Journal of Agricultural Science; Vol. 14, No. 5; 2022
ISSN 1916-9752 E-ISSN 1916-9760
Published by Canadian Center of Science and Education

Biochar After Thirteen Years of Agricultural Crops on the Physical Attributes and Organic Carbon of a Yellow Oxisol in Central Amazon

Heitor Marcel da Silva Ribeiro[1], Afrânio Ferreira Neves Jr.[2], Danielle Monteiro de Oliveira[3],
José Adcarlos Neles Ferreria[4], Reginaldo Barboza da Silva[5], Bruno Costa do Rosário[3],
Ricardo Bezerra Hoffmann[6], Francisca Alcivania de Melo Silva[5] & Newton Paulo de Souza Falcão[3]

[1] School of Agrarian and Veterinarian Sciences, Departament of Agronomy (Soil Science), São Paulo State University, Campus of Jaboticabal, Jaboticabal, São Paulo, Brazil

[2] Center for Distance Education Minicamps, Federal University of Amazonas, Amazonas, Brazil

[3] Technology and Innovation Coordination, National Institute for Amazonian Research, Manaus, Amazonas, Brazil

[4] Superintendence of the Manaus Free Trade Zone, Coordination of Agricultural Projects, Amazonas, Brazil

[5] College of Agricultural Sciences, Departament of Agronomy, São Paulo State University, Campus of Registro, Registro, São Paulo, Brazil

[6] Federal Institute of Education, Science and Technology of Acre, Acre, Brazil

Correspondence: Heitor Marcel da Silva Ribeiro, School of Agrarian and Veterinarian Sciences, Departament of Agronomy (Soil Science), São Paulo State University, Campus of Jaboticabal, Via de Acesso Professor Paulo Donato Castellane S/N-Vila Industrial, 14884-900, Jaboticabal, São Paulo, Brazil. Tel: (16)-320-971-107. E-mail: heitoribeiro85@gmail.com; heitor.marcel@unesp.br

Received: February 24, 2022 Accepted: March 23, 2022 Online Published: April 15, 2022
doi:10.5539/jas.v14n5p88 URL: https://doi.org/10.5539/jas.v14n5p88

Abstract

Biochar has been identified as a conditioner for the physical, chemical and biological properties of the soil. In this perspective, it is reckoned that when added in the long term, this material may condition improvements in the physical properties of agricultural soils. As a result, the objective of this work was to quantify changes in the physical attributes of the soil after thirteen years of the addition of biochar in a Yellow Dystrophic Oxisol in Central Amazon, in the agricultural ecosystem in Brazil. In a thirteen-year experiment (2006-2019) with rotation of agricultural crops, the physical properties of a clayey Yellow Oxisol with the addition of increasing doses of biochar, were studied. The experiment was conducted in randomized blocks, with four replications and four treatments, making up sixteen experimental units with a size of 10 m × 10 m (100 m^2). The analysis of the results did not indicate a positive effect on most of the physical attributes studied, however, there was significance only for two sets of data. Compared to soil without biochar, there was a decrease in the density of soil particles, and an increase in soil resistance to penetration into the surface layer, in soil with biochar. No difference was found in the subsurface layer for all evaluated attributes.

Keywords: soil conditioner, soil physics, Amazonas

1. Introduction

The Yellow Oxisol is predominantly the soil class that constitutes the most representative pedogenetic unit in the Amazonian mainland ecosystem (Radambrasil, 1975; Leite & Medina, 1984). Despite the fact it presents good physical properties, for the most part with regard to the structure (Leite & Medina, 1984), the effects of land occupation in the Amazon that begins with the clearing of the forest for subsequent replacement by agriculture and pasture cause numerous changes in the attributes soil, often causing degradation of these soils (Cravo & Smyth, 1997; Marques et al., 2004; Soares et al., 2016).

In the State of Amazonas, mainly in areas near to Manaus, intensive cultivation of the soil and its preparation in inadequate conditions modify its physical characteristics. This is often attributed to the high annual rainfall that occurs in this region and to the indiscriminate use of mechanization when preparing the soil (Souza et al., 2004). For Oliveira et al. (2015) changes in soil attributes can be aggravated due to the management to which the soil is subjected. Thus, the process of replacing forested areas with agricultural crops, results in changes in the values of soil density, porosity, pore diameter and aeration porosity, water infiltration, aggregation and organic matter content (Leite, 1996; Klein et al., 1998; Longo, 1999; Carvalho et al., 1999; Mello Ivo & Mielniczuk, 1999; Reis et al., 2009).

An alternative to mitigate the impacts caused on the physical properties of these soils is the adherence to the use of biochar in management, since in the region a lot of coal is produced, with the disposal of waste that consequently generates accumulations. As well as ash from coal production, coal fines are also discarded, making it necessary to study technological applications for these materials (Siqueira et al., 2012).

Biochar (BC) is considered to be the product from incomplete biomass pyrolysis, produced with or without low oxygen conditions, at a relatively low temperature (< 700 °C) (Castellini et al., 2015). Unlike charcoal, this material is produced with the objective of being added to the soil due to its corrective action (Lehmann & Joseph, 2009), which can increase the development and productivity of agricultural crops (Glaser et al., 2002; Jeffery et al., 2011) due to its inherent properties to a high specific surface area and its effects on soil properties (Yamato et al., 2006; Steiner et al., 2007; Sun et al., 2015). Furthermore, it is a technology that can benefit soils with low levels of Organic Carbon (Blanco-Canqui, 2017).

Despite its importance, studies on the use of biochar in soils have focused more on the effects linked to the chemical properties of the soil than on the effects on physical properties (Atkinson et al., 2010). However, an improved understanding of how the physical properties of the soil respond to the addition of biochar is indispensable for the overall performance of the soil (Blanco-Canqui, 2017). In addition, most studies were carried out with incubation in laboratories and pot testing in a greenhouse, however, reports on field studies are only now emerging (Obia et al., 2016), with short-term experiments (≤ 4 years) (Pandian et al., 2016; Qin et al., 2016; Usowicz et al., 2016; Zheng et al., 2016).

The addition of biochar potentially decreases the density of the soil (Ds) by an average of 12% (Omondi et al., 2016; Blanco-Canqui, 2017), in the same way that it reduces the soil particles density (Dp) from 14% to 64% according to the volume of C added (Githinji, 2014), and consequently it can increase the total porosity (Pt) of the soil between 2% to 41% (Omondi et al., 2016; Blanco-Canqui, 2017). On the other hand, biochar may not reduce resistance to soil penetration in the short term (Rogovska et al., 2014; Bekele et al., 2015; Obia et al., 2017). Despite these discoveries, the effects of BC on physical attributes in clay soils is still an open question. Therefore, our hypothesis is that increasing doses of BC affect the physical characteristics of the clayey Yellow Oxisol when analyzed after a long term.

Therefore, the objective of this study was to verify the effect of increasing doses of biochar after 13 years on the modifications of the basic physical attributes and organic carbon, in a clayey Yellow Dystrophic Oxisol from Central Amazon.

2. Materials and Methods

2.1 Study Area

The study was conducted in a Yellow Dystrophic Oxisol at the Experimental Station of Tropical Fruit of INPA (EEFT), located in the northwest region of Amazonas (latitude 2°37′12″S and longitude 60°2′27″W), distant 45 km from the capital Manaus (Figure 1). According to the Köppen classification, the climate is of the Af type with two well-defined climatic seasons: the rainy season from November to June, and another dry season from July to October. The average annual precipitation is 2286 mm, with a relative humidity of 80%, and temperature variations between 23.3 °C to 31.4 °C, presenting an annual average of 26.7 °C (Alvares et al., 2013).

Figure 1. Location of the experimental area (EEFT), km 45 da BR174, Manaus, Amazonas, Brazil

Before the area opening, the existing vegetable composition was a 30-year old capoeira, which was removed in 2003 and shortly before the installation of the experiment in 2006, using conventional cutting techniques and without burning the residues, aiming later to test the effects of increasing doses of biochar on the soil. Thus, in the beginning of 2006 there was a delimitation of the experimental area according to the total area felled (0.44 ha).

The biochar (fines of coal) was obtained from the production of commercial coal in the metropolitan charcoal plants of Manaus, produced in artisanal ovens known as “hot tail” that can reach temperatures from 470 °C to 600 °C with no oxygen (Swami et al., 2009).

Before application to the soil, samples of the biochar were collected, ground and sieved at 2.00 mm for chemical characterization (Table 1). The material was added manually to the soil in the months of February and March 2006, being incorporated at 0.20 m from the soil, with the aid of hand tools (hoe). From that, a rotation system for agricultural crops was implemented, followed by complementary mineral fertilization, use of mechanization for clearing, and intercalated fallow periods. Finally, the area was prepared prior to the planting of Pau-rosa seedlings (Aniba rosaeodora Ducke) as illustrated in (Table 2).

Table 1. Chemical characteristics of the bio-charcoal added to the EEFT Dystrophic Yellow Oxisol in 2006

Material	**C**	**N**	**Ca**	**Mg**	**K**	**P**	**Zn**	**Mn**
	-------- $g\ kg^{-1}$ --------						------ $mg\ g^{-1}$ ------	
Biochar	873.26	8.93	6.22	1.30	2.08	0.16	12.00	67.00

Table 2. History of complementary fertilization, agricultural crops in the crop rotation system, and type of mechanization in land preparation

Year	Range	Soil Culture	Soil preparation[a]	Urea		
				45% N	42% P_2O_5	60% K_2O
				kg ha^{-1}		
2006	1°	*Zea mays*	mechanization	66	177	100
2007	2°	*Zea mays*	no mechanization	66-133[b]	-	-
	1°	*Vigna unguiculata*	no mechanization	-	-	-
2008	3°	*Zea mays*	mechanization	133	350	200
	2°	*Vigna unguiculata*	no mechanization	-	-	-
2012	3°	*Vigna unguiculata*	mechanization	-	-	-
2016	4°	*Zea mays*	mechanization	-	-	-
2018	-	*Aniba rosaeodora* Ducke	mechanization	-	-	-

Note. [a] Use of an agricultural tractor in periodic clearings (Massey Ferguson 250X year 1998); [b] Fertilization in two stages, first 66 kg ha^{-1} before sowing and the second 133 kg ha^{-1} after sowing.

2.2 Experimental Design and Treatments

The design was applied in randomized blocks with four replications and four treatments, totaling 16 experimental units (plots). The size of each plot corresponded to 10 × 10 m (100 m^2). The treatments B_0, B_{40}, B_{80} and B_{120} formulated from the increasing doses of biochar 0, 40, 80 and 120 Mg ha^{-1}, respectively, were incorporated proportionally in the plots, obeying the draw in the field.

2.3 Soil Sampling

Sampling was completed 13 years after the addition of the bio-charcoal in October 2019, preceding the planting of Pau-rosa seedlings (Aniba rosaeodora Ducke). With the soil at field capacity, standard samples were collected, as well as deformed samples, at depths 0.0-0.10 m and 0.10-0.20 m. The standard samples were removed by the volumetric cylinder method with the aid of a soil sampler, using metallic cylinders that measure 5 cm in diameter, 5 cm in height, and a total volume of 98.175 cm^3 (Elisabeth & Claessen, 1997).

A Dutch auger was used to collect samples with deformed structures, and to collect soil resistance to penetration (SRP) data, a field impact penetrometer was used at depths of 0.0-0.10 m; 0.10-0.20 m.

A 5 × 5 m quadrant was established in the center of each sampling unit (usable area), so the standard samples were collected at the vertices of these quadrants (4 points), and the deformed samples in the center of the quadrants. In this way, 4 standard samples and 4 deformed samples per plot were collected, making a total of 128 samples for each type of sampling (deformed and standard). That is, 4 treatments × 4 repetitions × 4 samples per plot × 2 depths = 128 samples × 2 types of samples = 256 total soil samples.

For the PR variable, 3 readings (simple samples) were taken close to the collection point of each standard sample in the plot, totaling 12 readings per plot. Then, the average was calculated and 4 readings were obtained per plot, maintaining a sample size and / or number of elements (n) equal for all variables evaluated.

2.4 Analysis of Soil Physical Attributes

The standard ones were weighed in the field to regulate the wet mass, with the aid of a digital scale containing three decimal places, and then they were packed with aluminum foil, and transported to the Thematic Laboratory of Soils and Plants (LTSP) of the National Institute of Amazon Research-INPA Manaus, for subsequent drying in an oven at 105 °C for 24 hours.

In the determination of Gravimetric Moisture (GM) we used the method of difference of the water mass present in the sample under collection conditions, and the dry mass of the sample in an oven. In this case considered: CGA (kg kg^{-1})-gravimetric water content; a (g)-mass of the wet sample; b (g)-mass of the sample dried at 105° C for 24 hours (Teixeira et al., 2017).

$$\text{CGA} = \frac{a - b}{b} \tag{1}$$

Soil density (SD) was measured using the volumetric cylinder method. This methodology is based on the volume of the cylinder and the mass of the sample dried at 105 °C for 24 hours, following the following criteria: Ds: soil density (g cm^{-3}); ma: mass of the dry sample (g); V: volume of the volumetric cylinder (cm^{-3}) (Teixeira et al., 2017).

$$Ds = \frac{m_a}{V} \quad (2)$$

The data on the density of soil particles (SPD) were obtained using the volumetric flask method (Forsythe, 1971; Teixeira et al., 2017). Therefore, the total porosity (TP) was determined through the calculation using the two densities (SD, SDP) as demonstrated in the formula, where, Pt: total porosity (m^{-3} m^{-3}); Ds: soil density (g cm^{-3}); Dp: density of soil particles (g cm^{-3}) (Donagema et al., 2011).

$$Pt = \frac{D_P - D_S}{D_P} \quad (3)$$

Soil resistance to penetration (PR) was verified using a SONDATERRA impact penetrometer, ModeloPI-60, in which the conversion of data into MPa follows the principles (Stolf, 1991). In addition, for the organic carbon data, the Walkley and Black method was used, which is based on the analysis of the wet soil by oxidation with potassium dichromate (Walkley & Black 1934; Teixeira et al., 2017).

The granulometry of the soil was determined by the pipette method (Gee & Bauder, 1986), using a 1 mol L^{-1} NaOH solution as a chemical dispersant and mechanical agitation in a high-speed apparatus for 15 minutes, then the clay fraction was separated by sedimentation, sand by sieving and silt was calculated by difference, according to Embrapa's methodology (Teixeira et al., 2017).

Knowing that the granulometry is a very stable physical attribute, in this work the granulometry data of the soil particles were used only for textural classification of the soil (Table 3) (Leite & Medina, 1984).

2.5 Statistical Analysis

All data were submitted to the Levene and Shapiro-Wilk tests ($p < 0.05$) in order to verify the homogeneity of the variances and the normality of the data sets, respectively. Analysis of variance (ANOVA) was applied, and when there was a significant difference between the means, the Tukey test ($p < 0.05$) was used, thus analyzing the effects of treatments on soil attributes. All analyzes were performed using the statistical software R 3.6.0.

Table 3. Textural class and particle distribution of a Yellow Oxisol from Central Amazon

Treatments	**Biochar Doses**	**Depth**	**Soil Particle**			**Textural Class**
			Sand	**Clay**	**Silt**	
	Mg ha^{-1}	m	----------------	g kg^{-1}	---------------	
B_0	0	0.0-0.10	252	610	138	Clay
B_{40}	40	0.0-0.10	249	630	121	Clay
B_{80}	80	0.0-0.10	228	645	128	Clay
B_{120}	120	0.0-0.10	252	641	107	Clay
B_0	0	0.10-0.20	245	654	101	Clay
B_{40}	40	0.10-0.20	201	668	130	Clay
B_{80}	80	0.10-0.20	213	686	101	Clay
B_{120}	120	0.10-0.20	212	684	104	Clay

3. Results and Discussion

3.1 Main Effects of Biochar on Soil Physical Attributes

The treatments (increasing doses of biochar) represented the explanatory variables, while the physical attributes of the soil the response variables. The data were analyzed separately considering the two depths established, superficial (0.0-0.10 m) and subsurface (0.10-0.20 m) (Table 3). In addition, most of the data sets followed normality, with variable (RP) data being transformed (log-normal) in the superficial layer, and (RP; CO) in the subsurface layer.

After applying the analysis of variance (ANOVA) in the classes of surface depth data, a significant difference was detected for Ds ($p < 0.05$*) and RP ($p < 0.001$**). Therefore, the Tukey test ($p < 0.05$) was used to assess sensitivity and distinguish differences. From this, the following sequence is noted in the differences in Ds between treatments ($B_0 = B_{40} = B_{120} > B_{80}$), observing the lowest mean in treatment B_{80} (2.24±0.12 g cm^{-3}), which makes it different from the control treatment B_0 (2.38±0.10 g cm^{-3}) due to the decrease of 0.14 g cm^{-3} equivalent to 5.9% (Figure 2).

In addition, significant differences were detected for RP in the surface layer, demonstrated by treatments B_{40}** and B_{80}**, which presented the highest averages between the analyzed treatments (1.78±0.8 MPa) and (1.78±0.09

MPa), respectively (Figure 2). In this case, there is a difference between treatments, in which $B_{40} = B_{80} > B_0 = B_{120}$, caused by an increase of 0.18 MPa in treatments B_{40} and B_{80}, a change that corresponds to 11% in relation to treatments B_0 and B_{120}.

Furthermore, no significant differences were found in the subsurface layer, since the ANOVA values for all tested attributes resulted in $p > 0.05$ (Table 4), with the use of a posteriori test being discarded.

Table 4. Results of ANOVA and Tukey's test in relation to the physical attributes and organic carbon of the soil of the experiment with increasing doses of biochar in Central Amazon. (n = 16)

Depth		Ug	Ds	Dp*	Pt	PR**	CO
0.0-0.10 m		kg kg^{-3}	------------ g cm^{-3} ------------		m^{-3} m^{-3}	MPa	g kg^{-1}
Treatments	B_0	0.28 a	1.27 a	2.38 a	0.47 a	1.60 b	15.1 a
	B_{40}	0.28 a	1.24 a	2.31 ab	0.47 a	1.78 a	18.2 a
	B_{80}	0.30 a	1.20 a	2.24 b	0.47 a	1.78 a	18.1 a
	B_{120}	0.29 a	1.24 a	2.30 ab	0.46 a	1.60 b	17.0 a
	CV (%)	9.02	8.16	5.88	12.22	5.43	21.04
Depth		Ug	Ds	Dp	Pt	PR	CO
0.10-0.20 m		kg kg^{-3}	------------ g cm^{-3} ------------		m^{-3} m^{-3}	MPa	g kg^{-1}
Treatments	B_0	0.28 a	1.29 a	2.34 a	0.45 a	2.21 a	13.5 a
	B_{40}	0.27 a	1.35 a	2.31 a	0.41 a	2.34 a	13.6 a
	B_{80}	0.27 a	1.32 a	2.35 a	0.44 a	2.18 a	12.2 a
	B_{120}	0.28 a	1.33 a	2.37 a	0.44 a	2.25 a	12.2 a
	CV (%)	8.65	5.82	4.35	9.44	12.75	24.89

Note. Gravimetric Moisture (Ug). Soil density (Ds). Density of soil particles (Dp). Total porosity (Pt). Soil resistance to penetration (RP). Organic carbon (CO). Coefficient of variation (CV). * Significance (α) 0.05. ** significance (α) 0.001. Means followed by the same letters do not differ statistically, and means followed by different letters indicate significant differences by the Tukey test.

The results gap on the effects of the use of biochar in clayey Oxisol in the Central Amazon is evident, especially when referring to long-term field studies involving assessments of physical quality indexes. Therefore, our results establish unique discoveries about the basic analysis of the physical attributes of this type of soil managed with biochar in this region. Although for most of the variables there were no significant changes, the hypothesis was confirmed that in agricultural soils with a high content of clay fraction and low use of mechanization, the addition of biochar reduces the density of soil particles, but can increase the resistance of the soil to penetration in the superficial layer, without causing effects in the subsurface layer.

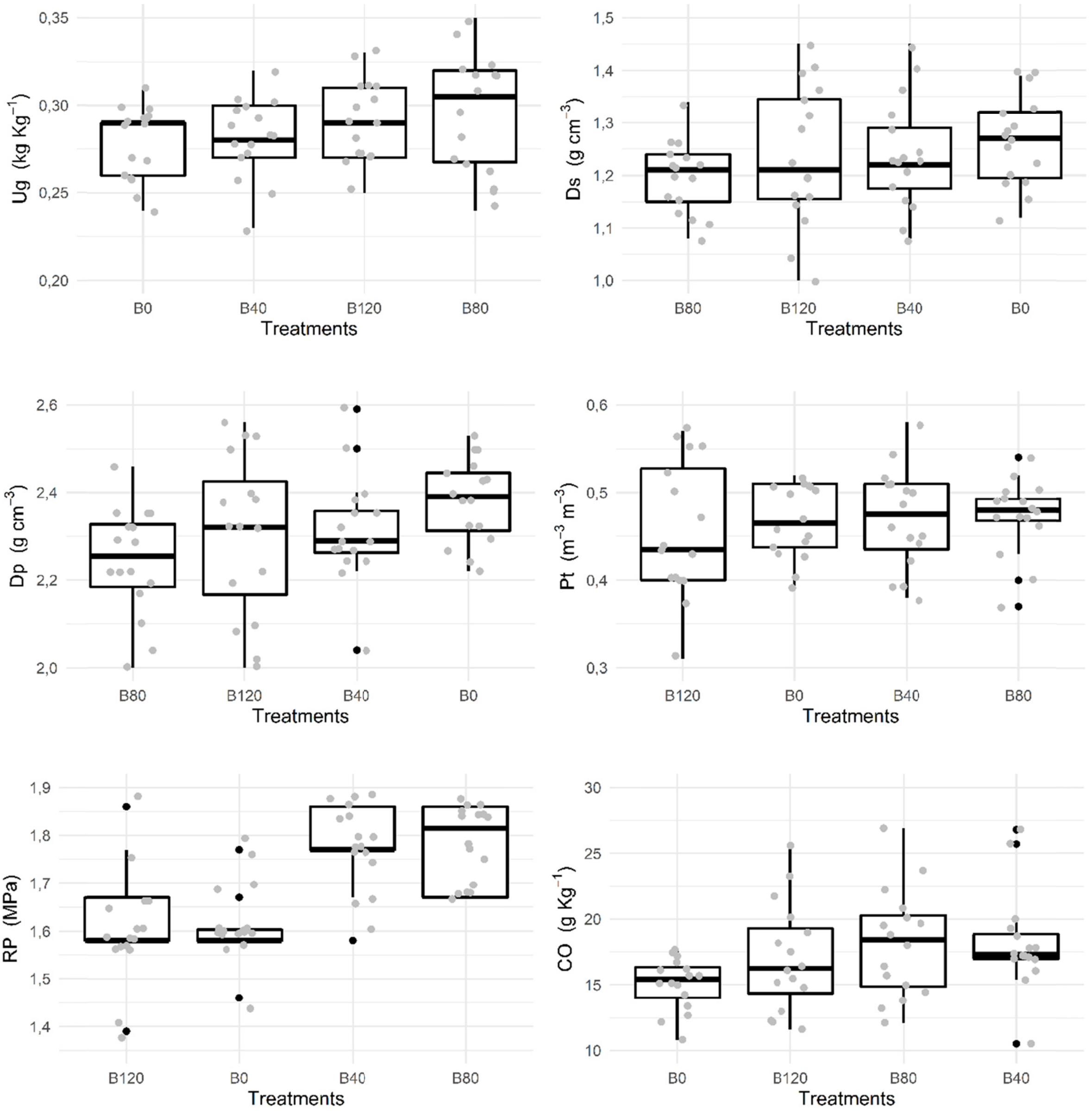

Figure 2. Effects of increasing doses of biochar (treatments) on the physical attributes and organic carbon of a Yellow Dystrophic Oxisol in the Central Amazon, at a depth of 0.0-0.10 m. The treatments are plotted in ascending order according to the averages. The gray dots correspond to the 16 observations (n), and the black dots indicate the occurrence of outliers

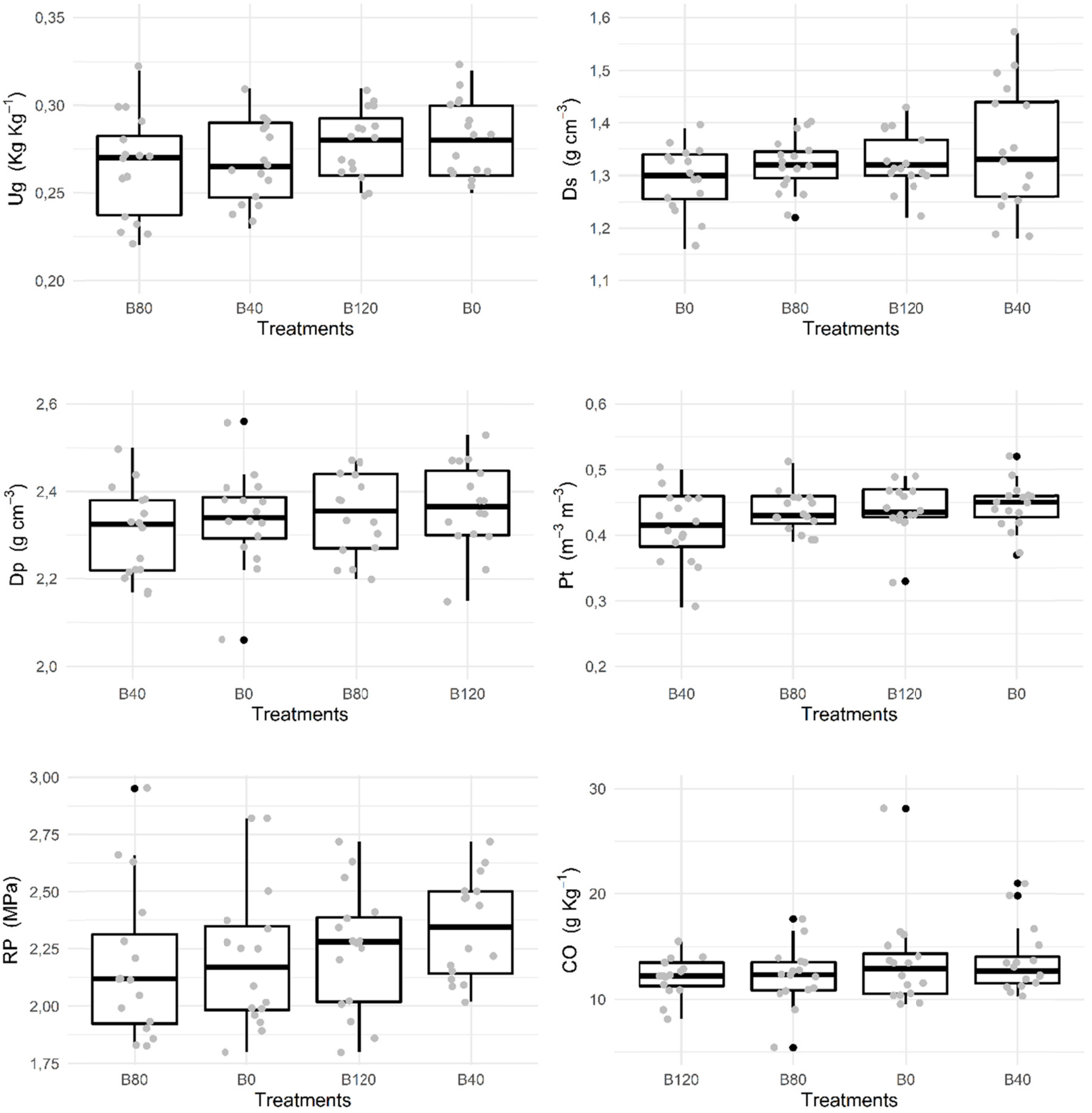

Figure 3. Effects of increasing doses of biochar (treatments) on the physical attributes and organic carbon of a Yellow Dystrophic Oxisol in the Central Amazon, at a depth of 0.10-0.20 m. The treatments are plotted in ascending order according to the averages. The gray dots correspond to the 16 observations (n), and the black dots indicate the occurrence of outliers

3.2 Effects of Biochar on Soil Gravimetric Moisture

The data from the present study show that there was no difference in Gravimetric Moisture (Ug) between the treatments investigated at both depths ($p > 0.05$). This means that even an arable layer of soil (0.20 m) does not change even when increasing doses of biochar are added.

Considering that the edaphic quality of natural ecosystems has been proposed as a reference (Gregorich, 2002), these results are similar to the findings by Fernandes et al. (2014) who investigated the effects in Ug as a result of the replacement of forested areas by different pastoral systems on the physical attributes of a Yellow Dystrophic Oxisol. From this, it is proven that the crop rotation system adopted in this research, independently, presents greater Ug when compared to pasture systems, as well as being similar to the results of a native forest in medium texture soil, which in this context, did not show degradation of this attribute for this type of land use. Nevertheless, Ramos et al. (2010) noted that even with changes in the Ds due to animal trampling, it was not possible to consider the difference in Ug of these pastoral systems in relation to the native forest in fine textured soil. Therefore, although high doses of biochar did not affect the current moisture gravimetric water content in the clayey Yellow Oxisol, the stability of the high values of Ug in this system can be attributed both to the textural class, and to the low impact due to mechanization and the absence of animal trampling.

3.3 Effects of Biochar on Soil Density

The findings of this research point out that the Ds in the superficial layer is explained with a small reduction when the amount of biochar was increased, with the lowest mean in the B_{80} treatment (1.20±0.07 g cm^{-3}). Not least, in the 0.10-0.20 m layer, there was an increase in Ds in the treatments that contained biochar, as observed in the sequence ($B_{40} > B_{120} > B_{80} > B_0$). Despite this, there were no existing effects of biochar on the density of the soil under study, since in this case the B_0 control treatment (without biochar) presented the lowest average (1.29±0.06 g cm^{-3}) with a slight increase when biochar was added, finding the highest average B_{40} treatment (1.35±0.09 g cm^{-3}).

These results are in line with a similar study developed in the short term in clayey soil, which, by adding increasing doses of biochar from fruit tree pruning residues, had no significant effect on soil density (Castellini et al., 2015). This lack of significance or decrease can be attributed to heterogeneity in the BC particle sizes used in this experiment, since for Obia (2016) the quantity of BC is more important in the changes of Ds in sandy soils, while the particle size and the amount of BC is preponderant for the reduction of Ds in soils with clay texture. Despite this, it is possible to observe that the reductions in Ds in the superficial layer (0.0-0.10 m) compared to the control treatment, varied from 0.03-0.07 g cm^{-3}. These results converge with those presented by Obia et al. (2016), who demonstrated the reducing action of BC on the Ds of a sandy-clay soil between 0.04-0.06 g cm^{-3}.

Although it is possible to find in some literature that, as the doses of biochar increase, the density of the soil decreases (Blanco-Canqui, 2017), it is believed that this amount may be limiting for these effects in some cases, since in soils with rates > 60 Mg ha^{-1} have a lesser effect on the decrease in Ds when compared to doses < 60 Mg ha^{-1} (Rogovska et al., 2014), not significantly reducing with amounts < 10 Mg ha^{-1} of biochar (Usowicz et al., 2016). In this context, it was proven that from high applications of biochar (up to 50 Mg ha^{-1}) there is no decrease in soil density (Pratiwi & Shinogi, 2016), since this effect depends on the specific characteristics of the biochar (Blanco-Canqui, 2017).

In addition, it is suggested that the application of biochar probably reduces the density of the soil through the mixing effect. That is, the biochar has a lower apparent density (< 0.6 g cm^{-3}) than the soil (~1.25 g cm^{-3}) (Blanco-Canqui, 2017). This explains the greater effects on sandy soils, which happens due to the greater difference between densities. In fact, the difference in apparent density between biochar (0.6 g cm^{-3}) and clay soils (1.1 g cm^{-3}) is less than biochar (0.6 g cm^{-3}) and sandy soils (1.5 g cm^{-3}) (Blanco-Canqui, 2017).

Considering the results of the present work, it is noted that high rates of biochar (coal fines) do not promote changes in the Ds in soils with a very clay texture even in the long run. It is necessary to carry out previous studies on the specific characteristics of the applied material (biochar), as well as the determination of the granulometry or size of the biochar particles.

3.4 Effects of Biochar on Soil Particle Density

The density of the particles of a soil depends exclusively on the composition of the solid particles, being a very stable attribute that can be changed over time, mainly due to the influence of anthropic actions. Mineral soils are commonly found in variations between 2.60 to 2.70 g cm^{-3} (Lier, 2010), and this can be explained by the fact that in the superficial layers, generally richer in organic matter, the values of this physical attribute are relatively lower (Leite & Medina, 1984; Souza et al., 2004; Lier, 2010). Previous studies have reported that these changes occur because different agroecosystems impact on the variability of physical attributes in a clayey Oxisol, attributed to the greater accumulation of organic matter in some cases, whose low specific weight of organic matter contributes to decreasing the particle density (Souza et al., 2004). In this way, changes in Dp values were observed at depths of 0.0-0.20 m; 0.20-0.40 m, which in this context ranged from 2.49 to 2.51 g cm^{-3} in the area occupied by forest, and between 2.50 to 2.59 g cm^{-3} for areas with annual and perennial fruit crops. These results are part of a research developed in the Central Amazon (Souza et al., 2004).

The results of the present work demonstrate that the addition of biochar induces a decrease in Dp at a depth of 0.0-0.10 m by approximately ~6% when 80 Mg ha^{-1} of biochar is applied, or B_{80} treatment (2.24±0.12 g cm^{-3}) compared to the soil without biochar, or B_0 control (2.38±0.10 g cm^{-3}). There was a decrease in Dp as it increased with the amount of coal, observed in the sequence $B_0 > B_{40} > B_{120} > B_{80}$. Githinji, (2014), states that this expansion effect by the addition of biochar is explained by the application of particles that contain higher organic matter and with lower densities, generally less than 1.0 g cm^{-3}. In addition, a decrease in this physical attribute of the soil is related to the concentration of C in the soil (Blanco-Canqui, 2017), being able to reduce Dp by up to 14%, as evidenced by (Usowicz et al., 2016).

However, in the subsurface layer (0.10-0.20 m) there was no significant effect from the addition of biochar in relation to the density of soil particles, even so, a slight variation was found between treatments ($B_{120} > B_{80} > B_0 > B_{40}$), in which it occurs contrary to the effects on the surface layer. Even so, there were no significant differences between the superficial and subsurface layers, demonstrating that this attribute is constant in the agricultural layer (up to 0.20 m deep) for this type of soil.

Based on the data from this research, in fact, the dose of 80 Mg ha^{-1} of BC is considered the ideal rate to cause effects on the Dp of soils with a very clayey texture. In this context, Blanco-Canqui, (2017) reports that doses (> 60 Mg ha^{-1}) can induce changes in the Dp of sandy soils. On the other hand, the application of 30 Mg ha^{-1} of BC reduced the Dp of the sandy soil from 2.55 g cm^{-3} to 2.20 g cm^{-3} (Usowicz et al., 2016). Corroborating these results, findings by Pranagal et al. (2017) approved that after the application of biochar in a clayey soil, there was a temporary decrease in Dp in the layer 0.0-0.10 m, as well as increasing rates of biochar (25%, 50%, 75% v/v) cause reductions of (0.19, 0.25, 0.53, 1.02 g cm^{-3}) in Dp in sandy soil (Githinji, 2014).

3.5 Effects of Biochar on Total Porosity

There was no difference between treatments at both depths ($p > 0.05$) for the total porosity variable (Pt), with only a slight decrease when the depth was increased. These results are in line with the findings by Souza et al. (2004) when demonstrating that in very clayey Oxisol, changes in total porosity are influenced by different uses. These changes can be associated with the use of machinery, accumulation or loss of organic matter, and type of culture (Reis et al., 2009; Oliveira et al., 2014). However, the addition of biochar systems with mechanization and without crops with high biomass production potential below and above ground, does not mitigate the impact on total porosity when compared with ecosystems such as the native forest.

Although the Pt results of this work show better yields compared to systems with no-tillage in medium texture Oxisol (Tormena et al., 2002), they indicate similarities to the systems used in overcrowded pastures, and fruit plantations with mechanization in Oxisol clayey, which cause negative and compromising differences in comparison to forest and capoeira areas (Souza et al., 2004). On the other hand, this Pt approached satisfactory values found in Amazonian Dark Earths, with Pt superior to the area of native forest in yellow Oxisol in the southern region of Amazonas (Soares et al., 2016). After all, there is incongruity between these results and those presented by Obia et al. (2016), who claim to increase total porosity by 2% by adding biochar to the sandy soil, without the effect of this on crops. On the other hand, through experiments ≤ 4 years, it was demonstrated that changes in Pt occur in soils with sandy texture, these changes being insignificant for soils with fine texture, regardless of the amount of biochar (Usowicz et al., 2016; Zheng et al., 2016; Burrell et al., 2016).

3.6 Effects of Biochar on Soil Resistance to Penetration

Among the different physical attributes of the soil, soil resistance to penetration (RP) has been used as an index of soil quality (Carvalho et al., 2006). This is because in addition to being a measure that assesses the quality of agricultural systems, it is related to the growth of plants and it is easily and quickly determined (Smith et al., 1997).

It is found in the literature that the limiting values can vary depending on different cultures and types of soil (Ferreira et al., 2012), although there is consensus that for most cases 2.0 MPa is the critical value related to the root growth (da Silva et al., 1994; Tardieu, 1994; Taylor et al., 1966; Tormena et al., 1998). Despite being an important variable in investigations aimed at the physical characteristics of the soil, field-scale studies relating biochar and RP are not available, and the few existing results were taken from experiments conducted in small plots, under greenhouses and in the short term (< 2 years). These data are incomplete, considering that the biochar may require long periods to react with inorganic soil particles and generate some effect on soil compactibility (Blanco-Canqui, 2017).

From the results obtained in this work it is necessary that, after a long term, the addition of biochar between 40 and 80 Mg ha^{-1} can result in an increase in the RP in the initial layer of the soil (up to 0.10 m in depth), and when enabled 120 Mg ha^{-1}, there is no difference compared to the control treatment (without biochar). Thus, it was attested that in the high layer of 0.0-0.10 m doses of biochar does not reduce the RP in clay, and may cause an increase but not compromising root growth since for all treatments including without biochar, as the averages were below the value estimated critical value (< 2.0 MPa). And in the 0.10-0.20 m layer there was no difference between treatments, even so, for all treatments the levels were considered limiting (> 2.0 MPa). In this context, it is understood that biochar does not cause changes that can cause root growth in this type of system.

In summary, the few data indicate that biochar has little or no effect on resistance to soil penetration (Busscher et al., 2011; Mukherjee et al., 2014; Rogovska et al., 2014; Bekele et al., 2015; Blanco-Canqui, 2017). From another perspective, a positive result pointed to a reduction in RP through an incubation experiment with a short duration (96 days), which shows that the RP decreases with the application of 44 Mg ha^{-1}, not reporting the same effect at lower rates of application (Busscher et al., 2010). This was proven by Eastman (2011), who evaluated applications of increasing doses (0, 5 and 25 Mg ha^{-1} of biochar) in clayey soil of Ohio, USA, did not find a significant difference in the RP values after one year. However, it is suggested that high rates of biochar application may be necessary to significantly alter the soil RP, and thus reduce the risks of soil compaction (Blanco-Canqui, 2017). This statement differs from the results found in this work, considering that the increase in RP can increase the risks of compaction over time.

Moreover, some authors consider that the soil texture alone impacts the different resistance to penetration, since it was observed that a medium textured soil has a lower penetration resistance than a clayey texture in the presence of BC (Dexter et al., 2007; Obia, 2017). However, these data are allowed to make definitive science about the effects of the textural class on RP (Blanco-Canqui, 2017).

The direct comparison of our results with the aforementioned studies is difficult due to the different environments in which the experiments were carried out, textures and types of soils, raw materials for biochar, pyrolysis temperatures, as well as the time periods used in each study. However, the conclusions of these few studies strengthen the discussion and stimulate applications for more research related to changes in the physical attributes of agricultural soils managed with biochar, since in Central Amazon there is a demand for alternative technologies that condition the increase in productivity and the conservation of natural resources.

3.7 Effects of Biochar on Organic Carbon and Organic Matter in the Soil

The levels of organic carbon (CO) and soil organic matter (SOM) did not differ statistically between treatments. However, it was possible to observe slight variations, in which the soil with 40 Mg ha^{-1} showed higher values of CO and SOM in the two depths analyzed. According to Guimarães et al. (2017), the absence of differences can be attributed to the C stability of the non-oxidizable or slightly oxidizable biochar to the reagent used in the methodology, the potassium dichromate, which is an oxidizing agent but does not oxidize carbon in the aromatic structures of the biochar. Proving that in this case, with the Walkley Black method it was not possible to infer differences in the organic carbon of the soil as a function of the C of the added biochar (Petter, 2010), as this method is recommended to quantify only those oxidizable or decomposable materials, being discriminated that of origin from carbonate or recalcitrant compounds such as coal (Walkley & Black 1934).

However, the results presented in this work show that the crop rotation system with fallow intervals does not differ from mechanized agricultural systems and overcrowded pastures (Souza et al., 2004), regardless of the addition of BC. Thus, it is clear that biochar is a recalcitrant material, and even after thirteen years it did not cause differences in the accumulation of SOM. This shows that the application of biochar in the soil, even after thirteen years, did not promote any positive effect that characterized improvements in the physical quality of the soil. In addition, our results show that there is stability in the basic physical attributes for this type of agricultural soil managed with rational use of machines in agricultural rotation systems. Therefore, more studies involving different soils with biochar are needed to verify the effectiveness of this technology in different soils under different use situations, in the Amazon region.

4. Conclusions

The results did not indicate a positive effect of the addition of biochar on the physical attributes of the Yellow Oxisol.

In the superficial layer of the soil there was a significant reduction in the density of soil particles in the treatments that contained 80 Mg ha^{-1} of biochar.

Increasing doses of biochar caused an increase in soil resistance to soil penetration with 40 Mg ha^{-1} and 80 Mg ha^{-1} of biochar.

Acknowledgements

This research was supported by the Coordination for the Improvement of Higher Education Personnel (CAPES) through a scholarship granted to H.M.S. Ribeiro and the National Institute for Research in the Amazon (INPA) through the Graduate Program in Agriculture in the humid Tropic. We would like to thank the Terra Preta Nova research group, the team from the INPA V8 Thematic Laboratory for Soils and Plants, and the technicians from the Experimental Station of Tropical Fruit at INPA.

References

Ajayi, A. E., Holthusen, D., & Horn, R. (2016). Changes in microstructural behaviour and hydraulic functions of biochar amended soils. *Soil Tillage Research, 155*, 166-175. https://doi.org/10.1016/j.still.2015.08.007

Alvares, C. A., Stape, J. L., Sentelhas, P. C., de Moraes Gonçalves, J. L., & Sparovek, G. (2013). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift, 22*, 711-728. https://doi.org/10.1127/0941-2948/2013/0507

Atkinson, C. J., Fitzgerald, J. D., & Hipps, N. A. (2010). Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: A review. *Plant Soil*, 1-18. https://doi.org/10.1007/s11104-010-0464-5

Bavoso, M. A. (2012). *Resiliência física de solos sob plantio direto*. Esalq/USP.

Bekele, A., Roy, J. L., & Young, M. A. (2015). Use of biochar and oxidized lignite for reconstructing functioning agronomic topsoil: Effects on soil properties in a greenhouse study. *Canadian Journal of Soil Science, 95*, 269-285. https://doi.org/10.4141/cjss-2014-008

Blanco-Canqui, H. (2017). Biochar and Soil Physical Properties. *Soil Science Society of America Journal. Am. J., 81*, 687. https://doi.org/10.2136/sssaj2017.01.0017

Burrell, L. D., Zehetner, F., Rampazzo, N., Wimmer, B., & Soja, G. (2016). Long-term effects of biochar on soil physical properties. *Geoderma, 282*, 96-102. https://doi.org/10.1016/j.geoderma.2016.07.019

Busscher, W. J., Novak, J. M., & Ahmedna, M. (2011). Physical Effects of Organic Matter Amendment of a Southeastern US Coastal Loamy Sand. *Soil Science, 176*(1). https://doi.org/10.1097/SS.0b013e3182357ca9

Busscher, W. J., Novak, J. M., Evans, D. E., Watts, D. W., Niandou, M. A. S., & Ahmedna, M. (2010). Influence of Pecan Biochar on Physical Properties of a Norfolk Loamy Sand. *Soil Science, 175*, 10-14. https://doi.org/10.1097/SS.0b013e3181cb7f46

Carter, M. R., & Gregorich, E. G. (2007). *Soil Sampling and Methods of Analysis*. CRC Press, Boca Raton. https://doi.org/10.1201/9781420005271

Carvalho, E. J. M., Figueiredo, M. de S., & Costa, L. M. da. (1999). Comportamento físico-hídrico de um podzólico vermelho-amarelo câmbico fase terraço sob diferentes sistemas de manejo. *Pesquisa Agropecuária Brasileira, 34*, 257-265. https://doi.org/10.1590/S0100-204X1999000200015

Carvalho, G. J., Carvalho, M. de P., Freddi, O. da S., & Martins, M. V. (2006). Correlação da produtividade do feijão com a resistência à penetração do solo sob plantio direto. *Revista Brasileira de Engenharia Agrícola e Ambiental, 10*, 765-771. https://doi.org/10.1590/s1415-43662006000300033

Castellini, M., Giglio, L., Niedda, M., Palumbo, A. D., & Ventrella, D. (2015). Impact of biochar addition on the physical and hydraulic properties of a clay soil. *Soil and Tillage Research, 154*, 1-13. https://doi.org/10.1016/j.still.2015.06.016

Castellini, M., Niedda, M., Pirastru, M., & Ventrella, D. (2016). Effect of biochar application on soil hydrological properties and physical quality of sandy. *Soil Use and Management, 30*, 423-434. https://doi.org/10.1111/sum.12137

Collares, G. L., Reinert, D. J., Reichert, J. M., & Kaiser, D. R. (2006). Qualidade física do solo na produtividade da cultura do feijoeiro num Argissolo. *Pesquisa Agropecuária Brasileira, 41*, 1663-1674. https://doi.org/10.1590/S0100-204X2006001100013

Cravo, M. S., & Smyth, T. J. (1997). Manejo Sustentado da Fertilidade de um Latossolo da Amazônia Central Sob Cultivos Sucessivos. *Revista Brasileira de Ciência do Solo*, 607-616. https://doi.org/10.1590/S0100-06831997000400011

da Silva, A. P., Kay, B. D., & Perfect, E. (1994). Characterization of the Least Limiting Water Range of Soils. *Soil Science Society of America Journal. Soc. Am. J., 58*, 1775. https://doi.org/10.2136/sssaj1994.03615995005800060028x

Damaceno, J. B. D. (2017). *Biocarvão e Efeito Residual de Adubação Fosfatada em Mudas de Castanheira-do-Brasil (Berthollethia excelsa Bonpl.) em Latossolo da Amazônia*. Instituto Nacional de Pesquisas da Amazônia, Brazil.

Dexter, A. R. (2004). Soil physical quality Part I . Theory , effects of soil texture , density , and organic matter , and effects on root growth. *Geoderma, 120*, 201-214. https://doi.org/10.1016/j.*geodermaa*.2003.09.005

Dexter, A. R., Czyz, E. A., & Gațe, O. P. (2007). A method for prediction of soil penetration resistance. *Soil and Tillage Research, 93*, 412-419. https://doi.org/10.1016/j.still.2006.05.011

Donagema, G. K., Campos, D. V. B., Calderano, S. B., Teixeira, W. G., & Viana, J. H. M. (2011). *Manual de métodos de análise de solo* (Embrapa Solos. Documentos, 132). Rio de Janeiro: Embrapa Solos.

Eastman, C. M. (2011). *Soil physical characteristics of na Aeric Ochraqualf amended with Biochar*. Graduate Program in Environmental and Natural Resources, The Ohio State University, Columbus.

Elisabeth, M., & Claessen, C. (1997). *Metodos Embrapa Analise Solo*.

Fernandes, K. L., Ribon, A. A., Hermógenes, V. T. L., Custódio, G. D., & Barros, L. R. (2014). Atributos físicos de solo sob cerrado em diferentes sistemas de uso e manejo de pastagens e mata nativa. *Cultivando o Saber, 7*, 14-23.

Ferreira, A., Junior, N., Pires, A., Noronha, N. C., & Cerri, C. C. (2012). Sistemas De Manejo Do Solo Na Recuperação De Uma Pastagem Degradada em Rondônia. *Revista Brasileira de Ciência do Solo, 37*, 232-241. https://doi.org/10.1590/S0100-06832013000100024

Gama, R. T. da. (2018). *Biocarvão e Adubação Nitrogenada Influenciando o Crescimento e o estado Nutricional de Mudas de Castanheiras-do-Brasil em um Latossolo da Amazônia Central*. Instituto Nacional de Pesquisas da Amazônia, Brazil.

Gee, B. (1986). Particle-size analysis. *Powder Technology, 1*(2), 120. https://doi.org/10.1016/0032-5910(67)80021-4

Githinji, L. (2014). Effect of biochar application rate on soil physical and hydraulic properties of a sandy loam. *Archives Agronomy and Soil Science, 60*, 457-470. https://doi.org/10.1080/03650340.2013.821698

Glaser, B., Lehmann, J., & Zech, W. (2002). Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal—A review. *Biol Fertil Soils, 35*, 219-230. https://doi.org/10.1007/s00374-002-0466-4

Gregorich, E. G. (2002). Quality. In R. Lal (Ed.), *Enciclopedia of Soil Science* (pp. 1058-1061). New York: Marcl Dekker.

Guimarães, R. D. S., Padilha, F. J., Cedano, J. C., Damaceno, J. B., Gama, R. T., De Oliveira, D. M., … Falcão, N. P. D. S. (2017). Efeito Residual de Biocarvão e Pó de Serra nos Teores de Carbono e Nitrogênio Total em Latossolo Amarelo na Amazônia. *Revista Virtual de Química, 9*, 1944-1956. https://doi.org/10.21577/1984-6835.20170114

Herath, H. M. S. K., Camps-Arbestain, M., & Hedley, M. (2013). Effect of biochar on soil physical properties in two contrasting soils: An Alfisol and an Andisol. *Geoderma, 209-210*, 188-197. https://doi.org/10.1016/j.geoderma.2013.06.016

Jeffery, S., Verheijen, F. G. A., van der Velde, M., & Bastos, A. C. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture Ecosystems Environment, 144*, 175-187. https://doi.org/10.1016/j.agee.2011.08.015

Klein, V. A., Libardi, P. L., & Silva, A. P. (1998). Resistência mecânica do solo à penetração sob diferentes condições de densidade e teor de água. *Engenharia Agrícola, 18*, 45-54.

Lehmann, J., & Joseph, S., (2009). *Biochar For Environmental Management: Science And Technology.* Earthscan, London, UK.

Leite, J. A. (1996). *Influência dos sistemas de manejo sobre os atributos físicos e físico-hídricos de um Latossolo Amarelo (Typic Haplortox)* (37 f. Tese (Livre-Docência em Manejo e Conservação do Solo e da Água), Universidade do Amazonas, Manaus).

Leite, J. A., & Medina, B. F. (1984). Efeito dos sistemas de manejo sobre as propriedades físicas de um Latossolo Amarelo do Amazonas. *Pesquisa Agropecuária Brasileira, 19*, 1417-1422.

Lier, Q. de J. van. (2010). *Física do Solo*. Sociedade Brasiel, Viçosa, MG.

Longo, R. M. (1999). *Modificações em parâmetros físicos e químicos de Latossolos argilosos decorrentes da substituição da Floresta Amazônica e do Cerrado por pastagens* (102 f. Tese (Doutorado em Água e Solo), Universidade Estadual de Campinas, Campinas).

Maia, C. M. B. F. (2010). Biochar: Uma Nova Ferramenta no Manejo de Solos (p. 7). II Seminário de Atualização Florestal e XI Semana de Estudos Florestais, Colombo.

Mangrich, A. S., Maia, C. M. B. F., & Novotny, E. H. (2011). Biocarvão-As terras pretas de índios e o sequestro de carbono. *Ciência Hoje*.

Marques, J. D. de O., Libardi, P. L., Teixeira, W. G., & Reis, A. M. (2004). Estudo de parâmetros físicos, químicos e hídricos de um Latossolo Amarelo, na região Amazônica. *Acta Amazonica, 34*, 145-154. https://doi.org/10.1590/s0044-59672004000200002

Mello Ivo, W. M. P., & Mielniczuk, J. (1999). Influência da estrutura do solo na distribuição e na morfologia do sistema radicular do milho sob três métodos de preparo. *Revista Brasileira de Ciências do Solo, 23*, 135-143. https://doi.org/10.1590/S0100-06831999000100017

Menezes, D. S. de. (2018). *Efeito da Interação Biocarvão e Adubação Potássica na Fertilidade do Solo e no Crescimento de Mudas de Castanheiras-do-Brasil (Bertholletia excelsa Bonpl.) em Latossolos Amarelo da Amazõnia Central*. Instituto Nacional de Pesquisas da Amazônia, Brazil.

Mukherjee, A., & Lal, R. (2013). Biochar Impacts on Soil Physical Properties and Greenhouse Gas Emissions. *Agronomy, 3*, 313-339. https://doi.org/10.3390/agronomy3020313

Mukherjee, A., Lal, R., & Zimmerman, A. R. (2014). Impacts of 1.5-Year Field Aging on Biochar, Humic Acid, and Water Treatment Residual Amended Soil. *Soil Science, 179*(7), 333-339. https://doi.org/10.1097/SS.0000000000000076

Novotny, E. H., Maia, C. M. B. de F., Carvalho, M. T. de M., & Madari, B. E., (2015). Biochar: Carbono pirogênico para uso agrícola-Uma revisão crítica. *Revista Brasileira de Ciência do Solo, 39*, 321-344. https://doi.org/10.1590/01000683rbcs20140818

Obia, A., Børresen, T., Martinsen, V., Cornelissen, G., & Mulder, J. (2017). Effect of biochar on crust formation, penetration resistance and hydraulic properties of two coarse-textured tropical soils. *Soil and Tillage Research, 170*, 114-121. https://doi.org/10.1016/j.still.2017.03.009

Obia, A., Mulder, J., Martinsen, V., Cornelissen, G., & Børresen, T. (2016). *In situ* effects of biochar on aggregation, water retention and porosity in light-textured tropical soils. *Soil and Tillage Research, 155*, 35-44. https://doi.org/10.1016/j.still.2015.08.002

Oliveira, I. A. de, Campos, M. C. C., Aquino, R. E. de, Marques, J., Freitas, L. de, & Souza, Z. M. de. (2014). Semivariograma escalonado no planejamento amostral da resistência à penetração e umidade de solo com cana-de-açúcar. *Revista de Ciências Agrárias. Amazonian Journal of Agricultural and Environmental Sciences, 57*, 287-296. https://doi.org/10.4322/rca.ao1421

Oliveira, I. A. de, Campos, M. C. C., Freitas, L. de, & Soares, M. D. R., (2015). Caracterização de solos sob diferentes usos na região sul do Amazonas. *Acta Amazonica, 45*, 1-12. https://doi.org/10.1590/1809-4392201400555

Omondi, M. O., Xia, X., Nahayo, A., Liu, X., Korai, P. K., & Pan, G. (2016). Quantification of biochar effects on soil hydrological properties using meta-analysis of literature data. *Geoderma* 274, 28-34. https://doi.org/10.1016/j.geoderma.2016.03.029

Pandian, K., Subramaniayan, P., Gnasekaran, P., & Chitraputhirapillai, S. (2016). Effect of biochar amendment on soil physical, chemical and biological properties and groundnut yield in rainfed Alfisol of semi-arid tropics. *Archives Agronomy. Soil Science, 62*, 1293-1310. https://doi.org/10.1080/03650340.2016.1139086

Petter, F. A. (2010). *Biomassa Carbonizada Como Condicionador De Solo: Aspectos Agronômicos E Ambientais Do Seu Uso Em*.

Petter, F. A., Lima, L. B. de, Morales, M. M., Júnior, B. H. M., & Alves, L. (2016). *Biocarvão no solo: Aspectos agronômicos e ambientais* (pp. 73-81). Embrapa, Brazil.

Pranagal, J., Oleszczuk, P., Tomaszewska-Krojańska, D., Kraska, P., & Różyło, K. (2017). Effect of biochar application on the physical properties of Haplic Podzol. *Soil and Tillage Research, 174*, 92-103. https://doi.org/10.1016/j.still.2017.06.007

Pratiwi, E. P. A., & Shinogi, Y. (2016). Rice husk biochar application to paddy soil and its effects on soil physical properties, plant growth, and methane emission. *Paddy Water Environ, 14*, 521-532. https://doi.org/10.1007/s10333-015-0521-z

Qin, X., Li, Y., Wang, H., Liu, C., Li, J., Wan, Y., … Liao, Y. (2016). Long-term effect of biochar application on yield-scaled greenhouse gas emissions in a rice paddy cropping system: A four-year case study in south

China. *Science of the Total Environment, 569-570*, 1390-1401. https://doi.org/10.1016/j.scitotenv.2016.06.222

Radambrasil. (1975). *Projeto Radambrasil: Lev. de Rec. Nat. 101* (p. 510). Ministério das Minas e Energia, Dep. Nac. de Prod. Mineral. Folha SA-21-Santarém. Rio de Janeiro, Brazil.

Ramos, F. T., Monari, Y. C., Nunes, M. C. M., Campos, T. da S., & Ramos, D. T. (2010). *Indicadores de Qualidade em um Latossolo Vermelho-Amarelo 2125* (pp. 112-120).

Reichert, J. M., da Rosa, V. T., Vogelmann, E. S., da Rosa, D. P., Horn, R., Reinert, D. J., … Denardin, J. E. (2016). Conceptual framework for capacity and intensity physical soil properties affected by short and long-term (14 years) continuous no-tillage and controlled traffic. *Soil and Tillage Research, 158*, 123-136. https://doi.org/10.1016/j.still.2015.11.010

Reis, M. da S., Fernandes, A. R., Grimaldi, C., Desjardins, T., & Grimaldi, M. (2009). Características químicas dos solos de uma topossequência sob pastagem em uma frente pioneira da Amazônia Oriental. *Revista de Ciências Agrárias, 52*, 37-47.

Rezende, E. I. P., Angelo, L. C., Dos Santos, S. S., & Mangrich, A. S. (2011). Biocarvão (Biochar) e sequestro de carbono. *Revista Virtual de Química, 3*, 426-433. https://doi.org/10.5935/1984-6835.20110046

Rogovska, N., Laird, D. A., Rathke, S. J., & Karlen, D. L. (2014). Biochar impact on Midwestern Mollisols and maize nutrient availability. *Geoderma, 230-231*, 340-347. https://doi.org/10.1016/j.geoderma.2014.04.009

Sadeghi, M., Babaeian, E., Arthur, E., Jones, S. B., & Tuller, M. (2018). Soil Physical Properties and Processes. *Handbook of Environmental Engineering* (pp. 137-207). John Wiley & Sons, Inc., Hoboken, NJ, USA. https://doi.org/10.1002/9781119304418.ch7

Silva, F. R. da, Albuquerque, J. A., Costa, A. da, Fontoura, S. M. V., And, C. B., & Warmling, M. I. (2016). Physical Properties of a Hapludox after Three Decades under Different Soil Management Systems. *Revista Brasileira de Ciência do Solo, 40*, 1-14. https://doi.org/10.1590/18069657rbcs20140331

Siqueira, J.S., Souza, C.A.G., Souza, J.A.S., (2012). Reaproveitamento de cinzas de carvão mineral na formulação de argamassas. *Cerâmica, 58*, 275-279. https://doi.org/10.1590/S0366-69132012000200020

Smith, C., Johnston, M., & Lorentz, S. (1997). The effect of soil compaction and soil physical properties on the mechanical resistance of South African forestry soils. *Geoderma, 78*, 93-111. https://doi.org/10.1016/S0016-7061(97)00029-3

Soares, M. D. R., Campos, M. C. C., Oliveira, I. A., Cunha, J. M., Santos, L. A. C., Fonseca, J. S., & Souza, Z. M. de. (2016). Atributos físicos do solo em áreas sob diferentes sistemas de usos na região de Manicoré , AM. *Amazonian Journal of Agricultural and Environmental. Sci., 59*, 9-15. https://doi.org/10.4322/rca.2020

Souza, Z. A., Leite, J. A., & Beutler, A. N. (2004). Comportamento de Atributos Físicos de um Latossolo Amarelo Sob Agroecossistemas do Amazonas. *Engenharia Agrícola, 24*, 654-662. https://doi.org/10.1590/S0100-69162004000300017

Steiner, C., Teixeira, W. G., Lehmann, J., Nehls, T., de Macêdo, J. L. V., Blum, W. E. H., & Zech, W. (2007). Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. *Plant Soil, 291*, 275-290. https://doi.org/10.1007/s11104-007-9193-9

Stolf, R. (1991). Theory and test of formulas for transforming impact penetrometer data in soil resistance (en). *Revista Brasileira de Ciência do Solo, 3*, 229-235.

Sun, Z., Arthur, E., de Jonge, L. W., Elsgaard, L., & Moldrup, P. (2015). Pore Structure Characteristics After 2 Years of Biochar Application to a Sandy Loam Field. *Soil Science, 180*, 41-46. https://doi.org/10.1097/SS.0000000000000111

Swami, S. N. (2009). Charcoal Making in the Brazilian Amazon: Economic Aspects of Production and Carbon Conversion Efficiencies of Kilns. In W. I. Woods, W. G. Teixeira, J. Lehmann, C. Steiner, A. Winkler Prins, & L. Rebellato (Eds.), *Amazonian Dark Earths: Wim Sombroek's Vision A*. Springer, Dordrecht.

Tan, Z., Lin, C. S. K., Ji, X., & Rainey, T. J. (2017). Returning biochar to fi elds : A review. *Apllied Soil Ecology, 116*, 1-11. https://doi.org/10.1016/j.apsoil.2017.03.017

Tardieu, F. (1994). Growth and functioning of roots and of root systems subjected to soil compaction. Towards a system with multiple signalling? *Soil and Tillage Research, 30*, 217-243. https://doi.org/10.1016/0167-1987(94)90006-X

Taylor, H. M., Roberson, G. M., & Parker, J. J. (1966). Soil strength-root penetration relations to coarse textured materials. *Soil Science, 102*, 18-22. https://doi.org/10.1097/00010694-196607000-00002

Teixeira, P. C., Donagemma, G. K., Fontana, A., & Teixeira, W. G. (2017). *Manual e Métodos de Análise de Solo*. Embrapa, Brazil.

Tormena, C. A., Barbosa, M. C., Costa, A. C. S. da, & Gonçalves, A. C. A. (2002). Densidade, porosidade e resistência à penetração em Latossolo cultivado sob diferentes sistemas de preparo do solo. *Scientia Agricola, 59*, 795-801. https://doi.org/10.1590/S0103-90162002000400026

Tormena, C. A., Silva, A. P., & Libardi, P. L. (1998). Caracterização do intervalo hídrico ótimo de um latossolo roxo sob plantio direto. *Revista Brasileira de Ciência do Solo, 22*, 573-581. https://doi.org/10.1590/S0100-06831998000400002

Usowicz, B., Lipiec, J., Łukowski, M., Marczewski, W., & Usowicz, J. (2016). The effect of biochar application on thermal properties and albedo of loess soil under grassland and fallow. *Soil and Tillage Research, 164*, 45-51. https://doi.org/10.1016/j.still.2016.03.009

Verheijen, F., Jeffery, S., Bastos, A. C., Van Der Velde, M., & Diafas, I. (2010). Biochar Application to Soils: A Critical Scientic Review of Effects on soil Properties, Processes and Functions. *JRC Scientific and Technical Report* (JRC55799). Luxembourg: European Commission. https://doi.org/10.2788/472

Walkley, A., & Black, I. A. (1934). An examination of the degtjareff method for determining soil organic matter and proposed modification of the chromic acid titration method. *Soil Science, 1*, 29-38. https://doi.org/10.1097/00010694-193401000-00003

Yamato, M., Okimori, Y., Wibowo, I. F., Anshori, S., & Ogawa, M. (2006). Effects of the application of charred bark of Acacia mangium on the yield of maize, cowpea and peanut, and soil chemical properties in South Sumatra, Indonesia. *Soil Science and Plant Nutrition, 52*, 489-495. https://doi.org/10.1111/j.1747-0765.2006.00065.x

Zheng, J., Chen, J., Pan, G., Liu, X., Zhang, X., Li, L., … Jinwei, Z. (2016). Biochar decreased microbial metabolic quotient and shifted community composition four years after a single incorporation in a slightly acid rice paddy from southwest China. *Science of the Total Environment, 571*, 206-217. https://doi.org/10.1016/j.scitotenv.2016.07.135

Copyrights