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Article

Soil hydrophysical and chemical attributes in ferralsol amended with wood biochar

Isabella Menuzzo Lucon[1], Ruan Carnier[1], Aline Renée Coscione[1,*], Cristiano Alberto de Andrade[2], Wellingthon da Silva Guimarães Júnnyor[3], Isabella Clerici De Maria[1]

1. Instituto Agronômico – Centro de Solos e Recursos Ambientais – Campinas (SP), Brazil.
2. Empresa Brasileira de Pesquisa Agropecuária – Meio Ambiente – Jaguariúna (SP), Brazil.
3. Universidade Estadual do Mato Grosso do Sul – Agronomia – Cassilândia (MS), Brazil.

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***Corresponding author:** aline.coscione@sp.gov.br

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ABSTRACT: Most studies concerning biochar, which can enhance chemical, physical, and biological soil qualities and increase crop yields, are short-term experiments in controlled environments with temperate regions and sandy soils. Biochar amendment benefits for clayey soils in tropical climate regions are uncertain. Herein, field conditions in clayey soil were investigated for 28 months. Eucalyptus biochar was obtained from charcoal production and incorporated in soil with disc plows (0.00–0.20 m). Treatments comprised six single biochar application amounts–0 (control), 10, 20, 30, 40, and 50 $Mg{\cdot}ha^{-1}$. The experiments were conducted in April 2016, and corn was cultivated in 2016/17 and 2017/18. Soil samples were collected in 2018 for macro/micronutrient, bulk density, porosity, macroporosity, microporosity, water availability, and soil penetration resistance evaluations in the 0.00–0.05-, 0.05–0.10-, 0.10–0.20-, 0.20–0.30-, and 0.30–0.40-m layers. Chemicals P, K and Ca increased compared to the control. The K and Ca increases were related to the biochar composition (6% K and 2% Ca). Soil bulk density decreased by 0.07 $kg{\cdot}dm^{-3}$, and macro/microporosity (total porosity) increased linearly by 2.5% in the 0.05–0.10-m layer with increasing biochar application amount. Soil penetration resistance was unaffected. For each 1 $Mg{\cdot}ha^{-1}$ of biochar applied, a 500-$L{\cdot}ha^{-1}$ increase in available water occurred, which may be important for crops with low water demand and to overcome water restriction periods.

Key words: charcoal fines, soil fertility, soil porosity, soil water availability, field experiment.

INTRODUCTION

Biochar (BC) consists of a material originating from the thermal decomposition of a selected biomass, usually with the partial or total absence of oxygen, at temperatures ranging from 350 to 1,000°C. Eucalyptus and pine BCs in Brazil have advantages in terms of production, as they are generated as a byproduct of the charcoal industry (Benites et al. 2010). Biochar has been studied for several applications, including soil remediation, as fertilizers and conditioners, to improve the chemical, physical, and microbiological attributes of soil (Gabhane et al. 2020, Lopes et al. 2021, Carnier et al. 2022). The effects of BC on soil characteristics depend on various factors, such as the source of the pyrolyzed biomass, temperature and time of pyrolysis, dose of application and edaphoclimatic conditions (Mukherjee and Lal 2013).

The application of BC can increase the ion retention capacity, number of plant nutrients, surface area and water retention capacity (WRC) and reduce soil bulk density and penetration resistance (Mukherjee and Lal 2013, Liu et al. 2017, Melo et al. 2022). The reduction in the bulk density of soil may be associated with the low density of BC, which increases soil porosity, aeration, water infiltration, and water retention (Basso et al. 2013, Obia et al. 2016, Herath et al. 2013). In an experiment with pine BC (0, 4, 20 and 100 $Mg{\cdot}ha^{-1}$) applied to soils with different textures (5, 10, 19, 16, 11, 5, 34, and 37% clay), Peake et al. (2014) observed increases in the available soil water, with more pronounced effects in sandy soils and less evident effects in clayey soils (ranging from 0.3 to 48% with the maximum amount of BC).

Although several chemical and physical benefits are reported by using biochar in the soil, most of these studies were conducted under controlled laboratory and greenhouse conditions. Therefore, the application of this feeedstock in the field is limited, and there is a possibility of not being able to verify the same effects due to other interactions not considered in the original studies. In a tropical environment, Carvalho et al. (2016) conducted a field experiment with dry rice cultivation in clayey soil and wood BC rates (0, 8, 16, and 32 $Mg \cdot ha^{-1}$) for 3.5 years. The authors reported that the addition of BC reduces the amount of water readily available to the plants, but it does not interfere with rice productivity, concluding that long-term field research is needed to investigate soil–root interactions and changes in the physical and hydric attributes of soil due to the addition of BC. This conclusion is supported by the results obtained by Peake et al. (2014), who reported great resistance to changes in physical and water attributes due to the addition of BC in soil with a clayey texture.

Thus, understanding the mechanism by which BC, when applied in amounts comparable to those applied in the field, interferes with the chemical and physical attributes of soil is fundamental for the recommendation of this feedstock. In this context, the objective of this study was to evaluate the effects of the application and incorporation of eucalyptus BC on the physical attributes of a clayey soil after 28 months under tropical conditions.

MATERIALS AND METHODS

The experiment was performed at the Centro Experimental Central of the Instituto Agronômico, in Campinas, São Paulo, Brazil (22°54'S and 47°3'W; at 600-m altitude). The climate in the region is classified as humid subtropical (Cwa) (Alvares et al. 2013), with dry winters and rainy summers, according to the Köppen climate classification. The average temperature in the region was found to be 23°C, and the average annual precipitation was obtained as approximately 1,350 mm (CEPAGRI 2020).

The soil was classified as Rhodic Ferritic Ferralsol (Clayic, Eutric), according to World Reference Base for Soil Resources/ Food and Agriculture Organization (IUSS 2015). The granulometric and chemical characterization of the soil in the 0.00–0.20-m layer before the experiment is presented in Table 1.

Table 1. Physical[1] and chemical[2] attributes of the Rhodic Ferritic Ferralsol (Clayic, Eutric) soil (layer 0.00–0.20 m) with grain crops, in Campinas, SP (Brazil).

OC	pH	P	Ca	Mg	K	S. B.	H+Al	CEC	V
$g \cdot dm^{-3}$		$mg \cdot dm^{-3}$	---------------------------		$mmol_c \cdot dm^{-3}$	--------------------------------			%
16.1	5.4	11	18	5	2	25	28	53	47

Clay ($g \cdot kg^{-1}$)	Silt ($g \cdot kg^{-1}$)	Sand ($g \cdot kg^{-1}$)		
		Total	Coarse	Fine
< 0.002 mm	0.053–0.002 mm	2.00–0.053 mm	2.00–0.210 mm	0.210–0.053 mm
518	85	397	278	119

[1]Analyses according to Camargo et al. (2009); [2]analyses according to Raij et al. (2001): OC (colorimetric), pH in $CaCl_2$ 0.01 $mol \cdot L^{-1}$, total acidity (H+Al), P, K, Ca, Mg, S. B., CEC and V%; OC: organic carbon; S. B.: sum of bases; H+Al: potential acidity; CEC: capacity of cation exchange; V: saturation of bases.

Biochar was obtained by the pyrolysis of two different species of eucalyptus wood–*Eucalyptus urophylla* and *Eucalyptus saligna*–at 400°C. The resulting BC is a byproduct of the wood charcoal manufacturing process performed in the Brazilian steel industry. This material is called charcoal fines, and it has particles with diameters of less than 9.54 mm (Brasil 2017).

The carbon (C), hydrogen (H) and nitrogen (N) levels in the BC were determined by dry combustion in a C–H–N elemental analyzer (Perkin Elmer 2400) in duplicate. The ash content was determined in triplicate according to American Society for Testing and Materials (ASTM) D1762-84 (ASTM International 2007). The oxygen (O) content was obtained by the difference between 100 and the sum of the C, H, N and ash contents (Kim et al. 2012). To illustrate the BC surface, a scanning electron microscopy image was obtained using a Leo 440i model. The image is presented with 500× at 20 μm.

The other chemical characteristics were obtained in duplicate according to Resolution no. 498/2020 (CONAMA 2020) (Table 2) on the agricultural use of sewage sludge, which is often taken as a basis for the characterization of other materials intended to be added to soil. The following parameters were determined: moisture at 65°C, total solids (105°C) and volatile solids via loss of mass at 500°C, total Kjeldahl nitrogen, organic carbon (OC) by digestion with dichromate in digester block, and semitotal contents of P, Ca, Mg, K, Cu, Fe, Mn, and Zn. The Brunauer–Emmett–Teller–N_2 method (Brunauer et al. 1938) was used to determine the surface area of the BC. The cation exchange capacity was determined by the official Ministry of Agriculture procedure for soil fertilizers and amendments; this procedure employs the saturation of the exchange complex with H^+, displacement of the H^+ by calcium acetate, and titration of the acetic acid formed (Brasil 2017).

Table 2. Eucalyptus biochar attributes.

Parameter	Unity*	Result
Total carbon	% (m·m^{-1})	66.1 ± 0.6
Total nitrogen	% (m·m^{-1})	1.10 ± 0.03
Hydrogen	% (m·m^{-1})	2.24 ± 0.04
Oxygen	% (m·m^{-1})	25.05 ± 0.23
pH (water 1:10)	-	7.6 ± 0.0
Moisture (65 ± 5°C)	% (m·m^{-1})	7.7 ± 0.1
Total solids	% (m·m^{-1})	92.9 ± 0.4
Volatile solids	% (m·m^{-1})	49.8 ± 0.2
Ash content	% (m·m^{-1})	5.51 ± 0.01
Organic carbon	g·kg^{-1}	499 ± 5
Kjeldahl nitrogen	g·kg^{-1}	9.4 ± 0.1
CEC	mmol$_c$·kg^{-1}	79.5 ± 0.1
P	g·kg^{-1}	1.5 ± 0.1
Ca	g·kg^{-1}	20.3 ± 1.0
Mg	g·kg^{-1}	1.3 ± 0.1
K	g·kg^{-1}	63.8 ± 8.8
Mn	mg·kg^{-1}	275 ± 8.8
Cu	mg·kg^{-1}	13.7 ± 0.5
Fe	mg·kg^{-1}	1285 ± 85.6
Zn	mg·kg^{-1}	40.4 ± 9.8
Surface area (BET-N2)	m^2·g^{-1}	41.77

*Results expressed based on the dry basis; CEC: cation exchange capacity (Brasil 2017); BET: Brunauer–Emmett–Teller.

Before the experiment, the area had been used for grain crop production in rotation systems (in summer: beans, sorghum, or corn; in winter: oats, or wheat) for more than 10 years. The soil was tilled with plows and disc harrows.

The experiment was installed in 2016 in a randomized block design (4) and six treatments, resulting in a total of 24 experimental plots, that measured 27 m^2 (4.5 × 6 m).

In April 2016, BC was applied in doses equivalent to 0, 10, 20, 30, 40, and 50 Mg·ha^{-1} on the soil surface and incorporated into the 0.00–0.20-m layer using a disc plow; these doses of BC were equivalent to the application of 0, 0.5, 1, 1.5, 2 and 2.5% BC, respectively, considering the 0.00–0.20-m application layer with a soil bulk density of 1.20 g·cm^{-3} and a BC density of 0.33 g·cm^{-3}. The experiment was conducted over two agricultural years (2016/17 and 2017/18), with corn cultivation starting in December 2016 and 2017, respectively.

Twenty-eight months after BC incorporation, undisturbed soil samples were collected from layers 0.00–0.05, 0.05–0.10, 0.10–0.20, 0.20–0.30 and 0.30–0.40 m to determine soil density, total porosity, macro/microporosity, water availability and soil penetration resistance. The undisturbed samples were collected with the aid of volumetric cylinders in the central region of each of the four plots from trenches opened between the rows of each treatment. For each plot and soil layer, two volumetric rings were removed to quantify the abovementioned attributes. Soil samples (0–0.20 m) were collected for chemical characterization of OC, pH, P, K, Ca, Mg, Cu, Fe, Mn, and Zn, as previously described.

To determine the hydrophysical characteristics of soils, samples were prepared and saturated by capillarity on a tray. The height of the water sheet corresponded to two-thirds of the cylinder, and saturation was conducted for 48 h. The samples were submitted to matrix potentials (Ψm) of -0.006 MPa in a suction table (Dane and Hopmans 2002) and -0.033 MPa in Richards extractors (Klute 1986). After reaching hydraulic equilibrium at Ψm -0.033 MPa, each sample was submitted to the test of soil penetration resistance using the Shimpo bench penetrometer model FGV-250 PVL, the digital dynamometer model FGV-50XY and a displacement speed of 10 mm·min^{-1} (Figueiredo et al. 2011). The samples were then dried in an oven at 105 ± 5°C for 48 h to determine the soil bulk density (Blake and Hartge 1986).

Deformed samples, which were collected in the same trenches, were placed in polyvinyl chloride core cylinders, saturated with water for 48 h and submitted to the -1,500-MPa matrix potential in Richards' extractors to determine the permanent wilting point. For the determination of macro/microporosity, Klein and Libardi's (2002) classification method was used. The macropores had diameters larger than 0.05 mm and lost water at matrix potentials smaller than -0.006 MPa. Conversely, the micropores had diameters between 0.05 and 0.0002 mm and lost water at Ψm values between -0.006 and -1,500 MPa. The water available for crop development was calculated as the volume of water retained between Ψm = -0.006 MPa (field capacity) and Ψm = -1,500 MPa (permanent wilting point).

The results were subjected to analysis of variance at 95% probability and subsequent regression analysis for BC rates using first- and second-degree polynomial models, using SIVAR (Ferreira 2001).

RESULTS AND DISCUSSION

The surface area of the BC used in this study was 41.77 m^2·g^{-1} (Table 2). The BC was composed of pores of different sizes (Fig. 1). Similar surface areas were found by Yargicoglu et al. (2015) when analyzing BC from pine pyrolyzed at 400°C (40.63 m^2·g^{-1} surface area). Changes in porosity, bulk density, penetration resistance, and water holding capacity of the soil in response to BC application depended on the surface area and the presence of micropores in the BC (Mukherjee and Lal 2013).

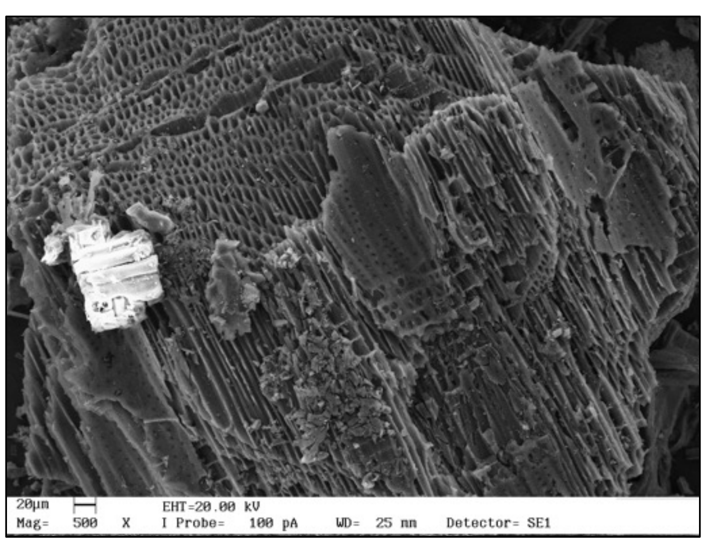
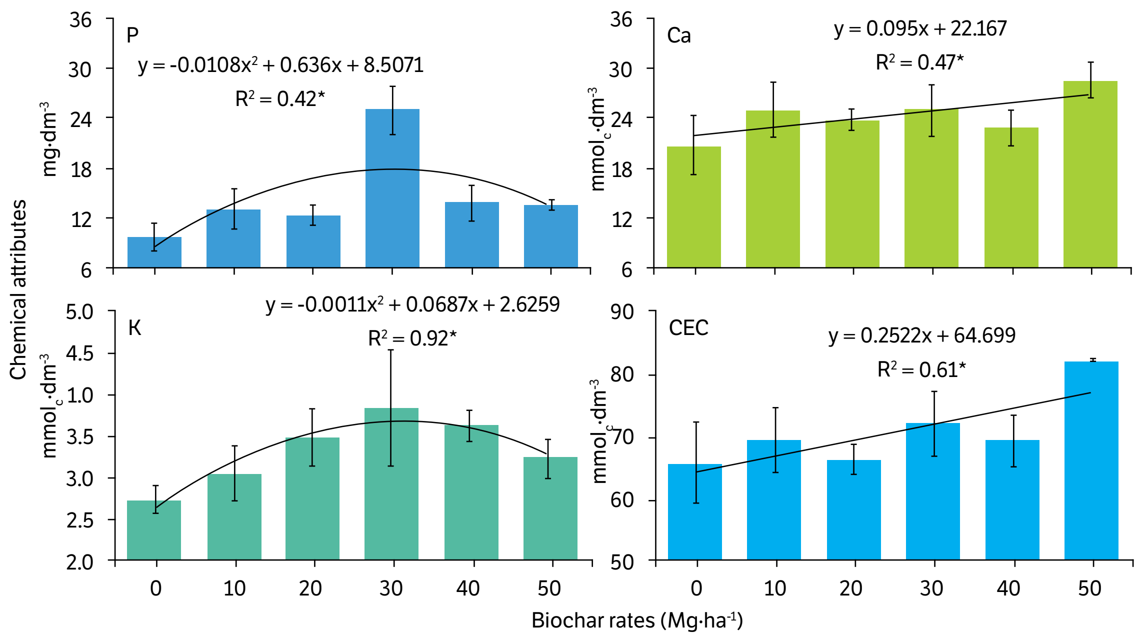


Figure 1. Scanning electron microscopy of eucalyptus biochar (magnification of 500×).

Considering the chemical attributes of soil after 28 months of experimentation, significant regression ($p \leq 0.05$) was observed for P, K, Ca, and CEC for the BC rates studied (Fig. 2). The levels of P and K in the soil responded to the increase in BC rate application according to a second-degree polynomial model, with the point of maximum nutrient availability corresponding to the amount of 30 $Mg \cdot ha^{-1}$. Ca and CEC increased linearly with increasing BC application amount. The increase in the soil K and Ca available was determined to be related to the high levels found in BC, approximately 6 and 2%, respectively (Table 2).



*Significant regression ($p \leq 0.05$). Bars indicate the standard deviation ($n = 4$).

Figure 2. Regression of soil chemical attributes 28 months after initiating the experiment.

The other evaluated attributes of soil fertility were not affected by the use of BC, with average values of 21.6 $g \cdot dm^{-3}$ for OC, 4.6 for pH and 6 for Mg. For micronutrients, the average values were 0.26, 6.94, 25.67, 26.58 and 2.46 $mg \cdot dm^{-3}$ for B, Cu, Fe, Mn, and Zn, respectively. Thus, altough the sorption of micronutrients by BC might occur (Joseph et al. 2021), the levels did not change compared to the control. Importantly, the nonresponse of soil OC to BC application probably arose due to the analysis method used–wet oxidation in an acidic medium (CONAMA 2020). Wet oxidation did not satisfactorily recover total carbon from BC (Carnier et al. 2021). The effect of BC on the increase in total soil carbon has been relatively well documented (Grutzmacher et al. 2018, Li et al. 2022, Ding et al. 2023), and its high recalcitrance in the soil is known, with a half-life ranging from hundreds to thousands of years (Fang et al. 2015, Zimmerman 2010). Conversely, it is important to verify that the nonresponse of soil organic carbon to BC, in the case of this study, indicates that Biochar did not cause any loss of original C in the soil, therefore, without the occurrence of a priming effect, which is in accordance with literature data (Chagas et al. 2022).

Changes in the total porosity of the soil by the application of BC were only verified for the 0.05–0.10-m layer (Table 3), in which there was a linear increase with the increase in the application amount. The total porosity increases were discrete, on the order of 0.07% for each ton of applied BC. This discreteness probably arose due to the porosity of the BC. A similar result was found by Karhu et al. (2011) in sandy loam textured soil in a five-years field experiment in which a 2% increase in the total porosity of the 0.00–0.20-m soil layer was observed due to the application of 1.2% wood BC (equivalent to the result between 20 and 30 $Mg \cdot ha^{-1}$ BC in the present study). An increasingly pronounced effect on total porosity was observed by Dempster et al. (2012) in an experiment conducted in a greenhouse for 10 weeks after applying 2.2% eucalyptus BC (between 40 and 50 $t \cdot ha^{-1}$ of BC). The scholars documented an 8% increase in total porosity in sandy soil.

Table 3. Total soil porosity after 28 months of application of biochar doses.

Soil depth (m)	Doses of biochar ($Mg \cdot ha^{-1}$)						CV (%)	Regression*
	0	10	20	30	40	50		
	Porosity (%)							
0.00–0.05	56	56	59	53	57	58	4.1	ns
0.05–0.10	50	50	52	52	52	54	3.1	y = 0.07 x + 49.81 r^2 = 0.83 p = 0.001
0.10–0.20	49	49	52	51	49	51	3.1	ns
0.20–0.30	50	51	50	51	49	49	4.2	ns
0.30–0.40	49	49	50	49	49	48	3.2	ns

*Significant ($p \leq 0.05$); ns: non significant.

Notably, the main responses to the application of BC are expected in the 0.00–0.05- and 0.05–0.10-m layers since the effective operating depth in conventional soil preparation did not exceed 0.15 m (Bavoso et al. 2010). Moreover, the more superficial layers were subjected to further alterations due to soil management and interactions with crop/crop residues and microbiota. Thus, if the responses to the application of BC were discrete, they could be masked by natural variations, especially in the most superficial layer (0.05–0.10 m).

In terms of water–soil interactions, the distribution of pores according to size is more important than the total porosity (Lal 2020) since water drainage and water retention are governed directly by soil macroporosity and microporosity, respectively (Table 4). Additionally, for these attributes, an effect of the application of BC was observed only in the 0.05–0.10-m layer, with increases in both macroporosity and microporosity.

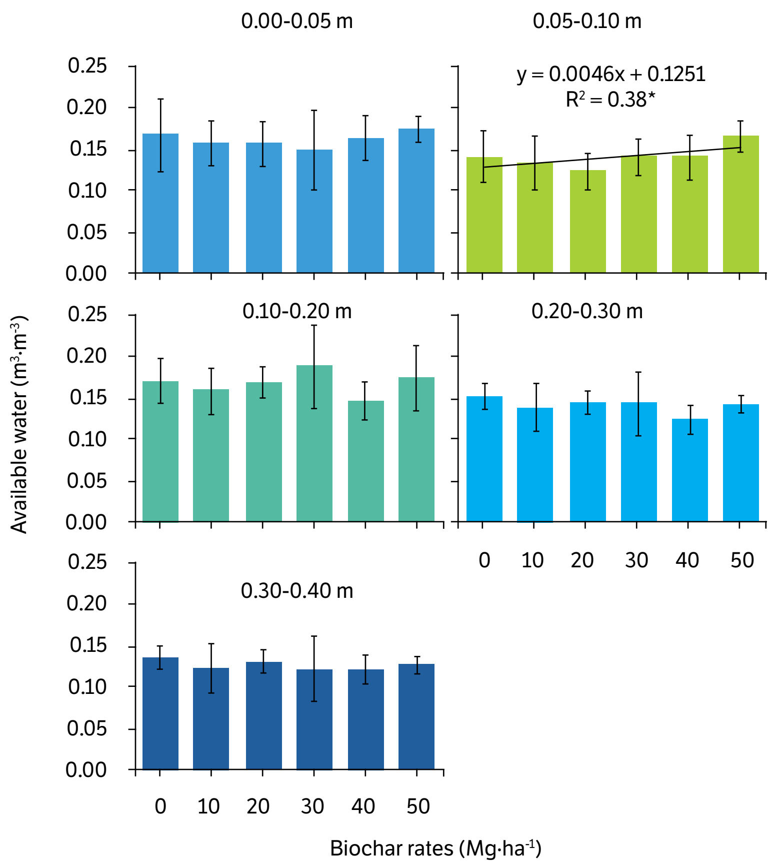
Table 4. Macroporosity and microporosity of the soil after 28 months of application of doses of biochar.

Soil depth (m)	Doses of biochar ($Mg \cdot ha^{-1}$)						CV (%)	Regression*
	0	10	20	30	40	50		
	Macropores (%)							
0.00–0.05	22	22	26	22	22	24	10.4	ns
0.05–0.10	16	15	-**	18	18	20	12.3	y = 0.086 x + 15.16 r^2 =0.838; p < 0.001
0.10–0.20	13	12	15	12	13	15	14.3	ns
0.20–0.30	15	17	15	16	15	15	13.9	ns
0.30–0.40	15	15	17	14	14	14	13.8	ns
	Macropores (%)							
0.00–0.05	17	16	16	15	16	17	13.1	ns
0.05–0.10	14	13	-**	14	14	17	11.0	y = 0.051 x + 13,07 r^2 = 0.489; p = 0.020
0.10–0.20	17	16	17	19	15	17	12.4	ns
0.20–0.30	15	14	14	14	12	14	12.6	ns
0.30–0.40	14	12	13	12	12	13	11.4	ns

**Data lost; *Significant ($p \leq 0.05$); ns: not significant ($p > 0.05$).

The increases in macroporosity per t of applied BC were 0.07%. For microporosity, the increase was 0.06% per t of applied BC. These values indicated that, for the highest dose of biochar tested, the gains were 3.5 and 3% for macroporosity and microporosity, respectively. Notably, the BC had high stability (97%) after soil application, presenting 516 years of average residence time (Wang et al. 2016). This stability was corroborated by the H/C ratio of soil (0.40); ratios lower than 0.7 indicated the presence of many aromatic rings within the structure and, therefore, high stability in soil (IBI 2015). Thus, successive applications in the same area tended to present cumulative effects.

Similar to the changes in the total porosity, macroporosity, and microporosity, there was an increase in the available water for the plants as a function of the amount of BC applied to the soil only in the 0.05–0.10-m layer (Fig. 3). The angular coefficient of the equation in Fig. 3 for the 0.05–0.10-m layer indicated a 0.001-m3 increase in water availability for each 1 m3 of soil. When considering 1 hectare, this increase corresponded to a volume of 500 L per t of applied BC.



*Significant regression ($p \leq 0.05$). Bars indicate the standard deviation ($n = 4$).

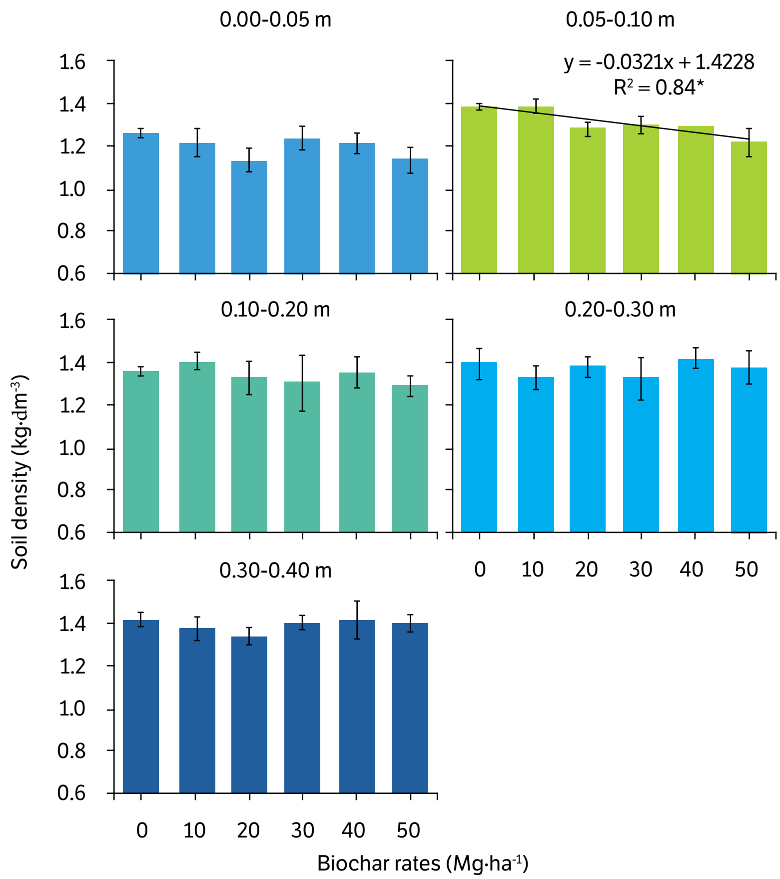
Figure 3. Available water in soil (layers 0.00–0.05; 0.05–0.10; 0.100–0.20; 0.200–0.30 and 0.30–0.40 m) 28 months after applying 0, 10, 20, 30, 40 and 50 Mg·ha^{-1} of biochar.

Thus, for 50 Mg·ha^{-1} of BC, an additional 25,000 L of water was available for the crops. Nevertheless, this amount of water was insufficient to benefit the corn crop, which had a high-water demand (3 mm·day^{-1} for 6–7 established leaves and 5–7.5 mm·day^{-1} during ear formation and maturation). Conversely, winter crops, such as wheat, could benefit from this increase, especially in the establishment and tillering phases, which have water needs of 0.70 and 0.93 mm/day (7,000 and 9,300 L·ha^{-1}), respectively (Libardi and Costa 1997).

Several authors (Busscher et al. 2010, Briggs et al. 2012, Case et al. 2012, Novak et al. 2012) have reported increases in the WRC of soil with the use of BC, including Kammann et al. (2011), who found increases of 23.9 and 36.1% in the WRC of soil with the addition of 100 and 200 Mg·ha^{-1} of quinoa BC, respectively. Alkhasha et al. (2018) found an 8.1% increase in the WRC at low voltages (Ψm smaller than -0.010 MPa), suggesting an increase in macroporosity and therefore an improvement in water drainage of the soil. However, the BC rates applied in these experiments were quite high, at least twofold higher than the high rate evaluated in this study.

Other issues concern the buffering effect and resilience of clayey soils rich in iron oxides/hydroxides and aluminum hydroxide, in which the responses of soil hydrophysical attributes are less evident than in sandy soils, requiring more BC, as shown in the meta-analysis performed by Edeh et al. (2020). However, it is important to mention that an economic assessment must be made in relation to the cost-benefit of applying high doses of BC (Maroušek et al. 2017).

Furthermore, the addition of BC provided a change in soil bulk density (Fig. 4) in the 0.05–0.10-m layer. There were decreases in the soil bulk density values according to the increase in the dose of BC applied. The higher dose of BC applied (50 Mg·ha^{-1}) provided a 0.07-kg·dm^{-3} decrease in soil bulk density (1.38 kg·dm^{-3} for the control treatment and a 1.21-kg·dm^{-3} decrease for the treatment with 50 Mg·ha^{-1}). The mixing effect in soil bulk density was characterized by the incorporation of material with a reduced density to another material with an increased density, resulting in an average value dependent on the proportions of the components and the initial differences in their material density (Melfi and Montes 2001).



*Significant regression ($p \leq 0.05$). Bars indicate the standard deviation ($n = 4$).

Figure 4. Soil bulk density (layers 0.00–0.05; 0.05–0.10; 0.10–0.20; 0.20–0.30 and 0.30–0.40 m) 28 months after applying 0, 10, 20, 30, 40 and 50 Mg·ha^{-1} of biochar.

When only the mixing effect occurs, it appears in all soil layers because of the differences between the original densities of soil and BC (0.33 and 1.38 kg·dm^{-3}, respectively). However, the effect only appeared in the 0.05–0.10-m layer, demonstrating the interactions between BC and soil particles, with an aggregation and porosity response extending beyond the simple mixture of two contrasting materials. Similarly, this phenomenon is evidenced in the work of Zhang et al. (2012), in which, after the first application of 40 Mg·ha^{-1} of BC (density of 0.65 kg·dm^{-3}), there was a reduction in the original soil density of 0.10 kg·dm^{-3} in the first year and 0.06 kg·dm^{-3} in the second year.

With the increase in total porosity and decrease in soil bulk density in the 0.05–0.10-m layer, a decrease in soil resistance to penetration in this same layer was expected. However, the BC did not interfere with the soil penetration resistance (Fig. 5). This result was similar to that reported by Mukherjee and Zimmerman (2013), who found no effect of the addition of BC (0.5% w/w) on the penetration resistance of a clayey soil. In sandy-textured soil, Busscher et al. (2010) observed reduction in the soil penetration resistance with the addition of BC, with values of 1.04 MPa for the treatment without BC and 0.82 MPa for the treatment with 20 g·kg^{-3} of BC added to the soil (approximately 40 Mg·ha^{-1} BC). Notably, the resistance to soil penetration reported by Busscher et al. (2010) showed values lower than those in layers deeper than 0.05 m, making it difficult to perceive small changes.

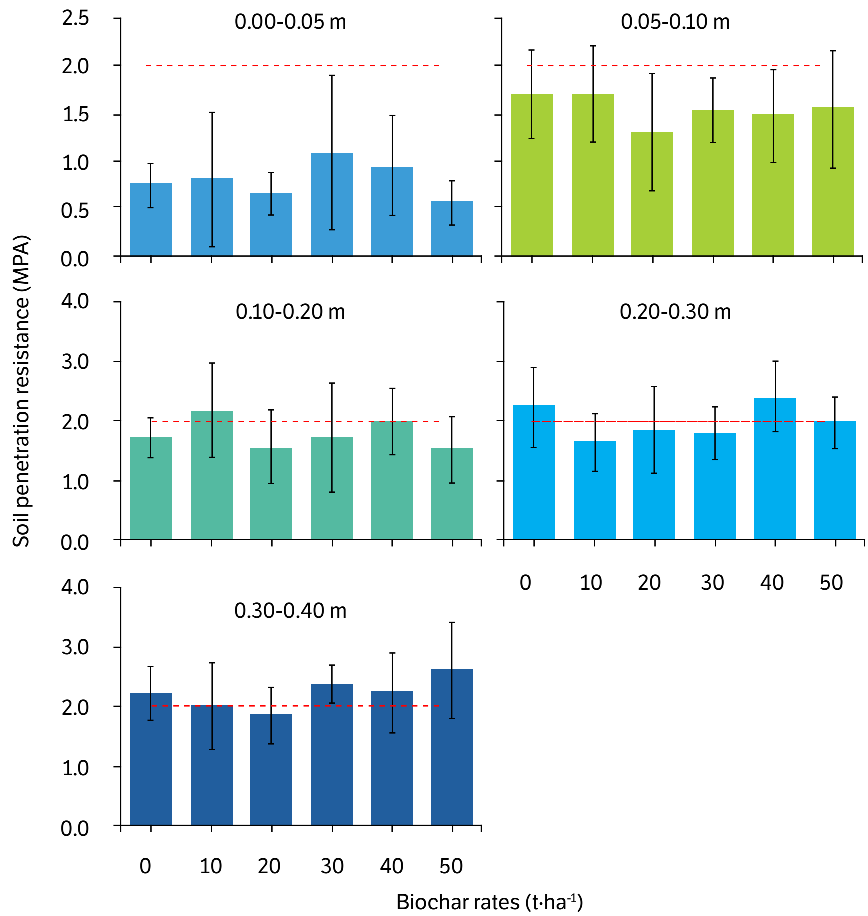


Figure 5. Soil resistance (layers 0.00–0.05; 0.05–0.10; 0.10–0.20; 0.20–0.30; and 0.30–0.40 m) after 28 months of application of doses of biochar equivalent to 0, 10, 20, 30, 40 and 50 t·ha^{-1}. Equilibrium soil moisture after being submitted to -0.033 Mpa Ψm. Limiting value for the growth and development of root systems (Tormena et al. 1998). Bars indicate de standard deviation (n = 4).

CONCLUSION

In a tropical environment with a clayey highly weathered soil that is rich in oxides and hydroxides of Fe and Al, under field conditions, applying BC in amounts between 30 and 50 Mg·ha^{-1} improved some soil fertility attributes in the 0–0.2-m soil layer. This improvement occurs due to the availability of P, Ca and K, the retention of exchangeable cations, and the hydrophysical attributes (porosity and water availability) in the 0.05–0.10-m layer.

CONFLICT OF INTEREST

Nothing to declare.

AUTHORS' CONTRIBUTION

Conceptualization: Coscione, A. R., Andrade, C. A. and Maria, I. C.; **Investigation:** Lucon, I. M., Maria. I.C., Coscione, A. R., Andrade, C. A. and Guimarães Júnnyor, W. S.; **Methodology:** Maria, I. C. and Guimarães Júnnyor, W. S.; **Writing – Original draft:** Lucon, I. M. and Coscione, A. R.; **Writing - Review & Editing:** Coscione, A. R., Andrade, C. A. and Carnier, R.;

Formal analysis: Guimarães Júnnyor, W. S. and Lucon, I.M.; **Data Curation:** Coscione, A. R.; **Resources:** Coscione, A. R.; **Project Administration:** Coscione, A. R. and Andrade, C. A.; **Supervision:** Coscione, A. R.

DATA AVAILABILITY STATEMENT

All dataset were generated and analyzed in the current study.

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