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Biochar increases soil water content and total organic carbon but has no effects on soil respiration in a Regosol of Caatinga

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A B S T R A C T

Soil respiration (Rs) is the largest flux of CO_2 emission from terrestrial ecosystems and an important component of global carbon balance. Small variations in Rs can promote large alterations on atmospheric CO_2 concentration, it is therefore necessary to find management practices that reduce Rs and increase total organic carbon (TOC). Biochar application has been proposed as an effective measure to reach this aim. Thus, several studies measured the effect of biochar on Rs in different ecosystems; however, none was made in sandy soils of Brazilian tropical dry forest, namely Caatinga biome. We assess Rs, TOC and soil water content (SWC) from a Regosol in Caatinga in response to biochar addition. A greenhouse pot experiment, quantifying the Rs, SWC and TOC, no (B0) and with 20 t ha^{-1} biochar (B20) and two hydric conditions of soil (dry and wet soil) was conducted. B20 had higher TOC and SWC. There was a seasonal variation of Rs, with wet soil having higher Rs than dry soil; however biochar had no effects on Rs. This is a significant finding considering that biochar addition does not increase Rs and, hence, confirms its' high potential to mitigate climate and land use changes in sandy soils of Caatinga biome.

Keywords**:** Semiarid; sandy soil; soil management.

Biocarvão aumenta a umidade e o carbono orgânico, mas não afeta a respiração de um Neossolo Regolítico sob Caatinga

R E S U M O

A respiração do solo (Rs) é o maior fluxo de emissão de CO_2 dos ecossistemas terrestres e um importante componente do balanço global de carbono. Pequenas variações na Rs podem promover grandes alterações na concentração de CO_2 atmosférico e, portanto, torna-se necessário se encontrar práticas de manejo que reduzam a Rs e aumentem o carbono orgânico total (COT). A aplicação de biocarvão no solo tem sido proposta como uma prática efetiva para se alcançar esse objetivo. Desse modo, várias pesquisas mediram o efeito do biocarvão na Rs em diferentes ecossistemas, contudo, até o momento, nenhuma pesquisa foi feita em solos arenosos de florestas tropicas secas no Brasil, principalmente no bioma Caatinga. Assim, nesse trabalho mediram-se a Rs, o COT e a umidade do solo (Us) de um Neossolo Regolítico em área de Caatinga em função da aplicação de biocarvão. Foi conduzido um experimento em casa de vegetação para se medir a Rs, o COT e a Us em tratamentos sem biocarvão (B0) e com 20 t ha^{-1} de biocarvão (B20), sob duas condições de umidade do solo (seco e úmido). O tratamento B20 teve maior COT e Us, sendo que existiu uma variação sazonal da Rs, com o solo úmido tendo maior Rs do que o solo seco, contudo a Rs não foi afetada pela adição de biocarvão. Este resultado é

muito importante, devido ao fato da adição de biocarvão não aumentar a Rs e, portanto, confirmar seu elevado potencial de mitigar os efeitos das mudanças climáticas e de uso da terra em solos arenosos do bioma Caatinga.
Palavras-chave: Semiárido; solo arenoso; manejo do solo.

Introduction

Soil respiration (Rs) is the sum of processes that include root respiration and microbial activity (Zhou et al., 2017; Ferreira et al., 2018), being the largest flux of CO_2 emission from terrestrial ecosystems and an important component of global carbon cycle (Zhang et al., 2015; Wang et al., 2019).

Small changes in the magnitude of Rs could have a large influence on atmospheric CO2 concentration and accurate estimates of Rs from different ecosystems can help effectively to quantify terrestrial C storage (Zhang et al., 2015; Duan et al., 2019). Therefore, it is necessary to perform researches to find alternatives to reduce Rs and increase the organic carbon stock. Thus, one of the most promising alternatives today is the use of biochar.

Biochar is a product rich in carbon, the result of the pyrolysis process, obtained by different types of biomass (Lehmann et al., 2006; Kavitha et al., 2018; Lima et al., 2018). After pyrolysis, the product has a high carbon concentration and greater stability in the soil than the original biomass (Purakayastha et al., 2016).

Biochar addition to soil can be considered as a strategy to improve the soil chemical, physical and biological characteristics (Purakayastha et al., 2015; Silva et al., 2017; Dodor et al., 2018; Lima et al., 2018; Sheng and Zhu, 2018; Lima et al., 2020). Besides, biochar application has been proposed as an effective measure to mitigate greenhouse gas (GHG) emissions from soil (Lehmann et al., 2006; Lu et al., 2019) and therefore the amendment of soils with biochar can be considered as a valuable contribution to climate change mitigation (Woolf et al., 2016).

Several factors, including climate, soil properties and vegetation characteristics potentially contribute to variation in Rs (Chen et al., 2014), mainly soil temperature, soil water content and soil organic carbon (Lloyd and Taylor, 1994; Conant et al., 2004; Ribeiro et al., 2016; Ferreira et al., 2018; Liu et al., 2018). Thus, management practices, such as the biochar addition to soil can alter the Rs, since it promotes changes in these soil properties.

In this way, several studies measured the effect of biochar on Rs in different ecosystems and found conflicting results. Some showed that biochar promotes a reduction in Rs (Ouyang et al., 2016; Li et al., 2018; Ge et al., 2019), others that biochar promotes an increase (Smith et al., 2010; Zavalloni et al., 2011; He et al., 2017; Johnson et al., 2017) and others show no effect (Lu et al., 2014; Liu et al., 2016a; Liu et al., 2016b; Zhou et al., 2017; Lu et al., 2019).

However, to date, none study evaluated the effect of biochar on Rs with soils of the Caatinga biome. This biome covers an area of approximately one million km^2 and has enormous endemic biodiversity, with unique characteristics that make it an exclusive Brazilian biome (Menezes et al., 2012; Ribeiro et al., 2016). In this biome lives a population of more than 20 million people and approximately half is involved in agricultural production, mostly on low productivity, small subsistence farms (Sampaio et al., 2004; Menezes et al., 2012).

Large areas with sandy soils of poor retention properties (Silva et al., 2014; Almeida et al., 2015) and low TOC (Barros et al., 2019) cover this region. Thus, the biochar addition in these sandy soils can to enhance SWC (Lima et al., 2018), due to high specific surface area (SSA), and TOC due to the inputs of recalcitrant organic carbon (Zavalloni et al., 2011; He et al., 2017).

Here, we assess Rs in sandy soil from Caatinga biome in response to biochar addition. The main objective of the present work was to quantify and compare the Rs in soil amended and no amended with biochar. Another contribution is related to the effect of biochar on SWC and TOC. In this study, we hypothesized that the biochar will to increase SWC and TOC, but to decrease Rs, due to high recalcitrant organic C.

Materials and Methods

Location, soil and climate

The experiment was conducted in a greenhouse at the Federal University of Agreste Pernambuco (UFAPE) in Garanhuns. The soil, a Neossolo Regolítico eutrófico (Santos et al., 2018), which corresponding to a Lamellic Eutric Regosol, according to the classification system of the Food and Agriculture Organization (IUSS, 2015), used for the experiment was a topsoil (0–20 cm) collected locally in a patch of native forest (Caatinga) in the county of São João, Pernambuco (08º 48′ 34.2″ S, 36º 24′ 29.3″ W, altitude 705 m above sea level). The soil used in experiment has sand of 880 g kg^{-1} and 40 g kg^{-1} of clay, soil bulk density of 1.50 g cm^{-3}, field capacity (FC) of 0.135 m^3 m^{-3} and permanent wilting point (PWP) of 0.03 m^3 m^{-3}, low values (3.98 cmolc kg^{-1}) of cation exchange capacity (CEC) and specific surface area (SSA) of 0.005 m^2 g^{-1} (Lima et al., 2018).

The climate in the region is hot and humid (As') according to the Köppen classification system. The mean total annual rainfall is 782 mm, and the mean annual air temperature is 23.2 °C (Silva et al., 2014).

Experimental setup

The biochar used in experiment was produced with coffee husk residue. It has been charred during 10 to 12 h under oxygen-limited conditions in a slow pyrolysis process where temperature reached 530 °C in a homemade metallic kiln, which was based on a model widely used by Thai farmers (Prakongkep et al., 2015; Lima et al., 2018). Accordingly to Lima et al. (2018), the biochar was alkaline (pH of 10.31), with high values of total organic carbon (671.1 g kg^{-1}), P (470.65 mg kg^{-1}), K (22.17 cmolc kg^{-1}) and specific surface area (244.0 m^2 g^{-1}).

The experimentation consisted in testing the effect of two rates of biochar (0 and 20 Mg ha^{-1}), and two hydric conditions, that were wet (soil in or near the FC) and dry (soil in or near the PWP). Biochar was carefully mixed with the soil and placed in a pot with capacity of 5000 g.

The soils were irrigated with distilled water to keep the soil at FC. Then, the soils kept drying until they reached in or near the PWP, when it was irrigated again for FC.

The experiment out was carried from October 16 to November 13 2017 under controlled greenhouse conditions; the design was completely randomized, in scheme factorial (2 x 2), with two rates of biochar (0 and 20 Mg ha^{-1}), and two hydric conditions of soil (wet and dry), with four replicates.

Soil water content (SWC), total organic carbon (TOC) and soil respiration (Rs)

The soil gravimetric moisture (SM) was measured by daily weighing of the pots and was calculated by considering the volume of water required for the soil to reach the FC. Soil water content (SWC) was obtained by SM multiplied by soil bulk density.

At the end of the experiment soil samples were collected and the total organic carbon (TOC) concentrations were determined by dry combustion at 925 °C in a CHNS-O elemental analyzer (Perkin Elmer PE-2400).

The soil respiration (Rs) was measured daily, always between 9:00 AM and 11:00 AM, throughout of the experiment, using a system composed of a LI-8100A (LI-COR Biosciences, Lincoln, NE), soil collar and personal computer. Soil-Flux-Pro software was used to operate the system and analyze Rs data logged the personal computer (Figure 1).

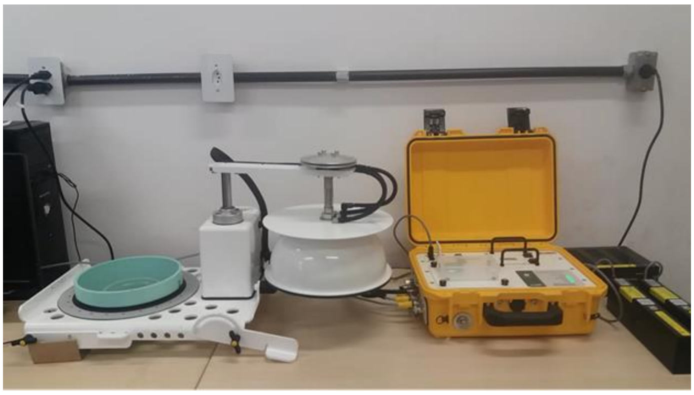

Figure 1. A view of the LI-COR carbon-dioxide sampling system.

Statistical analysis

Statistical analysis were performed in a programming platform using R language (R Core Team, 2019). Treatment effects (biochar, hydric conditions and their interaction) on Rs and SWC, and only biochar on TOC, were tested using analysis of variance (ANOVA) and significant differences between the means were carried out by using the Tukey test at 95% probability.

SWC was always higher ($p < 0.05$) in B20 than B0 for both hydric conditions of soil. SWC varied from 0.109 to 0.043 $m^3 m^{-3}$ in B20; while in B0 ranged from 0.098 to 0.030 $m^3 m^{-3}$. Results showed that addition of biochar increased SWC in these sandy soils and that the difference between the two treatments is increasing as the soil samples get drier (Table 1).

Results

Table 1. Soil water content (SWC) in Regosol no amended (B0) and amended (B20) with biochar under two hydric conditions of soil.

Treatments		
Hydric conditions	Biochar	SWC, $m^3 m^{-3}$
Wet	B0	0.098 Ab
Wet	B20	0.109 Aa
	Average wet	**0.104 A**
	Average B0	**0.064 β**
Dry	B0	0.030 Bb
Dry	B20	0.043 Ba
	Average dry	**0.037 B**
	Average B20	**0.076 α**

Values followed by the same lowercase letter in biochar and by the same uppercase letter in hydric conditions are not significantly different by Tukey test at $p < 0.05$. Greek lowercase letters compare the general average of the biochar treatments in different hydric conditions and Greek uppercase letters compare the general average of the hydric conditions in different biochar treatments

Application of biochar increased total organic carbon (TOC) in Regosol (Table 2), with B20 (6.2 g kg^{-1}) having significantly higher TOC ($p < 0.01$) than B0 (5.5 g kg^{-1}).

The average soil respiration (Rs) was 16 fold and significantly higher ($p < 0.05$) in wet soil than dry soil (Table 3), in both biochar treatments (B0 and B20).

Rs average value varied from 0.775 (B20) to 0.928 (B0) μmol $m^{-2} s^{-1}$ in wet soil, with an average value of 0.851 μmol $m^{-2} s^{-1}$; in dry soil values of Rs ranging from 0.048 (B20) to 0.058 (B0) μmol $m^{-2} s^{-1}$, with average from 0.053 μmol $m^{-2} s^{-1}$. It was shown that biochar addition induced a tendency to decrease Rs (reduction of 16.8%), however no significant effects ($p > 0.05$) for both hydric conditions.

Table 2. Total organic carbon (TOC) in Regosol no amended (B0) and amended (B20) with biochar.

Treatments	TOC, g kg^{-1}
B0	5.5 B
B20	6.2 A

Means followed with the same letter are not significantly different by Tukey test at $p < 0.05$

Table 3. Soil respiration (Rs) in Regosol no amended (B0) and amended (B20) with biochar under two hydric conditions of soil.

Treatments		
Hydric conditions	Biochar	Rs, μmol m^{-2} s^{-1}
Wet	B0	0.928 Aa
Wet	B20	0.775 Aa
	Average wet	**0.851 A**
	Average B0	**0.493 α**
Dry	B0	0.058 Ba
Dry	B20	0.048 Ba
	Average dry	**0.053 B**
	Average B20	**0.411 α**

Values followed by the same lowercase letter in biochar and by the same uppercase letter in hydric conditions are not significantly different by Tukey test at $p < 0.05$. Greek lowercase letters compare the general average of the biochar treatments in different hydric conditions and Greek uppercase letters compare the general average of the hydric conditions in different biochar treatments

Discussion

This research is the first, to our knowledge, that measured the effects of biochar amendment on soil respiration, soil water content and total organic carbon in sandy soil (Regosol) of Caatinga biome.

Soil water content (SWC) increased by 29% in soil amended with biochar in relation to control. As stated previously, biochar has a SSA of 244 m^2 g^{-1} that was about 50 fold higher than to SSA of Regosol. As observed by Lima et al. (2018), the SWC increased for the wet conditions and for the dry conditions. This can be explained by the internal micro- and nano pores of biochar for the dry conditions and by supplementary porous network created by: (i) biochar particles adsorbed at the surface of the sand grains, creating a superficial roughness increasing the holding capacity between the walls of the macro-pores, (ii) aggregated biochar particles forming bigger particles within the macro-pores, promoting the formation of water menisci to retain larger amounts of water. The addition of biochar with high SSA, mainly affected the surface roughness of the macro-pores.

Besides, according to Zimmerman (2010) the increase in SWC in biochar-amended soils can be likely related to the oxidation of biochar surfaces, with the subsequent increase in hydrophilicity.

Others authors also found similar results. For example, Głąb et al. (2016) found that in sandy soils amended with biochar, the available water significantly increased, especially when the biochar with finest fraction was used. These authors also considered the high SSA and intra-particle porosity as being the most important factors increasing soil water retention properties. Ge et al. (2019), in bamboo plantations in subtropical China, also found that biochar addition significantly improved SWC. Obia et al. (2016), in sandy soils at Zambia, found biochar increased available water content.

There are several factors that determine the effect of biochar on soil water retention, such as, soil texture, aggregation and soil organic matter content (Verheijen et al., 2010). Soil texture is considered to be the most important (Głąb et al., 2016). The application of biochar increased available water in sandy soil, but this effect decreased in soil with higher clay content (Mukherjee and Lal, 2013).

Soil organic matter also contributes to increase SWC (Acín-Carrera et al., 2013; Manns et al., 2016; Soltani et al., 2019) and biochar amendments increased the TOC. Hence it can be supposed that the increase of organic matter also had a positive effect on the increase of SWC.

The sandy soil amended with biochar showed higher TOC (+13%) than the control soil control, mainly due to the high organic carbon content of biochar (671.1 g kg^{-1}). The high C content of biochar is due the elevated temperature during the pyrolysis process (in this research temperature reached to 530 ^oC), that causes the release of hydrogen and oxygen containing groups, contributing to increase carbon content (Kavitha et al., 2018).

Despite, the TOC of this Regosol being low, as found by others authors for sandy soils in Caatinga biome (Barros et al., 2019; Santos et al., 2019). Donagemma et al. (2016) assessed the agricultural potential of several sandy soils in Brazil, with sand content varying from 443 to 998 g kg^{-1}, and found organic carbon ranging from 0.1 to 12.1 g kg^{-1}, corroborating our results.

The effects of biochar on TOC, presented in other studies showed results similar to this research, i.e., they found an increase of organic carbon in soil with biochar (Uzoma et al., 2011; Ojeda et al., 2015; Agegnehu et al., 2016; Bhaduri et al., 2016; Zheng et al., 2016; Lima et al., 2018). This can be due to higher physical protection that biochar promotes, increasing the proportion of carbon stored (Wang et al., 2017) and because biochar has high recalcitrant organic carbon (Zavalloni et al., 2011; He et al., 2017). In this sense, Ojeda et al. (2015) affirm that the increase of organic carbon in soil amended with biochar is mainly related to chemical stability of biochar.

The soil respiration (Rs) showed a trend of reduction (16.8%) with biochar addition, but the differences between the two treatments were not significant. Thus, in this study the amendment of soil with biochar (20 Mg ha^{-1}) do not affect soil respiration.

The effects of biochar on Rs are very distinct. For example, Zheng et al. (2016) assessing the effects of biochar on Rs, through 28 days incubation, found that there were no significant differences in emitted CO_2 between the amended and non-amended treatments over time, corroborating data of this study.

Under field conditions in China, Zhou et al. (2017) found that biochar increased Rs in temperate forests but had no effects in subtropical forests. In another study in China, Liu et al. (2016a) also found that biochar had no effect on Rs. In Canada, under controlled conditions, Johnson et al. (2017), measured the biochar influence on Rs under wetting and drying cycles for a forest soil and found that Rs was higher for the biochar-amended soil compared to the no biochar condition. While others authors as Li et al. (2018), in bamboo plantation in China, and Ge et al. (2019), found that biochar addition decreased Rs.

In studies in which biochar addition increased soil CO_2 emissions (Rs) was due mainly to increase of labile soil organic carbon (SOC) pools and mineralization of this SOC (Lu et al., 2019).

On other side, in studies where biochar amended soil reduced Rs, this may be caused by high aromatic carbon content of biochar, making resistant to microbial decomposition (Al-Wabel et al., 2018; Li et al., 2018; Ge et al., 2019).

Besides, as mentioned previously, there are studies that found a decrease and others an increase on soil respiration with biochar additions. Thus, the effects of biochar on Rs are varied because of differences in biochar type (pyrolysis temperature, feedstock, particles diameter, etc.), land use type (forest, grassland, crop planting), soil type (sandy, clayey, loam, etc.), climate type (temperate, tropical, semiarid), experimental conditions (short-term incubation, long-term under field), etc.

However, in sandy soils, which covers a great area in the Northeast of Brazil, with semiarid climate, biochar amendments could represent a valuable opportunity to increase yields and limit water and nutrients losses, as appointed by Lima et al. (2018). Additionally, as found by Johnson et al. (2017), the biochar amendment may contribute to improved forest management through increases to TOC and SWC.

Conclusions

The result found in this study are very important, as that biochar addition in sandy soil increased SWC and TOC and had no effects on Rs. Thus, the biochar is a management practice with high potential for promoting carbon sequestration in sandy soils of Caatinga biome. However, as this study was made under greenhouse conditions, more studies, under field conditions should be conducted to confirm these favorable conclusions.

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