after 295 d. Minimum significant (alpha = 0.05) differences between any two means are based on the Duncan post hoc test, and different letters denote the significant differences between treatments in each soil.

Treatment	WDPT[a] class	Contact angle
TK-Ctr	1	93.7a
TK-CS	1	94.3a
TK-350	1	92.5a
TK-550	1	93.4a
EG-Ctr	2	95.5b
EG-CS	2	95.5b
EG-350	1	92.9a
EG-550	2	94.2ab

[a] WDPT — water droplet penetration test (Täumer et al., 2005).

4.1. Soil aggregation

Enhanced formation of microaggregates – defined as those with a diameter <250 μm (Six et al., 2000) – with biochar application after 295 d of incubation was not observed in this study (data not shown). It was not an un-expected result because the creation of soil aggregates is a function of biological activity and time and unlikely to occur immediately upon biochar application. In addition the biochar used was a coarse particle size (≥0.5 mm), which may have limited soil–microbe–biochar interactions. Brodowski et al. (2006), when studying a long term field experiment site (25–85 y), suggested the role of charcoal contributing to the formation of microaggregates. Longer term studies are probably needed to assess the influence of biochar on formation of microaggregates.

In the present study at 295 d, an increase in aggregate stability was observed in amended treatments compared with the controls particularly in those to which biochar was added. This was probably associated with the formation of water-stable macroaggregates. These store more water than small aggregates (Liu et al., 2011) by increasing the total pore volume (Aggelides and Londra, 2000). The enhanced formation of slaking-resistant macroaggregates with exogenous amendments has been observed to occur within a few weeks (Clark et al., 2009; Wortmann and Shapiro, 2007) to several years (Liu et al., 2011). Macroaggregate stability in CS-amended soils was also higher than that of the control (except for the procedure I in the EG soil; Fig. 2). The increased aggregate stability in soils to which

Table 7
Total C and soil pH (H_2O) data determined after 295 d of the incubation study. Minimum significant (alpha = 0.05) differences between any two means are based on the Duncan post hoc test, and different letters denote the significant differences between treatments in each soil.

Sample	Total C (g C kg^{-1} soil plus amendment)	pH (H_2O)
TK-Ctr	38.1a	4.82a
TK-CS	41.5b	5.12a
TK-350	43.5c	5.05a
TK-550	42.7c	5.06a
EG-Ctr	96.5a	5.04a
EG-CS	97.9a	5.14a
EG-350	101.1b	5.13a
EG-550	102.7c	5.21a

organic amendments have been added has also been related to an increase in microbially-produced polysaccharides (Angers et al., 1993), especially those from fungi (Tiessen and Stewart, 1988). In fact, the SEM pictures taken after 295 d confirmed the presence of fungal hyphae within biochar pores (Fig. 5).

The observed resistance of the two soils against fast wetting (procedure I) in the biochar-amended pots (Fig. 2) denotes the higher aggregate stability provided by this amendment. In contrast to our findings, Peng et al. (2011) did not observe any effect of biochar on soil aggregation using the Le Bissonnais method; however, they determined the aggregate stability only after 11 d of incubation study. Differences observed in this study for MWD between the three procedures are in accordance with other studies using organic amendments other than biochar (Leroy et al., 2008a,b). CS-350 biochar had a greater effect on aggregate stability in the EG soil than that in the TK soil, while the opposite was observed for CS-550 biochar. More research is needed to understand the mechanisms of these different responses.

4.2. Total soil porosity

The observed overall increase of soil pore volume caused by the organic amendments was mainly attributed to the dilution effect of a low bulk density amendment to the soil (Bhogal et al., 2009; Hati et al., 2007; Soane, 1990), although the contribution of macroaggregate formation cannot be disregarded particularly after 295 d. However, as differences between the bulk density of the organic amendments and the soil were greater in the TK soil (soil bulk density = 1.13 g cm^{-3}) than in the EG soil (soil bulk density = 0.75 g cm^{-3}), the effects in the final total porosity were also more evident in the TK soil (Table 3). Other studies have noted an increase in total pore volume of soils caused by the application of biochars (Jones et al., 2010; Oguntunde et al., 2008; Teixeira and Martins, 2003) and other organic amendments (Aggelides and Londra, 2000; Bhogal et al., 2009; Du et al., 2009) but have not reported whether change occurred in micro- or macro-pore volumes. The newly created pore volume in the TK soil was mostly associated with macroporosity. As indicated before, most of the biochar particles (~90%) were found to be ≥0.5 mm (Fig. 1); these particles can create additional pore spaces by settling in between the particles of the matrix, without clogging pores, thus contributing to the generation of macroporosity (Steiner et al., 2011). The effect of biochar on the porosity of the EG soil after 295 d of incubation was more apparent at high tensions, and was attributed to the contribution of biochar to microporosity (Tseng and Tseng, 2005), as suggested by Novak et al. (2009). This

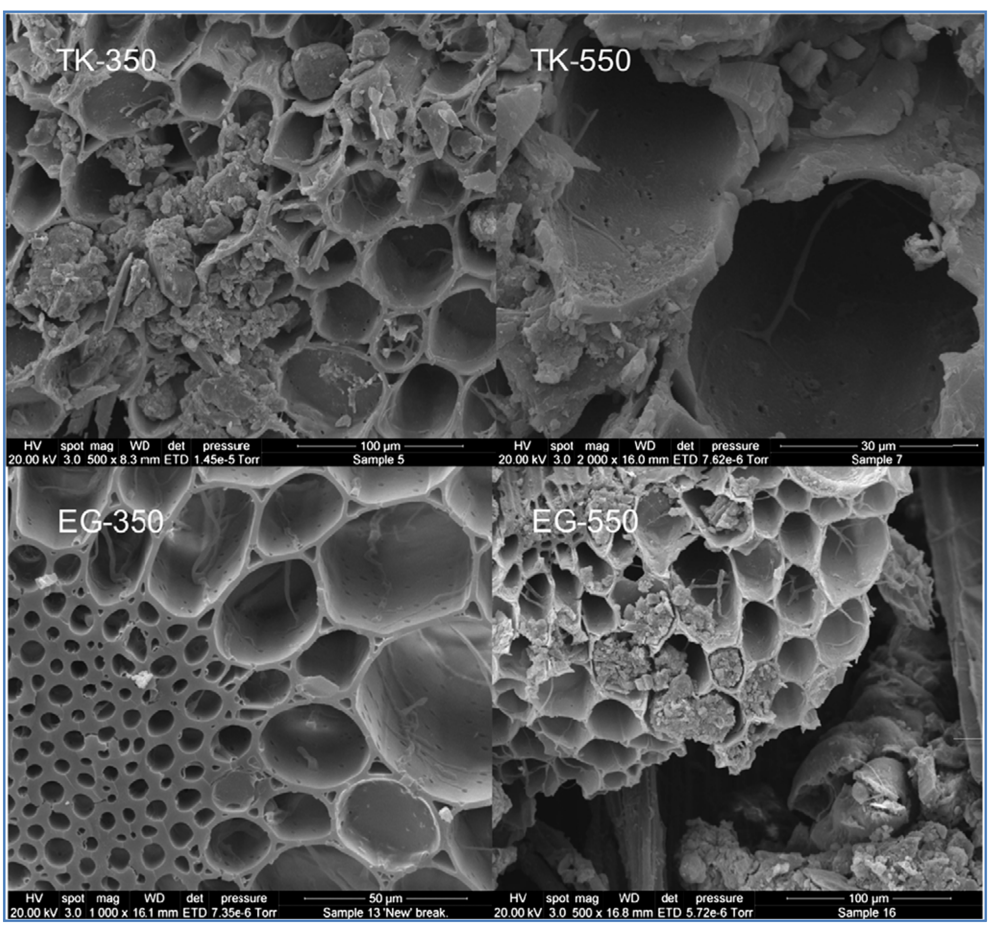

Fig. 5. The SEM images of CS biochar particles picked out from the experimental pots after 295 d.

was less evident in the TK soil, as this soil has a greater fraction of fine particles (silt and clay) than the EG soil.

4.3. Water holding capacity at different matric potentials

At a specific matric potential, the EG soil had always greater values of θ_V than the TK soil (Tables 3 and 4), which were attributed (i) to the greater native OC content of the former (102 g C kg^{-1} soil vs. 42 g C kg^{-1} soil), and (ii) to the presence of short-range order inorganic compounds (e.g., allophane) (Shoji et al., 1996). The nature of these two soils and specifically the different types of reactive surfaces of these soils have been discussed previously (Bolan and Baskaran, 1997). The observed increase in θ_V at any matric potential in both TK and EG soils after the addition of biochar at time 0, compared to the respective control treatments, is to a large extent related to the increase of macroporosity caused by the dilution effect. The effect of the CS amendment at T0 was less apparent, especially in the EG soil. The specific increase in soil θ_V observed in biochar-amended soils over 295 d (barely seen in the fresh CS-amended soils) can be likely related to the oxidation of biochar surfaces, with the subsequent increase in hydrophilicity (Zimmerman, 2010). In the TK soil, this effect was however only evident at low tensions (≥–0.3 bar), which corresponds to water mostly retained in macropores. In the EG soil, the effect of biochar was observed in a fraction of the meso- as well as macro-pore range (from −0.08 to −1 bar), but not in the −0.06 bar to saturation range.

For both the Alfisol (TK soil) and the Andisol (EG soil), water retained at −0.3 bar was considered as field capacity based on their textural properties (Nachabe, 1998) (Table 2). After 295 d incubation, field capacity increased by 16% in the TK soil and by 12–16% in the EG soil. These proportional increases are above those values obtained by Zeelie (2012) who used similar application rates of biochar made from pine saw mill waste pyrolysed at 450 °C temperature to amend a sandy soil. An increase of field capacity by 18% has also been reported for Anthrosols rich in charcoal (Glaser et al., 2002), although the historical application rates were not identified. Conversely, Busscher et al. (2010, 2011) found no effect on the water held at field capacity when biochar – produced at 700 °C from pecan shell – was applied to a Typic Kandiudult (a loamy sand soil).

There was no sizeable difference in θ_V at T295 between the TK soil or the EG soil when amended with biochar (either CS-350 or CS-550), except for specific matric potentials. The θ_V at permanent wilting point of both soils amended with CS-550 biochar was greater than the corresponding ones amended with CS-350 biochar. This is attributed to the increased biochar microporosity (Hina et al., 2010; Liang et al., 2006) achieved with increasing the maximum pyrolysis temperature (Kishimoto and Sugiura, 1985; Van Zwieten et al., 2009). However, BET surface area was found negligible in both biochars (data not shown). The increase in microporosity with time (data not shown) could be attributed to the dissolution of the ash fraction that was initially clogging micropores in the charcoal. However, more research is needed to prove this.

4.3.1. Available water content

In a climate with variable periodic rainfall an increase in AWC can cause increased plant growth (Uzoma et al., 2011; Van Zwieten et al., 2010; Yamato et al., 2006). Therefore, the extra AWC generated due to biochar application may help to decrease the irrigation frequency during dry spell and also will allow the plants to survive a longer time. The general increase in soil θ_V at T0 was not always paralleled by an increase in AWC. In fact, this was only observed in the EG soil amended with biochar. Moreover, the RAWC at T0 tended to decrease with organic amendment, although not always significantly at $P < 0.05$. Therefore, whereas the available water content of these two soils increased in the presence of organic amendments at T0, it is apparent that the plant water potential may need to become more negative in order to absorb water from the amended soils compared with plants growing in the control soils. Nonetheless, this decrease in RAWC was only observed at the start of the experiment.

At the end of the incubation (T295), the increase in AWC in the biochar-amended soils compared with the mean value of the unamended control was 22% in the TK soil and 19–33% in the EG soil, and is in agreement with other studies where biochar was applied to soil (Chan et al., 2007; Glaser et al., 2002; Tryon, 1948). However, those experiments used high rates of biochars, 50 and 100 t ha^{-1} (Chan et al., 2007), and ~70 t ha^{-1} (Tryon, 1948), which are not economically feasible at the farmer level. An increase of ~16% in AWC after the application of rice husk biochar, has been observed by Agusalim et al. (2010) using similar rates (10 t ha^{-1}) to the present study. Importantly, an increase in RAWC was observed after biochar application, especially in the TK soil, for all amendments, and in the EG soil for the CS-550 amended soils (although the latter was not significant at $P < 0.05$). This increase would be important particularly during dry spells in cropping seasons to keep more water stored in biochar-amended soils that is available for the plants' growth.

4.4. Hydraulic conductivity

The results on Ks followed a similar trend to that of aggregate stability in that the effect of CS-550 biochar was more prominent in the TK soil than that in the EG soil, whereas the reverse effect was observed for the CS-350 biochar. The increase in Ks agrees with the increase in the overall porosity of these soils. Development of macroporosity causes the hydraulic conductivity to increase, which reflects the drainage level of a given soil (Azooz and Arshad, 1996; Heard et al., 1988; Logsdon et al., 1990). As expected, the improvements observed in the Ks due to biochar application were corroborated by the increases of macropore volume, in particular in the poorly-drained TK soil.

The effect of fresh CS on the Ks of these two soils was opposite, with an increase in the TK soil and a decrease in the EG soil. The overall effect of the organic amendments on the Ks of the TK soil can have positive implications if aeration is to be increased in this poorly drained soil. However, the extent of this benefit will always depend on how the soil layer underneath the amended soil responds to drainage. Oguntunde et al. (2008) found comparable improvements of Ks from 7.5 10^{-6} m s^{-1} in unamended soil to a Ks of 1.3 10^{-5} m s^{-1} in charcoal amended soils under field conditions. Uzoma et al. (2011) reported Ks values several-folds higher than those of the present study using similar doses of biochar of 10 to 20 t ha^{-1} but working with a sandy soil (sand 95%, bulk density ~1.5 g cm^{-3}). Laird et al. (2010), however, found no effect of biochar (~5–20 t ha^{-1}) made from mixed hardwood on the Ks of a Typic Hapludoll.

4.5. Hydrophobicity

No changes in hydrophobicity were observed in biochar-amended soils compared to their respective controls, except for the CS-350 biochar treatment, which displayed a smaller hydrophobicity (Table 6). An increase in hydrophobicity would otherwise create negative impacts on soil hydraulic properties (Blanco-Canqui and Lal, 2009; Clothier et al., 2000). Nonetheless, arguments are found that a moderate hydrophobicity could help improve soil aggregation (Blanco-Canqui et al., 2007), but this needs to be further studied for different stable C sources, such as biochars, and under varied conditions. Hydrophobicity of biochar is expected to increase with the temperature of pyrolysis through decarboxylation reactions, although tars trapped within pores in the low temperature, poorly carbonised biochar (Antal and Grønli, 2003; Calvelo Pereira et al., 2011; Hina et al., 2010) may also contribute to hydrophobicity. Once charcoal is produced and comes in contact with moist air, its surface will tend to oxidise. This ageing process will continue once biochar is in the soil, and the acidic functional groups created will contribute to soil hydrophilicity (Zimmerman, 2010). The formation of these functional groups was confirmed by XPS spectroscopy (data not shown). It should be noted that the soil water repellency observed was clearly related to the type of soil, this being generally greater in the Andisol. The higher soil water repellency observed in the CS-amended soil compared with those amended with biochar (Table 4) may be related with the greater content of aliphatic-C compounds in the former (Capriel, 1997).

5. Conclusions

After 295 d of incubation, biochars produced from CS at 350 and 550 °C and added at a dose of 7.18 t C ha^{-1} had significant effects on the physical properties, partially influencing porosity of the two soils tested: an Alfisol (TK soil) and an Andisol (EG soil). Changes in porosity were reflected in changes in soil hydraulic properties. Biochar treatment led to increased soil water holding capacity, particularly at lower tensions in the TK soil, suggesting that these biochars may facilitate drainage in the poorly drained soil (the TK soil). However, the extent of this effect will always depend on how the soil layer underneath the amended soil responds to drainage. The trend of increasing the mesoporosity of both soils, which corresponds to increased AWC, may be important to the enhancement of plant productivity as well as to the reduction of irrigation frequency. For example, if rye grass growing in these soils, has a rooting depth of 60 cm, and evapotranspiration was 5 mm d^{-1}, and the soil water depletion fraction was 60%, it was estimated that in the presence of biochar, the irrigation interval could be extended for 1 d in the TK soil and up to 3 d in the EG soil. The present results are biochar-, dose- and soil-specific. It is expected that biochar–soil interactions will evolve with time, as biochar will continue oxidising and will likely contribute further to aggregate formation. Long-term field trials to determine the agronomic effectiveness of different biochars, application rates, and soil combinations would provide the ideal resource to test whether soil structure and water relations can be influenced permanently through biochar application.

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