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ORIGINAL RESEARCH

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Quantifying the influence of eucalyptus bark and corncob biochars on the physico-chemical properties of a tropical oxisol under two soil tillage modes

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Abstract

Purpose This study aimed to assess the impact of two biochars applied at the rate of 15 t ha^{-1} on physico-chemical parameters of an oxisol in Cameroon.

Methods The biochars were made from slow pyrolysis (~ 300 °C, 4 h) of eucalyptus tree bark and corncobs and then incorporated into the top 15 cm of the soil with or without straw. The soil tillage mode was either flat plots or furrows and ridges. Soil porosity, bulk density, saturated hydraulic conductivity, available water content, pH, nitrogen, potassium, phosphorus, cation exchange capacity and electrical conductivity were analysed before biochar application, then 6 and 12 months after.

Results None of the measured soil physical parameters were affected by the presence or type of biochar. The total porosity was lower during the second production period compared to the first, while available water content and van Genuchten parameters increased during the second production period. No significant difference was observed between soil nitrogen, phosphorus, potassium, cation exchange capacity and electrical conductivity of control and treated plots.

Conclusion We recommend that straw be pyrolysed and the resulting biochar incorporated into soil instead of burying straw (as is actually done in furrow and ridges tillage mode).

Keywords Biochar · Oxisol · Soil physico-chemical parameters · Furrows and ridges tillage mode · Flat plots tillage mode

Introduction

Biochar is the porous carbonaceous solid produced by pyrolysis, i.e. thermochemical conversion of organic materials in an oxygen-depleted atmosphere. Its physico-chemical properties have potential to contribute to long-term storage of carbon in the soil and improvement of soil structure and fertility (Kimetu and Lehmann 2010). Biochars made from diverse biomass are characterized by different morphological and physico-chemical properties, and also differ based on pyrolysis conditions, including temperature, rate and duration (Mukherjee et al. 2011; Butnan et al. 2015). Biochar has the potential to improve fertility of degraded soils either by direct supply of nutrients, by fixing nutrients followed by subsequent slow release or by improving soil structure and water retention (Unger et al. 2011).

In tropical areas such as in Cameroon, oxisols are among the dominant soil types. They are characterized by an acidic pH (3–5.5), high concentration of heavy metals, Al and Fe toxicities and low cation exchange capacity (CEC), all which limit plant nutrient availability, resulting in lower crop yield (Chintala et al. 2012). Organic and inorganic fertilizers could contribute to maintain or increase the fertility of these soils. However, under the economic conditions prevailing in many sub-Saharan African countries, resource-poor farmers use little chemical fertilizer (Craswell and Vlek 2013). In addition, benefits only last for a few growing seasons, since added nutrients are prone to leaching, given the low CEC of oxisols (Baligar and Bennett 1986). In these acidic soils, biochar has been shown to improve the holding capacity of nutrients, including: phosphorus (P), calcium (Ca),

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potassium (K), magnesium (Mg), sulphur (S) and nitrogen (N) (Mann 2002). Improvement of soil pH, electrical conductivity (EC), CEC and soil C were also reported (Chintala et al. 2014; Sohi et al. 2009).

Biochar and soil physical properties

Soil physical properties largely determine rooting depth and the availability of air and water within the rooting zone (Downie 2009). Bulk density (ρ_a) is one of the most important soil characteristics affecting rainfall infiltration (Ueckert et al. 1978). In a meta-analysis, Omondi et al. (2016) obtained an average value of 7.6% reduction in ρ_a following biochar application; this was attributed to the initial low ρ_a of biochar. Biochar impact on soil ρ_a varies, however, with application rate and soil type. Biochar amendment at 10 t ha^{-1} significantly reduced soil ρ_a in an Alfisol low in organic carbon, but had no effect in an Andosol high in organic carbon (Herath et al. 2013). Ventura et al. (2013) revealed an inverse linear correlation between ρ_a and biochar application rates (30 and 60 t ha^{-1}) for 5 cm and 10 cm depths, on a sub-alkaline clay loam soil.

Soil total porosity (Θ) affects rooting zone processes such as plant water uptake and soil microbial respiration by influencing gas movement (Hillel 2004). Increase in soil Θ after biochar application was found to be rate and soil specific: 4%, 3.5%, 8.6% and 19% increases were recorded, respectively, for low (< 20 t ha^{-1}), medium (21–40 t ha^{-1}), high (41–80 t ha^{-1}) and very high (> 80 t ha^{-1}) application rates (Omondi et al. 2016). The same author also noted an increase of 7.5% in Θ in coarse-textured soils (sandy loam and coarser) and 7.1% in fine-textured soils (clay loam and finer). However, Hardie et al. (2013) found no influence of biochar on Θ by either direct pore contribution, creation of accommodation pores or improved aggregate stability, 30 months after application at 47 t ha^{-1} of green waste biochar produced at 550 °C on a sandy loam soil.

Compared to other studies on soil physical parameters, there is limited comparable information on biochar impact on soil saturated hydraulic conductivity (Ks) (Castellini et al. 2015). Soil Ks governs water infiltration and solute movement within the soil profile, thus influencing the likelihood of soil surface runoff after a heavy rainfall or irrigation event (Omondi et al. 2016). Biochar produced using mesquite wood (*Prosopis* sp.) at 400 °C (average rate of 133 t ha^{-1}) decreased by 92% and by 67% the Ks of very permeable organic soil, but increased that of less permeable soils by 328% (Barnes et al. 2014; Githinji 2014). Laird et al. (2010a, b) observed no change in Ks of soil with intermediate permeability (repacked fine-loamy soil), 500 days after incorporating biochar made from slow pyrolysis of hardwood (*Quercus* and *Carya* spp.) applied at rates of 0, 5, 10 and 20 g biochar kg^{-1} soil.

Available water content (AWC) of soil is a key property in tropical climates because it contributes to reduce plant water stress. If biochar is able to increase soil water reserves in agricultural soils, it may be possible to reduce irrigation frequency and volume. Biochar was reported to mainly improve the AWC of poorly structured soils. Glaser et al. (2002) noted an increase of 18% in AWC on Terra Preta soils. Devereux et al. (2012) corroborated this result, reporting improved water retention through a change in soil porosity, pore size, bulk density and wetting ability, on repacked sandy loam soil amended with biochar made from wood charcoal. Ouyang et al. (2013) obtained an increased in the AWC of 5.2% for silty clay soil and 10.6% for sandy loam soil, using a biochar made from dairy manure at a ratio of 2% 5 cmw/w in dry weight basis. However, Ventura et al. (2013) found no difference in soil water retention on a clay loam, 2 years after application of biochar made from fruit tree pruning residues using a traditional oven, at rates of 10, 30 and 60 t ha^{-1}. Similarly, Ojeda et al. (2015) in a greenhouse experiment indicated no influence of biochar on water retention of a sandy loam after 1 and 20 months, using six types of biochar produced from different biomass sources (pine, poplar or sludge) and pyrolysis processes (slow, fast or gasification), applied at a mean dose of 0.018 kg biochar kg^{-1} soil.

Biochar and soil chemical properties

Soil pH is one of the fundamental soil properties influencing nutrient availability and many soil chemical processes (Hadi-Akbar Basri et al. 2013). Sanchez et al. (1983) observed that biochar increased the pH of amended soils by 0.4–1.2 pH units, with greater increases in sandy and loamy soils than in clayey soils. The short- and long-term implications of biochar on N immobilization and mineralization are specific to soil-biochar interactions (Clough et al. 2013; Prommer et al. 2014). In some cases, biochar application could decrease soil N availability and plant tissue N concentration (Barbosa de Sousa et al. 2014; Bargmann et al. 2014). In other cases, N and P uptake in corn plants grown in a sandy loam was increased after application of wood biochar but decreased in a silt loam soil (Yeboah et al. 2009). This is explained by the possible sorption of N by biochar (Reverchon et al. 2014) or immobilization of mineral N due to increased soil C/N ratio and input of labile C (Ippolito et al. 2014). Mitigation of N leaching loss following biochar addition reported by Zheng et al. (2013) was in part attributed to an increase in soil water holding capacity (WHC).

Reported mechanisms by which biochar can affect soil P content and plant uptake of P include: changing soil environment for microorganisms (Atkinson et al. 2010); alteration of soil P availability through anion exchange capacity (DeLuca et al. 2009); reduced P leaching due to sorption of both orthophosphate and organic P by biochar (Laird et al. 2010a, b); and direct release of soluble P after application (Parvage et al. 2013). However, we noted inconsistent results as to whether biochar application enhances P sorption or its release. Enhanced phosphorus availability in biochar was reported to be greatly affected by pyrolysis temperature regardless of feedstock; lower pyrolysis temperature biochar contained more potentially available P (Xu et al. 2016a, b). Soil P availability is also influenced by interaction with the soil conditions and properties, e.g. retention time in soil, coexistence of other anions and nutrients on exchange sites and soil acidity. The incorporation of biochars to acidic soil at 40 g kg^{-1} (4%) reduced the sorption and increased available P. In calcareous soil, application of alkaline biochars (corn stover and switchgrass biochars) significantly increased the sorption of P and decreased its availability (Chintala et al. 2014). Phosphorus release by biochars was also found to be highly dependent on the presence of other cations (Ca^{2+}, Mg^{2+}, Al^{3+}, Fe^{2+}) in the soil solution. Slow release was found to be due to the formation of precipitates between dissolved P and excessive Ca^{2+} and Mg^{2+} in an alkaline milieu (Qian et al. 2013), while Fe–P and Al–P bonds were observed in more acidic soils (Xu et al. 2014).

Biochar seems to be one of the most effective materials reducing soil K losses in regions with high rainfall (Widowati and Asnah 2014). Several studies reported soil exchangeable K increase after biochar application. This impact was in part due to a direct supply of K from biochar (Zong et al. 2016) or by indirect improvement in fertilizer use efficiency by adsorption of nutrients on exchange surfaces thus reducing leaching loss (Widowati and Asnah 2014).

From the cited literature, it is evident that the influence of biochar on soil physico-chemical properties is highly variable. Biochar effects on soil properties depend on factors including biochar properties (influenced by feedstock type, pyrolytic conditions), application rate, soil type, time after application and the interactions among these factors. Biochar appears to have more influence in coarse-textured soils, poorly drained or excessively drained soils, poorly structured soils and soils with low organic carbon content. Less influence is noted on soils containing high organic matter, in fine-textured and well-structured soils (Biederman and Stanley Harpole 2013; Burrell et al. 2016; Omondi et al. 2016).

Few studies have evaluated the effect of tillage in interaction with biochar application, such as in the context of the common cultural system of furrows and ridges (FR) in Cameroon (versus flat ploughing, FP). Considering the former system is predominant in many underdeveloped countries (because of topography, small size of most farms in forested zones or the low mechanization level) and has been proven appropriate on humid soils (Ker 1995), we investigated the effect of biochar in this context. We discuss how the addition of biochar affects physical and chemical properties of an oxisol cultivated under two different tillage modes for corn production in Cameroon. Straw is also considered in our study since it is an agricultural residue generally buried in conjunction with the FR tillage mode, and which is proposed as a raw material for biochar production.

Materials and methods

Site description and irrigation system

The study was conducted on an experimental field in the western highlands of Cameroon in Central Africa (5°36′52″N, 10°16′85″E) at 1418 m of altitude. The site is characterized by a typical weathered red soil with 5% slope, which had been under fallow for 3 years. The climate is tropical wet with a mean annual rainfall of 1850 mm mainly from March to October. Mean maximum and minimum temperatures are 29.4 °C and 12.9 °C. The soil has 34% clay, 26% silt and 40% sand thus representing a clay loam texture (USDA 2014), with an acid pH of 5.8 and a relatively low bulk density. Detailed soil characteristics are presented in Tables 1 and 2.

To ensure adequate soil moisture, an irrigation system was designed based on the following parameters: basic infiltration rate of the soil estimated at 2.50×10^{-4} m s^{-1} using the double ring infiltrometer method (ASTM-D5093 2008), corn water requirements as per growing stages (FAO 2016), actual evapotranspiration and soil water retention capacity. Water from a nearby river was pumped to irrigate the experimental plots by sprinklers, twice weekly during the dry season (first production period, from January to May 2014) and then occasionally, according to rain events during the rainy season (second production period, from July to November, 2014).

Biochar production and characterization

Biochars used in this study were made from local organic residues, eucalyptus tree bark (EB) and corncob (CCB). They were manufactured using a locally made retort kiln at a temperature of around 300 °C. Physical, chemical and biological parameters of both CCB and EB were characterized (Djousse et al. 2017a) using methods described in Table 3 and their characteristics presented in Tables 1 and 2.

Experimental setup

The treatments were organized in a split-plot design, with the main plots being the soil tillage mode (FP vs FR system), and with the subplots being one of the four treatments (T2–T5) plus a control (T1). The subplots were 4 × 4 m,

Table 1 Biochar and soil physical parameters

Symbols	Parameters	Units	CCB[a]	EB[a]	Value at beginning (±CV)	Value at the end of first PP (±CV)		Value at the end of second PP (±CV)	
						FR	FP	FR	FP
Granular size parameters									
–	0.05 < % < 2	%	97	89	40	42 ± 1	41 ± 1	42 ± 0	42 ± 0
–	0.025 < % < 0.05	%	3	10	26	24 ± 2	25 ± 2	26 ± 0	26 ± 0
–	% < 0.025	%	0	1	34	34 ± 1	34 ± 0	32 ± 0	32 ± 0
–	Texture	–		–		Clay loam			
MPD	Mean particle diameter	mm	0.24	0.13	–	–	–	–	–
UC	Uniformity coefficient	–	2.12	2.43	–	–	–	–	–
Porosity related parameters									
ρ_a	Bulk density	g cm^{-3}	0.33	0.46	0.76 ± 10	0.75 ± 9	0.72 ± 13	0.80 ± 9	0.77 ± 9
ρ_s	Particle density[b]	g cm^{-3}	1.62	1.63	2.65	2.65	2.65	2.65	2.65
Θ	Total porosity	m^3 m^{-3}	0.79	0.72	71 ± 4	0.72 ± 3	0.73 ± 5	0.70 ± 4	0.71 ± 4
Water related parameters									
Θs	Saturation water	m^3 m^{-3}	–	–	0.68 ± 4	0.62 ± 1	0.74 ± 19	0.62 ± 16	0.72 ± 9
Θr	Residual water	m^3 m^{-3}	–	–	0.27 ± 11	0.21 ± 4	0.36 ± 32	0.18 ± 48	0.34 ± 24
AWC	Available water content	m^3 m^{-3}	–	–	0.04 ± 16	0.06 ± 3	0.08 ± 21	0.14 ± 29	0.15 ± 23
Ks	Saturated hydraulic conductivity	m s^{-1}	–	–	2.1E−4 ± 9	–	–	2.4E−4 ± 58	4.1E−4 ± 70
–	Capillary rise	g g h^{-1}	5.07	5.19	–	–	–	–	–
Θx	Relative humidity sorption	g g h^{-1}	6.17	6.14	–	–	–	–	–

NB: *CCB* Corncob biochar, *EB* Eucalyptus biochar, *PP* production period, *FP* flat plot, *FR* furrow-ridges

[a]Adapted from Djousse et al. (2017a)

[b]Soil particle density assumed to be 2.65 (not measured as with biochar)

Table 2 Biochar and soil chemical parameters

Symbols	Parameters	Units	CCB[a]	EB[a]	Value at beginning	Value at the end of first PP		Value at the end of second PP	
						Treated	Control	Treated	Control
pH_{H20}	pH water	–	9.31	8.11	4.4 ± 0.03	5.4 ± 0.1	5.1 ± 0.0	5.4 ± 0.1	4.9 ± 0.0
EC	Electrical conductivity	S m^{-1}	0.028	0.068	0.05 ± 0.1	0.04 ± 0.2	0.04 ± 0.2	0.11 ± 0.2	0.10 ± 0.2
(CEC)	Sum of cations	cmol(+) kg^{-1}	28.55	24.24	12.7 ± 0.1	12.8 ± 0.3	12.5 ± 0.3	11.2 ± 0.3	10.8 ± 0.3
N	Total Nitrogen	g g^{-1} × 100	0.88	0.47	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.2	0.1 ± 0.2
P	Exchangeable Phosphorus	cmol(+) kg^{-1}	4.56	4.25	8.7 ± 0.1	7.79 ± 0.4	7.2 ± 0.5	4.89 ± 0.3	4.2 ± 0.4
K	Exchangeable Potassium	cmol(+) kg^{-1}	26.47	7.54	0.07 ± 0.1	9.0 ± 0.8	5.7 ± 0.4	1.1 ± 0.4	0.9 ± 0.4
Ca	Exchangeable Calcium	cmol(+) kg^{-1}	0.80	14.73	–	–	–	–	–
Mg	Exchangeable Magnesium	cmol(+) kg^{-1}	0.78	1.01	–	–	–	–	–
Na	Exchangeable Sodium	cmol(+) kg^{-1}	0.50	0.96	0.01 ± 0.0	1.5 ± 0.4	1.3 ± 0.2	0.8 ± 0.2	0.8 ± 0.0
OM	Organic matter	g g^{-1} × 100	–	–	3.8 ± 0.1	8.8 ± 0.3	6.6 ± 0.3	10.3 ± 0.2	8.4 ± 0.4
–	Graphitic Carbon	g g^{-1} × 100	37.7	24.9	–	–	–	–	–
OC	Organic carbon	g g^{-1} × 100	29.7	27.8	2.2 ± 0.1	5.1 ± 0.3	3.8 ± 0.3	5.9 ± 0.2	4.9 ± 0.4
C/N	Carbon nitrogen ratio	–	76	112	30 ± 0.0	82.5 ± 0.3	62.7 ± 0.3	85.5 ± 0.3	78.4 ± 0.5

NB: Soil samples collected from the top 10 cm of soil; *CCB* Corncob biochar; *EB* Eucalyptus biochar, *FR* furrow-ridges plots, *FP* flat plots, *PP* production period

[a]Adapted from Djousse et al. (2017a)

separated from each other by an alley of 0.8 m. Replicates were assured with three blocks set perpendicularly to the slope gradient. The control consisted of fertilizer and the incorporation of straw (T1), while the other treatments

Table 3 Summary of methods used for analysing biochar and soil

Symbol	Names	Units	Methods	Equipment	References
Biochar physical properties[a]					
ρ_a	Tapped bulk density	$g\ cm^{-3}$	Tapped density after 3 falls from 0.15 m	Cylinders	ISO 5311:1992 (1992)
ρ_s	Particle density	$g\ cm^{-3}$	Gas displacement pycnometer	(AccuPyc 1330 Micromeritics Norcross, GA, USA)	ASTM B923-10 (2015)
Θ	Total porosity	$m^{-3}\ m^{-3}$	$\Theta = 1 - \left(\frac{\rho_a}{\rho_s}\right)$	–	Flint and Flint (2002)
	Particle size distribution	%	Mechanical and ultrasonic sieving	(RX-29, Ro-Tap, W.S. Tyler, Mentor, Ohio, USA) and an Allen Bradley sonic sifter	ASTM B923-10 (2015)
MPD	Mean particle diameter	mm	$MPD = \frac{\sum_{i=1}^{i=n}(R_i \times N_i)}{100}$ $R_i = \left(\frac{F_i}{S}\right) * 100$	–	
UC	Uniformity coefficient	–	$UC = \left(\frac{D_{60}}{D_{10}}\right) * 100$	–	ASTM D2862-10 (2010)
θ_{qx}	Regression parameter for water sorption by capillarity under different tensions for 72 h	$g\ g^{-1}\ h^{-1}$	Tensions: −0.05, −0.25, −0,50, −0,75, −1 and −1.40	Tension table, nonlinear regression	Adapted from Allaire and Parent (2004)
θ_x	Total water sorption under different tension for 72 h	$g\ g^{-1}$	Tensions: −0.05, −0.25, −0,50, −0,75, −1 and −1.40	Tension table, nonlinear regression	Adapted from Allaire and Parent (2004)
θ_g	Moisture	$g\ g^{-1}$	Mass lost during 14 h at 105 °C	Muffle furnace	ASTM D1762-84 (1990)
Biochar chemical properties[a]					
pH	pH ($H_2$0)	–	Electrode	VWR Symphony SP80PC pH metre	Rajkovich et al. (2011)
EC	Electrical conductivity	$S\ m^{-1}$	Electrode	Radiometer Copenhagen CDM3 Conductivity metre,	
CEC	Sum of the	cmol(+) kg^{-1}	Calculated	sum of K, Ca, Mg, Na	
K, Ca, Mg, Na	Exchangeable bases	cmol(+) kg^{-1}	Agitation and filtration	Optical emission spectrophotometry with inductively coupled plasma (ICP-OES) Optima 4300DV, Perkin-Elmer instrument G10 GYROTORY shaker	
C_{tot}	Total carbon	$g\ g^{-1}$	Dry combustion, elemental analysis	LECO elemental analyser	Adapted from Meng et al. (2014); LECO (2009); (Brewer and Brown 2012)
CNSH-total	Total C, N, S and H	$g\ g^{-1}$	Dry combustion	CNS-LECO Truspect	(Brewer and Brown 2012)
C_{org}	Organic carbon	$g\ g^{-1}$	Pre-treatment with hydrochloric acid, volatilization at 1380 °C and calculation	LECO elemental analyser difference between the C_{graph} plus C_{org} and C_{graph}	ASTM (2002), CEAEQ (2015) and ISO (2006)
C_{graph}	Graphitic carbon	$g\ g^{-1}$	Pre-treatment with nitric acid and volatilization at 1380 °C	LECO elemental analyser	ASTM (2002); CEAEQ (2015); ISO (2006)

Table 3 (continued)

Symbol	Names	Units	Methods	Equipment	References
Soil physico-chemical analysis					
Soil physical analysis					
–	Texture	–	Bouyoucos hydrometer		Gee and Bauder (1986)
–	Moisture content	$g\ g^{-1}$	Gravimetric	Oven	ASTM-D4959 (2014)
ρ_a	Bulk density	$g\ cm^{-3}$	Cylinder method		ASTM-D7263 (2009)
Θ	Total porosity	$m^{-3}\ m^{-3}$	Calculated from $\boldsymbol{\rho_a}$ assuming a particle density $\boldsymbol{\rho_s}$ of 2.65 $g\ cm^{-3}$		Rühlmann et al. (2006).
Ks	Saturated hydraulic conductivity	$m\ s^{-1}$	Constant head permeameter with the undisturbed samples		Sarki et al. (2014)
–	Soil water retention curves (desorption)	–	Pressure plate		Durner and Flühler (2005)
–	Van Genuchten soil water retention curve parameters	–	Soil Water Retention Curve software (SWRC, version 3.00 beta)		Durval (2001)
–	Available water content (AWC)	$m^3\ m^{-3}$	Calculated as the difference in water content at − 0.3 and − 100 m of tension using measured values		Mohanty and Mousli (2000)
Soil chemical analysis					
pH-H_20	pH water	–	1:2.5 soil–water ratio after 16 h	CG822 pH metre with combine pH-electrode	(Pauwels et al. 1992)
EC	Electrical conductivity	$S\ m^{-1}$	1:5 soil–water ratio	Conductivity metre	
N	Total Nitrogen	$g\ g^{-1} \times 100$	Salicylic acid digestion—Kjeldahl procedure; steam distillation techniques	UDK 129 Kjeldahl distillation unit	(Pauwels et al. 1992)
P	Available Phosphorus	$mg\ kg^{-1}$	Bray II	UV–VIS Spectrophotometer at 660 nm.	
K	Exchangeable Potassium	$cmol(+)\ kg^{-1}$	Ammonium acetate method	Flame photometer	
Na	Exchangeable sodium	$cmol(+)\ kg^{-1}$	Ammonium acetate method	Flame photometer	
CEC	Cation exchange capacity	$cmol\ (+)\ kg^{-1}$	Ammonium acetate method	Extractor and Titrator	Ross and Kettering (2011)
CO	Organic carbon	$g\ g^{-1} \times 100$	Walkley and Black	Titrator	(Pauwels et al. 1992)

[a]Djousse et al. (2017a)

consisted of fertilizer with the addition of CCB (T2); fertilizer with the addition of EB (T3); fertilizer and the addition of CCB and straw (T4); and fertilizer with the addition of EB and straw (T5). Fertilization consisted of manual application of 4 (20–10–10) at the rate of 200 kg ha^{-1} and urea (46–0–0) at the rate of 100 kg ha^{-1}; this is the standard application rate used by farmers in the locality. The land was tilled using a rotor cultivator for FP and a hoe for FR. Due to its hilly landscape and the small size of agricultural plots, farmers in the region principally use this latter method. Straw from grasses present in each plot was either buried (T4 and T5) or removed (T2 and T3). For FR, grasses were pulled out with a hoe, then either kept aside, or partially buried in the furrow by applying a layer of soil over top. Two weeks later, biochar and fertilizer were applied manually on the entire surface of ridges, then immediately covered at a depth between 10 and 15 cm with a second layer of soil, in order to prepare the seedbed. Each plot had three ridges of 1 m each, spaced 50 cm apart. For FP, we first ploughed using the rotor cultivator at 10–15 cm depth. Two weeks later, biochar and fertilizer were manually spread on the entire surface of the plot and a second plough immediately completed to bury biochar and fertilizer, and to prepare the seedbed for sowing. Improved corn seeds (PANNAR 12TM) were sown manually at about 4 cm depth, Tables 1 and 4 at a density of 4 plants m-2 (50 × 60 cm in ridges and 50 × 65 cm in FP). The plots were irrigated when necessary as described in Sect. 2.1.

After harvesting (5 months later), the agricultural residues were removed from the field and plots were ploughed using the hoe for ridges and the rotor cultivator for FP surfaces. Ridges were not moved to form new ones, but were instead disturbed and remained in the same position. A second corn production period of 5 months was then completed on the same plots, without application of either fertilizer or biochar, as generally done by farmers in the locality.

Soil sampling and analysis

Soil samples were collected three times during the experiment: before ploughing, at the end of the first corn production before the second ploughing (6 months after treatment application), and at the end of the second production period (6 months after the second ploughing). For chemical and textural analysis, soil samples were collected between 1 and

Table 4 Analysis of variance for soil physical parameters (degree of freedom and *p* values)

Parameters	DF	Θ	θ_r	θ_s	ρ_a	AWC	Ks	θ_g	
								DF	*p*
Treatment versus control									
Production period (PP)	1	**0.003**	0.22	0.15	**0.007**	**< 0.0001**	–	2	**< 0.00**
Treatment (T)	4	0.19	0.53	0.28	0.27	0.22	0.83	4	0.70
T × PP	4	0.81	0.60	0.74	0.85	0.79	–	8	0.47
Soil tillage mode (STM)	1	0.46	**0.005**	**0.0009**	**< 0.0001**	0.0072	0.19	1	0.045
STM × PP	1	0.96	0.96	0.55	0.72	**< 0.0001**	–	2	0.34
T × STM	4	0.99	0.65	0.19	0.65	0.005	0.33	4	0.60
T × STM × PP	4	**0.009**	0.05	0.56	**0.60**	0.13	–	8	0.52
In between treatments									
Biochar type (BT)	1	0.75	0.64	0.46	0.78	0.76	0.56	1	0.43
PP	1	**0.007**	0.39	0.09	**0.01**	**< 0.0001**	–	2	**< 0.0001**
BT × PP	1	0.82	0.77	0.89	0.84	0.37	–	2	0.46
STM	1	0.35	**0.0005**	**0.0006**	0.0002	0.08	0.34	1	0.17
BT × STM	1	0.69	0.87	0.62	0.7	0.90	0.63	1	0.17
STM × PP	1	0.71	0.99	0.80	0.87	**0.0002**	–	2	0.49
BT × STM × PP	1	0.18	0.15	0.34	0.26	0.44	–	2	0.72
Straw (S)	1	0.25	0.49	0.47	0.31	0.03	0.74	1	0.62
BT × S	1	0.45	0.23	0.11	0.50	0.78	0.85	1	0.73
S × PP	1	0.21	0.40	0.66	0.26	0.77	–	2	0.38
BT × S × PP	1	0.86	0.95	0.08	0.87	0.73	–	2	0.84
S × STM	1	0.82	0.51	0.25	0.81	**0.0005**	0.80	1	0.44
BT × S × STM	1	0.76	0.95	0.82	0.29	0.50	–	1	0.35
S × STM × PP	1	**0.0005**	**0.01**	**0.04**	0.2865	0.12	–	2	0.12

NB: *DF* degree of freedom; Θ total porosity; θ_r residual water θ_s water content at saturation, ρ_a bulk density, *AWC* available water content, *Ks* saturated hydraulic conductivity, θ_g gravimetric water content

Significant *p* values are in bold characters

10 cm depth, while a 100 cm^3 core was sampled for other physical analyses. For initial soil characterization, 12 undisturbed soil cores (4 per block) and 3 composite soil samples (12 sub-samples per block) were collected. At the end of the first production period, 30 soil cores (1 per plot) and 30 composite samples (4 random sub-samples per plot) were also collected following diagonal transects. A similar soil sampling was carried out at the end of the second production period. During this period, 30 composite soil samples were also collected at 2-week intervals to assess gravimetric soil moisture content. These composite samples were immediately placed in plastic bags after collection to avoid evaporation. Theses samples were analysed as described in Table 3.

Statistical analysis

The data were analysed using the GLIMIX procedure of SAS followed by the Tukey HSD test for multiple comparisons. Analysis was carried out in two phases. First, the treatments T2, T3, T4 and T5 were compared to the control (T1) for the response variables. Second, the treatments were compared to each other, in order to interpret the effects of biochar type, soil tillage mode, production period and presence or absence of straw.

Results and discussion

Biochar and soil physical properties

Bulk density and total porosity

There was no significant effect of biochar treatment ($p=0.27$) or biochar type ($p=0.78$) on ρ_a, 6 and 12 months after its application (Tables 1, 4).

The ρ_a of our biochar ranged from 0.33 to 0.46 g cm^{-3}, while that of our soil was 0.76 g cm^{-3}. This was quite low compared to ρ_a of mineral soils (1–2 g cm^{-3}) but closer to ρ_a of organic soils (< 1 g cm^{-3}) (Hossain et al. 2015), probably because our plot was an old farmland and sampling was done only in the h dark surface layer. The effect of biochar was thus expected to be lower considering the bulk density of our soil (Verheijen et al. 2010). Similarly, Rogovska et al. (2016) did not find effects on ρ_a 3 years after application of biochar made at 450 ◦C from mixed hardwood biochar (*Quercus* spp., *Ulmus* spp. and *Carya* spp.) applied at the rate of 9.8 and 18.4 t ha^{-1}. Our results are in apparent disagreement with the work reported by Karhu et al. (2011) on agricultural soil, by Ventura et al. (2013) on a clay loam soil and a meta-analysis done by Omondi et al. (2016) on biochar-amended soils. This could be explained by the initial soil properties in our study. Flat plots (FP) had lower ρ_a compared to FR and ρ_a also decreased during the second production period; all these are due to soil mixing from one production period to another. All reported positive effects of biochar on ρ_a, over a wide range of biochar application rates, are explained by the low ρ_a of biochar resulting in lower soil ρ_a after application. The Θ was not affected by treatment or biochar type. These findings could be explained in part by either the initial high porosity of biochar, leading to an increase in total soil micro-pores, or an alteration in soil pore size distribution. In the present case, there was no difference between the initial porosity of our biochars (79% for CCB and 72% for EB) and that of the soil (71%) (Tables 1, 4), thus explaining our observations. Once more, these results are dissimilar to many previous studies (Bhattarai et al. 2015; Omondi et al. 2016), all of which reported increased soil porosity after the addition of biochar from different sources. Indeed, our results are supported by Omondi et al. (2016). The authors meta-analysis reported that soil porosity was not significantly affected by addition of biochar in highly porous soils and at low and medium application rates (3.5–4% which is equivalent to 23–36 kg ha^{-1} based on our biochar bulk density and assuming incorporation at 20 cm depth). These rates were almost twice those used in the present experiment and suggest that the studied oxisol might need higher doses of biochar with higher porosity to effectively alter the Θ. However, when incorporated into FP, straw increased the Θ during the second production period (Table 4). This could be due to increase in soil OM content following straw mineralization. Production period and soil tillage mode (STM) influenced ρ_a (Table 4), values being higher during the second production period compared to the first; and in FP compared to FR. The observed differences may be due to repeated tillage and to the effect of rainwater beating that favour soil aggregate breakdown and compaction. This is also in line with Θ that was lower during the second production period compared to the first ($p=0.003$).

Saturated hydraulic conductivity (Ks), available water content (AWC) and water retention curve parameters (θ_s, θ_r)

We observed no change in Ks values during the experiment (Tables 1, 4). Previous authors reported either a net short-term reduction in Ks after application of biochar in sand and organic soils (Barnes et al. 2014; Githinji 2014), a net increase (Herath et al. 2013; Uzoma et al. 2011) or no effect (Castellini et al. 2015; Ouyang et al. 2013). A net increase was related to the high porosity of biochar, while a net reduction was attributed either to the initial hydrophobicity of biochar or to the creation of torturous interstitial space between sand and biochar grains. Our results could be explained by the low biochar application rate, since many experiments in which a change was observed were characterized by higher rates (Omondi et al. 2016). In addition, Herath et al. (2013) reported that generally poorly drained soils exhibited a significant change in their Ks with biochar addition; this oxisol is well drained with high Ks (2.06×10^{-4} m s^{-1}). The high variability of Ks values could also have contributed to hinder statistical differences between biochar-amended and non-amended plots.

Biochar application had no significant effect on AWC ($p=0.22$), independently of the type of biochar ($p=0.76$) but production period did ($p<0.0001$). This could be explained by the fact that our biochar was produced at a relatively low temperature (300 °C), thus had higher levels of hydrophobic compounds impeding uptake of water into pore space, especially during the first production period. Reduction over time of this hydrophobicity, in addition to the increase in soil organic matter content (Table 2), could explain the higher value of AWC obtained during the second production period compared to the first. Hardie et al. (2013) also reported no significant effects of a green waste biochar applied at a rate of 51.8 t ha^{-1} on water retention curve parameters of a clay loam soil. Major et al. (2011) found no significant effect on either the water holding capacity or the Ks of a clay soil following wood biochar addition at the rate of 20 t ha^{-1}. At an application rate similar to the present study, Jeffery et al. (2015) indicated no improvement in soil hydrological function of a sandy soil after biochar application at 10 t ha^{-1}. Hence, the use of biochar at the equivalent rate of 15 t ha^{-1} may have also contributed to the observed lack of effect on hydrological function. In fact, some of the studies in which positive effects of biochar on soil hydraulic properties were reported used biochar application rates that are not feasible for field scale operational applications, such as 50 t ha^{-1} (Jeffery et al. 2015), 40, 80 t ha^{-1} (Jones et al. 2010), 88 t ha^{-1} (Gaskin et al. 2007) and 195 t ha^{-1} (Yu et al. 2013). Similarly, many studies reporting positive effects of biochar were carried out in pot experiments or with repacked soils under controlled environments, which do not reflect the field situation of oxisols (Hardie et al. 2013). However, soil AWC increased when straw was directly incorporated in flat plots, this could be due to fast mineralization of grasses and thus ready availability of organic matter and thus increased soil water storage.

Soil water content (SWC) was not influenced by biochar type or its presence but varied from one sampling period to another (Tables 1, 4). This can be explained by the low water sorption capacity of our biochar as previously discussed (Fig. 1) as well as the soil type (clay loam), which already has a good saturation water content related to its clay content. The greater SWC and AWC observed in FP compared to FR (Fig. 2) can be explained by the fact that in FR, furrows act like drains, reducing the soil moisture in ridges.

Fitted values of van Genuchten parameters (θ_s, θ_r) are presented in Table 1. Straw incorporated into soil in flat plots increased θ_s and θ_r during the second production period; this shares the same explanations as for those of

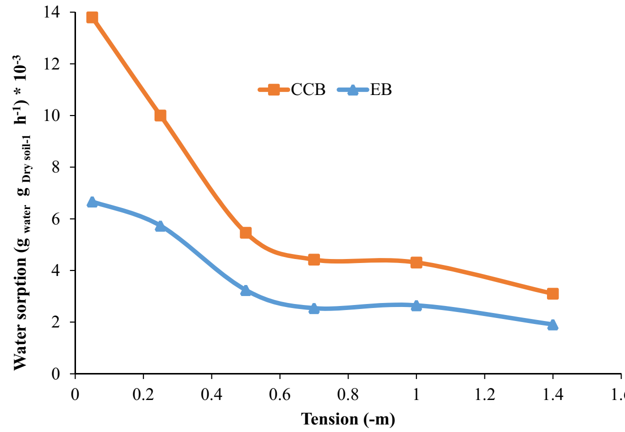

Fig. 1 Capillary rise of CCB and EB under tensions from −0.05 m (very wet) to −1.5 m (wet)

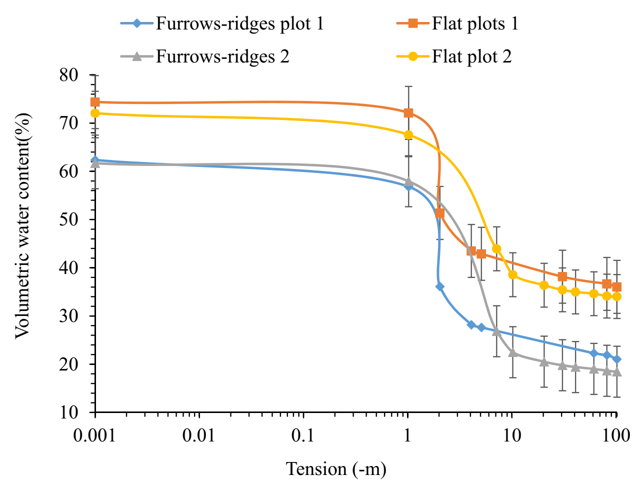

Fig. 2 Variation of soil water content as a function of production period and soil tillage mode

Θ and ρ_a. The θ_r was not affected by the addition of biochar ($p=0.53$) nor by biochar type ($p=0.64$). This was expected, as soil texture remains constant. Similar findings were reported by Uzoma (2011) with a biochar manufactured at 400 °C and applied at the rate of 10 t ha^{-1} on a sandy soil and by Eastman (2011) and Laird et al. (2010a, b) with an application rate of biochar up to 20 t ha^{-1} on a loam soil. Tillage mode, however, positively affected θ_r ($p=0.005$) with values being higher in FP during both production periods (Fig. 2). We hypothesize that organic matter content builds up more quickly in FP (grasses were sliced up with the rotor cultivator and buried) compared to FR (grasses were buried). In summary, biochar influenced none of the measured soil physical properties, but the interaction between straw, tillage mode and production periods did affect these properties.

Biochar and soil chemical characteristics

Soil pH (Table 2) increased ($p = 0.001$) 6 and 12 months after biochar application independently of the soil tillage mode; the average value was 5.10 in the control and 5.45 in treated plots during the first production period, and increased from 4.95 to 5.38 during the second production period; this could be due to the initial high pH value of these biochars. Pandian et al. (2016) reported similar results with an increase in pH between 0.5 and 0.6 units after application of biochar made of *Prosopis* on an acidic red soil at the rate of 5 t ha^{-1}. Several studies found that biochar addition may alter pH levels and the availability of soil nutrients such as Ca or Mg, while decreasing exchangeable Al^{3+} and H^+ concentrations (Novak et al. 2009). Calcium and Mg were found to limit maize growth in highly weathered tropical soils (Major et al. 2010), or the availability of B and Mo, which are important cofactors in biological N fixation (Rondon et al. 2007).

The EC of soil was not affected by biochar application, probably due to the dilution effect of soil and because the soil already contains high levels of Al and Fe, causing higher initial EC (0.05 ± 0.1 S m^{-1}) than the biochar ($0.028 < EC < 0.068$ S m^{-1}). However, the soil EC value significantly increased during the second production period in all plots. Also, straw positively interacted with soil when tilled flat, increasing EC. These are all imputable to the natural mineralization processes occurring in the soil since mineral fertilizers were not added during the second production. Soil CEC was not affected by any treatment, despite the higher value of biochar CEC (24.24 cmol(+) kg^{-1} for EB and 28.55 cmol(+) kg^{-1} for CCB) compared to that of the soil (12.7 cmol(+) kg^{-1}). This could be due to a dilution effect and leaching, since measurements were taken 6 months after biochar application. Minimal or no changes in CEC were also observed after addition of pecan shell-based biochar at the rate of 40 t ha^{-1} to a fine-loamy soil (Novak et al. 2009).

Based on chemical analysis of biochar (Table 2), its application at the rate of 15 t ha^{-1} was expected to contribute to additional N, available P and exchangeable K in the soil for at least one production period (Table 5). It was thus expected that soil N, P, K contents of plots receiving CCB and soil P, K and Ca of plots receiving EB will be different from that of control plots. This was not the case, 6 and 12 months after both types of biochar application (Table 6). This could be due to one of the following: rapid uptake by plants during the first production, leaching or sorption on biochar. Soil N and P contents were significantly higher in FR plots compared to FP (Table 6), probably because added NPK fertilizer was buried in ridges, while it was mixed in the FP tillage mode. Soil available P remains constant after biochar addition; this was also observed in acidic soils in other studies (Chintala et al. 2014; Schneider and Haderlein 2016; Zhang et al. 2016). A potential reason could be the fixation of P by Al, given the relative low soil pH. Soil exchangeable K and Na were significantly lower at the end of the second production period compared to the end of first, probably due to nutrient uptake by maize plants. Similarly, Steiner et al. (2007) did not observe greater K availability after one cropping season when wood biochar was added to a Brazilian Amazon oxisol at the rate of 11 t ha^{-1}.

Both biochars interacted positively with production period to increase soil OC and C/N ratio (Tables 2, 6). This is explained by the high OC content of biochar and the effect of mineralization. The relatively high content of graphitic-like carbon (Table 2) is also an indicator that applied biochar will remain stable for a longer period in these soils. Straw also contributed significantly to improve soil OC; this increase was more important during the second production period, likely due to straw mineralization with time. In summary, the biochar treatment positively affected soil pH and soil OC, both tillage mode and production period also affected several soil chemical variables.

Table 5 Equivalent rate for biochar nutrient and carbon supply, maize needs and recommended fertilizer application rate

Parameter	Units	CCB[a] (applied at 15 t ha^{-1})	EB[a] (applied at 15 t ha^{-1})	Recommended local mineral fertilization (200 kg ha^{-1} NPK + 100 kg ha^{-1} N)	Maize needs for 6 t ha^{-1}[b]	Maize needs for 3 t ha^{-1}[b]
Nitrogen	kg ha^{-1}	132	71	86	120	72
Phosphorus	kg ha^{-1}	27	25	9	22	16
Potassium	kg ha^{-1}	155	44	17	20	45
Calcium	kg ha^{-1}	5	86	–	24	–
Magnesium	kg ha^{-1}	5	6	–	25	–
Sodium	kg ha^{-1}	3	6	–	15	5
Organic carbon	kg ha^{-1}	4455	4170	–	–	–

[a]Adapted from Djousse et al. (2017b)

[b]Adapted from FAO et al. (2003)

Table 6 Analysis of variance for soil chemical parameters (degree of freedom and *p* values)

Parameters	DF	N	P	K	Na	CEC	EC	pH water	OC
Treatments versus control									
Production period (PP)	1	0.25	**< 0.0001**	**< 0.0001**	**< 0.0001**	0.12	**< 0.0001**	0.19	**0.0001**
Treatment (T)	4	0.11	0.51	0.64	0.36	0.95	0.12	**0.0001**	**0.01**
T × PP	4	0.49	0.30	0.46	0.36	0.96	0.46	0.85	0.31
Soil tillage mode (STM)	1	**0.03**	**0.02**	0.27	0.11	0.43	0.15	0.67	0.77
STM × PP	1	0.56	**0.01**	0.60	0.59	0.45	0.56	0.69	0.44
T × STM	4	0.27	**0.05**	0.67	0.74	0.98	0.06	0.37	0.72
T × STM × PP	4	0.43	0.13	0.64	0.85	1.00	0.75	0.24	**0.02**
In between treatments									
Biochar type (BT)	1	0.12	0.08	0.18	0.07	0.71	0.42	**0.0001**	0.68
PP	1	0.38	**< 0.00**	**< 0.00**	**< 0.00**	0.16	**< 0.0001**	0.42	**0.02**
BT × PP	1	0.12	**0.03**	0.14	0.12	0.59	0.73	0.45	0.66
STM	1	0.23	**0.0001**	0.47	0.26	0.29	**0.04**	0.48	0.56
BT × STM	1	0.95	0.08	0.74	0.88	0.75	0.10	0.36	0.37
STM × PP	1	0.26	**0.0001**	0.22	0.47	0.45	0.24	0.74	0.84
BT × STM × PP	1	0.14	0.06	0.80	0.67	0.62	0.79	0.77	0.22
Straw (S)	1	0.12	0.39	0.37	0.47	0.93	0.58	0.97	**0.03**
BT × S	1	0.74	0.89	0.74	0.88	0.82	0.36	0.60	0.96
S × PP	1	0.46	0.62	0.41	0.67	0.75	0.51	0.97	0.11
BT × S × PP	1	0.97	0.82	0.68	0.67	0.68	0.77	0.67	0.36
S × STM	1	0.10	0.06	0.74	0.32	0.81	**0.0001**	0.54	0.87
BT × S × STM	1	0.19	0.55	0.37	0.47	0.88	0.37	0.20	0.81
S × STM × PP	1	0.82	0.12	0.68	0.47	0.99	0.07	0.97	0.39

NB: *DF* degree of freedom, *N* total nitrogen, *P* exchangeable phosphorus; *K* exchangeable potassium, *Na* exchangeable sodium, *CEC* cation exchange capacity, *EC* electrical conductivity, *OC* organic carbon

Significant *p* values are in bold characters

Agronomic implications of the study

The selected application rate of 15 t ha^{-1} of biochar made from Eucalyptus bark and corncob residues (300 °C) did not have an important influence on soil physical properties, but did have an effect on chemical properties, at the end of 12 months and two production periods of maize. The obtained results have the following implications for farmers intending to use biochar for soil improvement.

- There is no drawback in using these biochars in oxisols under either tillage mode;
- The biochar did not affect water retention in these high porosity, low density and well-drained oxisols; biochar with a different particle size distribution might exhibit a different response;
- The tested biochars may be used to improve soil pH and OC, with both studied tillage modes;
- The furrow and ridges tillage mode contributed to better storage of soil total N and higher exchangeable K, compared to flat ploughing;
- The use of straw instead of biochars in furrow and ridges mode did not show any advantage as far as soil water retention is concerned. Given the reported positive side effects of biochar, mainly its reported C sequestration potential (Wang et al. 2016), we recommend that straw be pyrolysed and the resulting biochar incorporated into soil instead of burying straw (as is actually done in furrow and ridges tillage mode).

Conclusion

Biochars made from eucalyptus tree bark and corncobs in a retort kiln at 300 °C and applied at the rate of 15 t ha^{-1} on a clay loam soil in Cameroon (oxisol), significantly increased soil pH and organic carbon. Both biochars marginally increased θ_r, θ_s and AWC values of AWC being higher in flat plot soil tillage mode compared to furrow and ridges tillage mode. Total soil porosity was lower, and water retention was higher in the second production period, compared to the first. The use of biochar at higher application rate and the assessment of the longer-term fate of carbon from biochar could also constitute future research studies on these oxisols, in order to understand the potential for carbon sequestration.

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