

Soil fertility and upland rice yield after biochar application in the Cerrado

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Abstract – The objective of this work was to evaluate the effect of biochar made from *Eucalyptus* on soil fertility, and on the yield and development of upland rice. The experiment was performed during two years in a randomized block design with four replicates, in a sandy loam Dystric Plinthosol. Four doses of NPK 05-25-15, annually distributed in stripes (0, 100, 200 and 300 kg ha⁻¹), and four doses of biochar (0, 8, 16 and 32 Mg ha⁻¹), applied once in the first year – alone or with NPK – were evaluated. In the first year, biochar positively affected soil fertility [total organic carbon (TOC), Ca, P, Al, H+Al, and pH], at 0–10 cm soil depth, and it was the only factor with significant effect on yield. In the second year, the effect of biochar diminished or was overcome by the fertilizer. TOC moved down in the soil profile to the 0–20 cm depth, influencing K availability in this layer. In the second year, there was a significant interaction between biochar and the fertilizer on plant growth and biomass dry matter accumulation.

Index terms: biochar, macronutrients, plant biomass, plant growth, soil acidity, rice yield.

Fertilidade do solo e produtividade do arroz de terras altas no Cerrado após aplicação de “biochar”

Resumo – O objetivo deste trabalho foi avaliar o efeito do “biochar” de *Eucalyptus* sobre a fertilidade do solo, e sobre a produtividade e o desenvolvimento do arroz de terras altas. O experimento foi conduzido durante dois anos, em delineamento de blocos ao acaso, com quatro repetições, em Plintossolo Háptico franco-arenoso. Foram avaliadas quatro doses do fertilizante mineral NPK 05-25-15 (0, 100, 200 e 300 kg ha⁻¹), distribuídas anualmente em faixas, e quatro doses de “biochar” (0, 8, 16 e 32 Mg ha⁻¹), aplicadas uma única vez, no primeiro ano, sozinho ou com o fertilizante. No primeiro ano, o “biochar” afetou positivamente a fertilidade do solo [carbono orgânico total (TOC), Ca, P, Al, H+Al e pH], à profundidade de 0–10 cm, e foi o único fator com efeito significativo sobre a produtividade. No segundo ano, o efeito do “biochar” diminuiu ou foi superado pelo do fertilizante. O TOC se movimentou no perfil do solo para a profundidade de 10–20 cm, e isto influenciou a disponibilidade de K naquela camada. No segundo ano, houve interação significativa entre “biochar” e fertilizante quanto ao crescimento das plantas e ao acúmulo de massa de matéria seca.

Termos para indexação: “biochar”, macronutrientes, fitomassa, crescimento de planta, acidez do solo, produtividade do arroz.

Introduction

The Cerrado soils are generally acid and feature low-natural fertility with low-available P, K, and cation exchange capacity (CEC), and high-aluminum saturation (Fageria & Souza, 1995). Also, dry periods frequently occur during the growing season. In these conditions, upland rice production is considered an activity at risk.

Increasing soil organic matter (SOM) content generally improves soil chemical, physical, and biological properties, and increases nutrient recycling (Crusciol et al., 2005; Torres et al., 2005; Boer et al., 2007; Carpinim et al., 2008). No-tillage with crop rotation systems are relevant practices to raise SOM levels, at least at the top soil layers (Barreto et al., 2009). However, for upland rice, these management systems

have often lead to frustrations, due to the weak initial vigor of plants (Santos et al., 1997).

Recently, new form of use for pyrolysis byproducts has been proposed as soil amendment (biochar), to enhance soil properties, hence aggregating value to them. Biochar has beneficial effects on the chemical, physical and biological soil properties, besides contributing to enhance crop biomass and yield (Glaser et al., 2002; Kookana et al., 2011).

According to Madari et al. (2006), based on experiments in pots, upland rice is positively affected by eucalyptus charcoal addition to the soil. According to these authors, upland rice had a better initial vigor and biomass accumulation, a more uniform development, and larger seed dry mass. The application of biochar also enhanced soil properties, reducing potential acidity and increasing available P and K.

The objective of this work was to evaluate the effect of biochar made from *Eucalyptus*, in a sole application or in combination with mineral fertilizer, on soil fertility and on yield and development of upland rice.

Materials and Methods

The field experiment was implemented in Nova Xavantina, MT, Brazil, in the Cerrado biome (14°34'50"S, 52°24'01"W, at 310 m altitude), in November 2008. The soil was a Dystric Plinthosol (Nachtergaele, 2005). Before experiment implementation, the area was used as degraded pasture. The dominant species was *Urochloa ruziziensis*.

Data of rainfall distribution and temperature during the growing period of the rice are presented in Figure 1.

The NPK 05-25-15 doses at 0, 100, 200, and 300 kg ha⁻¹ were applied in stripes, and the eucalyptus biochar doses at 0, 8, 16 and 32 Mg ha⁻¹ were applied within the stripes, in a randomized block design. Sixteen treatments were used, with four replicates, in a total of 64 experimental plots. Each plot had nine rows, 10 m each, in a total of 40.5 m² as plot area, of which 25.2 m² were considered for the study.

Biochar was applied to the soil only once (in December, 2008), before planting, and it was incorporated into a 0–10 cm soil depth using a rotary hoe. This was the only occasion when the soil was physically moved. After that, the experiment was performed in no tillage system. Before incorporation into the soil, biochar was ground to pass through a 2 mm sieve. The elemental

composition of it is presented in Table 1, and its molecular composition, determined by ¹³C-nuclear magnetic resonance, in Figure 2. In this spectrum, the presence of aryl groups (C-aryl, ~ 130 ppm) – which are responsible for the stability of the material –, can be observed, as well as the presence also of phenolic carbon (~ 150 ppm), which may be responsible for much of the original chemical reactivity of the biochar, due to the dissociable –OH groups.

The upland rice cultivar BRS Sertaneja was sown in January 8th, 2009 (2008/2009, first year of the experiment) and in December 20th, 2009 (2009/2010, second year of the experiment), by distributing 100 kg ha⁻¹ seeds, with 0.22 m spacing between rows and

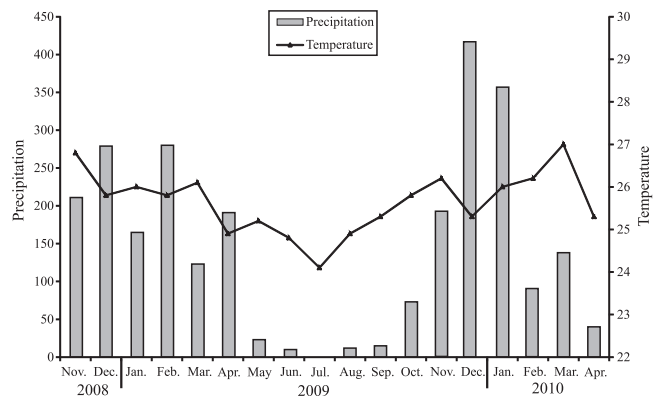


Figure 1. Precipitation (mm) and monthly average temperature (°C) in Nova Xavantina, MT, Brazil, during the experimental period. Source: Instituto Nacional de Meteorologia, Experimental Station in Nova Xavantina, MT.

Table 1. Elemental composition (total C and N) and extractable nutrients of the biochar used in the experiment.

Composition	Value
Total C (g kg ⁻¹)	774.0
Total N (g kg ⁻¹)	3.3
Oxidizable C ⁽¹⁾ (g kg ⁻¹)	33.0
Ca (cmol _c kg ⁻¹)	2.8
Mg (cmol _c kg ⁻¹)	2.3
Al (cmol _c kg ⁻¹)	0.0
H+Al (cmol _c kg ⁻¹)	0.0
P (mg dm ⁻³)	137.3
K (mg dm ⁻³)	1937.3
Cu (mg dm ⁻³)	1.0
Fe (mg dm ⁻³)	74.0
Mn (mg dm ⁻³)	88.0
Zn (mg dm ⁻³)	36.0
C:N ratio	273.6

1–3 cm sowing depth. Part of the chemical fertilizer was applied during the same operation. In the first year, the nitrogen doses – 0, 15, 32 and 50 kg ha⁻¹ – were applied as urea at 30 days after sowing (DAS). Consequently, the total amount of N applied to the treatments was 0, 20, 42 and 65 kg ha⁻¹. In the second year, the equivalent of 55 kg ha⁻¹ N was applied to all plots. During the development of rice, the following phytosanitary care was taken: 241.8 g ha⁻¹ a.i. of 2,4-D was applied for weed control; 420 g ha⁻¹ methamidophos for pests; and 225 g ha⁻¹ tricyclazole (fungicide) for disease control.

The soil variables assessed were: pH, determined using electrode method (Thomas, 1996); P, Ca, Mg and K, extracted by diluted concentration of strong acids (0.05 mol L⁻¹ HCl + 0.0125 mol L⁻¹ H₂SO₄; Mehlich I), as described by Kuo (1996). Phosphorus was determined by colorimetric method (Silva, 2009), Ca and Mg were determined by atomic spectroscopy, and K by flame emission spectrometry (Wright & Stuczynski, 1996). Aluminum was extracted using

potassium chloride solution and titrated by sodium hydroxide, according to Bertsch & Bloom (1996) modified by Silva (2009). Potential acidity (H + Al) was extracted by 0.5 mol L⁻¹ calcium acetate solution at pH 7.1–7.2, and titrated with 0.025 mol L⁻¹ NaOH, using 10 g L⁻¹ phenolphthalein as indicator according to Silva (2009). Cation exchange capacity was obtained through the sum of Ca, Mg and K (Faithfull, 2002). Soil texture was measured using a hydrometer method with a standard hydrometer which had the Bouyoucos scale (Gee & Bauder, 1996), and the texture was identified as sandy loam. Base saturation (V%) value was obtained using the following equation (Faithfull, 2002): $V(\%) = 100 \{ (Ca^{2+} + Mg^{2+} + K^+) / [Ca^{2+} + Mg^{2+} + K^+ + (H^+ + Al^{3+})] \}$. SOM was determined by the Walkley-Black method (Nelson & Sommers, 1996), without external heating, using sulfuric acid to generate internal heat for the reaction.

Soil samples were collected at 0–10 and 10–20 cm soil depth, during rice full flowering. Samples were composed by three subsamples, collected randomly within each plot. The original soil attributes were: pH H₂O, 5.6; P, 4.9 mg dm⁻³; K⁺, 110.0 mg dm⁻³; Ca²⁺, 0.75 cmol_c dm⁻³; Mg²⁺, 0.67 cmol_c dm⁻³; Al³⁺, 0.15 cmol_c dm⁻³; H⁺ + Al³⁺, 2.35 cmol_c dm⁻³; V, 41%; CEC, 4.05 cmol_c dm⁻³; SOM, 12.2 g kg⁻¹; clay, 170 g kg⁻¹; silt, 67 g kg⁻¹; and sand, 763 g kg⁻¹.

The effect of treatments on upland rice attributes was evaluated at 25, 40, 55 and 70 DAS. Dry matter accumulation (g per plant) was determined by collecting ten plants per plot; and the height (cm) of 20 plants per plot was measured with the aid of a graduated tape. The dry matter mass was obtained by drying the plants at 65°C, for 72 hours (Faithfull, 2002). Yield was evaluated with 14% grain humidity.

The generalized linear mixed model was adopted and accounted for the spatial autocorrelation among plots, by including rows and columns (coordinates of plots) as random effects. Thus, linear mixed models were fitted to investigate linear and quadratic effects of fertilizer, biochar and their interactions, treated as fixed effects. Analyses were performed using the SAS/STAT mixed procedure (SAS Institute, 2000).

Results and Discussion

At 0–10 cm soil depth, there was a significant effect of biochar and of its interaction with fertilizer on total organic carbon (TOC, Tables 2 and 3), in both years.

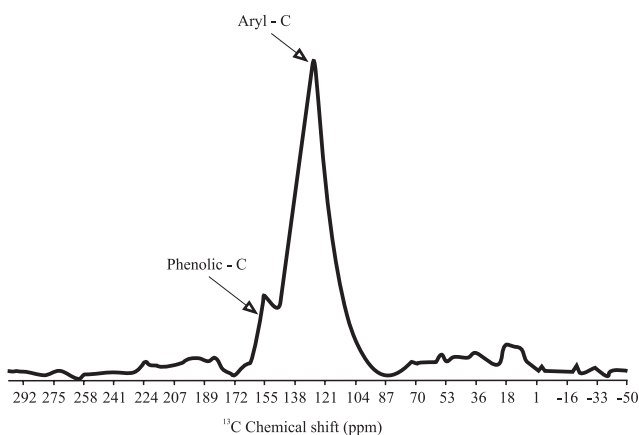


Figure 2. ¹³C-NMR spectrum of the eucalyptus biochar used in the experiment. The samples were analyzed by variable-amplitude cross-polarisation (VACP) solid-state ¹³C nuclear magnetic resonance (NMR), in a 500 MHz Varian spectrometer at ¹³C and ¹H frequencies of 125 and 500 MHz, respectively. The experiments were carried out using a magic-angle spinning (MAS) of 14 kHz, a cross-polarisation time of 1 ms, an acquisition time of 15 ms, a recycle delay of 500 ms and high-power two-pulse phase-modulation (TPPM) proton decoupling of 70 kHz. The cross-polarisation time was chosen after variable contact time experiments, and the recycle delays in CP experiments were chosen to be five times longer than the longest ¹H spin-lattice relaxation time (T₁H), as determined by inversion-recovery experiments. Spectra were processed with Gaussian apodization (gf = 0.004 secs).

The positive effect of biochar on TOC levels was expected due to its high-carbon content (77.4%). At 10–20 cm soil depth, in 2008/2009, a quadratic effect of the treatments on TOC was observed; however, the coefficient of determination ($R^2 = 0.21$) and the F were quite low. In 2009/2010, there was also a significant biochar effect and interaction at 10–20 cm depth, as it was observed at the 0–10 cm soil depth, in both years. The effect of biochar at this higher depth indicates the downward movement of TOC in the soil.

SOM was positively affected in the second year, at 0–10 cm soil depth, by biochar and fertilizer, but without a significant interaction between them (Tables 2 and 3). The effect of biochar on the SOM might have occurred due to its oxidizable C content (33.0 g kg^{-1} , Table 1). Zhang et al. (2012) also observed an increment of SOM levels under wheat straw biochar, on a paddy soil classified as Entic Hapludept planted with rice, in Jiangsu Province, China. At the 0–10 cm soil depth, the coefficient of determination was very low ($R^2 = 0.09$ and 0.11 in the first and second year, respectively), and the F value was also low, but significant.

Besides the macronutrients P and Ca, biochar positively influenced soil acidity (H+Al, Al and pH) at 0–10 cm soil layer, in 2008/2009 (Table 2). Significant effect of biochar on the P availability

was observed at 0–10 cm soil depth, featuring a faint linear behavior in the first year ($R^2 = 0.13$). The 32 Mg ha^{-1} dose of biochar resulted in 17% increase in the availability of this element, compared to the control (0 Mg ha^{-1}). These are consistent with data by Novak et al. (2009), who found 16% increase in P availability, at 0–10 cm soil depth, in a soil with 730 g kg^{-1} sand amended with biochar. These results, however, differ from those by Lehmann et al. (2003), in an Oxisol with lower sand content, in which carbon additions had no effect on P availability. The increased P availability due to biochar in very sandy soils, compared to soils of finer texture, may be related to the greater adsorption of P on soil solid phase with higher clay contents. According to Santos et al. (2008), in tropical and subtropical soils, oxides of Fe and Al are the main responsible for P adsorption to the mineral matrix of the soil.

Calcium levels in the soil also increased with biochar application ($R^2 = 0.41$), during the first year, at 0–10 cm soil depth (Table 2). The increase in Ca availability in the soil was of 36%, when 32 Mg ha^{-1} biochar was applied, compared to the control (0 Mg ha^{-1}). Novak et al. (2009) also found positive effects of biochar addition on Ca levels in a sandy soil, as well as Steiner et al. (2007) and Van Zwieten et al.

Table 2. Effect of the eucalyptus biochar (C) and NPK fertilization (N) on soil chemical attributes at 0–10 and 10–20 cm soil depths, in 2008/2009.

Parameter	Equation	R^2	F	p
0–10 cm soil depth				
pH	$5.77 + 0.01C^*$	0.48	56.68	0.0001
Ca	$0.75 + 0.009C^*$	0.41	42.62	0.0001
Mg	$0.69 - 0.0004N - 0.001C + 0.000007N^2 + 0.00005C^2 + 0.000006NC$	0.14	1.88	0.1100
Al	$0.16 - 0.0006N^* - 0.006C^* + 0.000001N^2 + 0.0001C^2 + 0.000004NC$	0.40	7.75	0.0001
H+Al	$2.38 + 0.00002N - 0.02C^* - 0.000003N^2 + 0.0002C^{2*} + 0.00001NC$	0.42	8.48	0.0001
P	$6.45 + 0.09C^*$	0.13	9.26	0.0030
K	$105.59 - 0.18N^* + 0.86C + 0.0007N^{2*} + 0.01C^2 - 0.001NC$	0.40	7.69	0.0001
TOC	$1.22 + 0.00004N - 0.06C - 0.000002N^2 + 0.003C^{2*} + 0.0002NC^*$	0.47	8.07	0.0001
SOM	$14.05 + 0.004N + 0.002C - 0.00001N^{2*} + 0.0002C^2 + 0.00002NC$	0.14	1.93	0.1000
10–20 cm soil depth				
pH	$5.61 + 0.0004N + 0.003C + 0.000003N^2 + 0.00005C^2 + 0.0000009NC$	0.41	8.12	0.0001
Ca	$0.74 - 0.04C$	0.04	2.85	0.0900
Mg	$0.59 - 0.00005N^* - 0.003C + 0.000002N^{2*} + 0.00008C^2 - 0.000002NC$	0.13	1.77	0.1300
Al	$0.17 + 0.0003N - 0.0002C - 0.000002N^2 - 0.00003C^2 - 0.000002NC$	0.21	3.03	0.0200
H+Al	$2.31 - 0.002N - 0.005C + 0.000002N^2 - 0.00002C^2 + 0.000005NC$	0.21	3.11	0.0200
P	$4.29 + 0.06N + 0.04C + 0.000004N^2 - 0.0002C^2 - 0.00005NC$	0.30	4.86	0.0009
K	$100.79 - 0.11N + 0.91C + 0.0005N^{2*} - 0.002C^2 - 0.002NC$	0.19	2.67	0.0300
TOC	$1.03 + 0.004N - 0.04C - 0.000009N^2 + 0.001C^2 + 0.00003NC$	0.21	2.36	0.0500
SOM	$10.66 + 0.05C^* - 0.002C^{2*}$	0.09	2.96	0.0500

*Significant at 5% probability; TOC, total organic carbon; SOM, soil organic matter.

(2010), who investigated the combined use of charcoal and fertilizer.

However, the effect of the biochar was not observed for P or Ca in the 10–20 cm layer (Table 2). This was expected because there was no biochar incorporation at this layer.

In the second year (Table 3), the biochar had a reduced effect, or its residual effect was overcome by the effect of the fertilizer, as the fertilizer was applied annually, and the charcoal only once at the beginning of the experiment.

The largest positive effect of the biochar occurred on the chemical reaction of the soil ($R^2 = 0.48$), at 0–10 cm layer, in the first year (Table 2). The pH increased with increasing doses of biochar. Similar results were obtained by Lehmann et al. (2003), who observed a reduction on acidity by 0.75 pH units (from 5.14 to 5.89) with the addition of 20% biochar in an Oxisol. In the first year, the potential acidity (H + Al) was reduced ($R^2 = 0.42$) by nearly 20% with 32 Mg ha⁻¹ biochar, at 0–10 cm soil depth, in comparison to the control. At 10–20 cm soil layer, as expected, the effect of the treatments was smaller. These results corroborate those obtained by Mbagwu & Piccolo (1997) and by Topoliantz et al. (2005),

who found lower levels of H + Al with the use of charcoal.

In the second year, there was no effect of the treatments on pH or H + Al parameters (Table 3).

The effect of biochar on available K was not observed in the first year (Table 2), in neither of the depths. This parameter was far more dependent on the application of the fertilizer. In the second year (Table 3), however, at 10–20 cm soil depth, the biochar increased available K levels, although with a low coefficient of determination ($R^2 = 0.22$). An explanation might be the downward movement of part of the finely ground (≤ 2 mm) biochar into the 10–20 cm soil layer, as it was discussed for TOC levels. Another explanation is that, in that layer, the effect of the fertilizer was lower, since it was placed at around 3 to 5 cm depth at sowing, and, therefore, the effect of biochar on K availability might have become observable. The biochar contains reasonable amounts of K, P and Ca, besides high levels of organic C (Table 1).

The treatments had no effect on available Mg, except for the second year at 0–10 cm soil depth (Table 3).

The application of biochar and fertilizer had a greater effect on plant physiological parameters (Table 4) than on the soil fertility ones. In the first year,

Table 3. Effect of the eucalyptus biochar (C) and NPK fertilization (N) on soil chemical attributes at 0–10 and 10–20 cm soil depths, in 2009/2010.

Parameter	Equation	R ²	F	p
0–10 cm soil depth				
pH	$5.19 + 0.001N^* + 0.003C - 0.000001N^2 + 0.00001C^2 + 0.00000009NC$	0.36	6.59	0.0001
Ca	$6.92 + 0.009N - 0.06C - 0.00003N^2 + 0.003C^2 + 0.0002NC$	0.35	6.37	0.0001
Mg	$5.80 + 0.006N - 0.05C - 0.00001N^2 + 0.002C^2 + 0.0002NC$	0.36	6.47	0.0001
Al	$2.35 + 0.0004N - 0.008C - 0.000002N^2 + 0.0002C^2 - 0.00009NC$	0.09	1.11	0.3600
H+Al	$25.99 - 0.05C$	0.02	1.02	0.3200
P	$7.75 + 0.05N^* + 0.14C - 0.00006N^2 - 0.004C^2 + 0.0003NC$	0.59	16.38	0.0001
K	$91.3 + 0.42C$	0.05	3.28	0.0700
Zn	$11.32 - 0.03N + 0.19 + 0.00006N^2 - 0.005C^2 - 0.0002NC$	0.07	0.85	0.5200
TOC	$1.01 + 0.002N + 0.05C^* - 0.000003N^2 - 0.0005C^2 - 0.00009NC^*$	0.40	7.69	0.0001
SOM	$7.97 + 0.01N^* - 0.09C^* - 0.00003N^2 + 0.003C^2 + 0.000004NC$	0.38	7.19	0.0001
10–20 cm soil depth				
pH	$5.32 + 0.001N + 0.03C - 0.0000009N^2 + 0.00004C^2 + 0.0000005NC$	0.33	5.77	0.0002
Ca	$8.04 - 0.007N - 0.08C + 0.000009N^2 + 0.003C^2 + 0.0002NC$	0.09	1.16	0.3400
Mg	$6.05 - 0.004N - 0.008C + 0.00002N^2 + 0.0004C^2 + 0.0001NC$	0.09	1.21	0.3200
Al	$2.46 + 0.002N - 0.008C - 0.00001N^2 - 0.0002C^2 + 0.00002NC$	0.03	0.37	0.8700
H+Al	$25.74 - 0.04C$	0.01	0.66	0.4200
P	$6.83 + 0.01N + 0.01C + 0.00001N^2 + 0.0003C^2 - 0.00001NC$	0.49	11.20	0.0001
K	$110.34 - 0.94C + 0.05C^2$	0.22	8.37	0.0006
Zn	$25.97 - 0.04N - 0.24C + 0.00005N^2 + 0.007C^2 - 0.00004NC$	0.10	1.25	0.2900
TOC	$0.9 + 0.001N + 0.03C^* - 0.0000007N^2 - 0.00007C^2 - 0.0001NC^*$	0.29	4.71	0.0010
SOM	$6.68 + 0.01N + 0.008C - 0.00002N^2 + 0.0005C^2 - 0.0001NC$	0.11	1.50	0.2000

*Significant at 5% of probability; TOC, total organic carbon; SOM, soil organic matter.

Table 4. Effect of the eucalyptus biochar (C) and NPK fertilization (N) on upland rice attributes measured in 2008/2009 and 2009/2010.

Parameter	Equation	R ²	F	p
2008/2009				
Height at 22 DAS	$25.02 + 0.07N^* + 0.08C - 0.0001N^{2*} - 0.0004C^2 - 0.0005NC^*$	0.74	32.80	0.0001
Height at 40 DAS	$54.87 + 0.04N^* - 0.11C - 0.00007N^2 + 0.002C^2 - 0.0001NC$	0.29	4.73	0.0010
Height at 55 DAS	$60.10 + 0.08N^* - 0.05C - 0.00008N^2 + 0.006C^2 - 0.001NC^*$	0.71	28.66	0.0001
Height at 70 DAS	$61.30 + 0.11N^* + 0.009C - 0.0002N^{2*} + 0.002C^2 - 0.0007NC$	0.83	57.12	0.0001
Dry matter at 22 DAS	$1.67 + 0.004N^* - 0.02C - 0.000005N^2 + 0.0005C^2 - 0.00005NC$	0.57	15.22	0.0001
Dry matter at 40 DAS	$3.74 + 0.005N + 0.04C + 0.00003N^{2*} - 0.001C^2 - 0.0001NC$	0.65	21.65	0.0001
Dry matter at 55 DAS	$15.39 - 0.04N^* - 0.05C + 0.0001N^{2*} + 0.001C^2 - 0.0002NC$	0.34	6.03	0.0001
Dry matter at 70 DAS	$18.56 + 0.03N^* - 0.05C - 0.00008N^{2*} + 0.0005C^2 - 0.00004NC$	0.17	2.36	0.0500
Yield	$498.45 + 22.55C^* - 0.16C^2$	0.77	104.50	0.0001
2009/2010				
Height at 22 DAS	$19.17 + 0.03N^* + 0.24C^* - 0.00004N^2 - 0.003C^2 - 0.0003NC$	0.44	8.94	0.0001
Height at 40 DAS	$46.9 + 0.11N^* + 0.04C - 0.0002N^{2*} + 0.001C^2 - 0.00005NC$	0.63	19.84	0.0001
Height at 55 DAS	$51.33 + 0.18N^* + 0.23C - 0.0004N^{2*} - 0.006C^2 + 0.00005NC$	0.81	48.14	0.0001
Height at 70 DAS	$76.27 + 0.05N^* + 0.09C - 0.0002N^{2*} - 0.002C^2 + 0.0005C$	0.31	5.31	0.0004
Dry matter at 22 DAS	$0.78 + 0.005N^* + 0.0002C - 0.00001N^{2*} + 0.00007C^2 + 0.00003NC^*$	0.71	28.12	0.0001
Dry matter at 40 DAS	$4.13 + 0.03N^* + 0.04C - 0.00008N^2 - 0.0007C^2 + 0.00001NC$	0.59	16.35	0.0001
Dry matter at 55 DAS	$6.72 + 0.05N^* + 0.12C^* - 0.0001N^{2*} - 0.001C^2 - 0.00001NC$	0.66	22.89	0.0001
Dry matter at 70 DAS	$17.87 + 0.03N + 0.29C - 0.00007N^2 - 0.008C^2 - 0.00008NC$	0.13	1.80	0.1300
Yield	$453.42 + 0.56N + 17.96C^* - 0.002N^2 - 0.1C^2 + 0.02NC^*$	0.84	60.84	0.0001

*Significant at 5% probability; DAS, days after sowing.

biochar had a linear effect on the rice yield ($R^2 = 0.77$), and a nonsignificant interaction with the fertilizer. In the second year, however, there was an interaction between the biochar and the fertilizer in their effect for the yield. A similar effect was reported by Steiner et al. (2007), who found an increment in upland rice yield in Manaus, when charcoal and mineral fertilizer were applied together, and by Zhang et al. (2012), in paddy-field rice. There are several reports on the positive effect of the biochar on the yield of different crops. Oguntunde et al. (2004) observed an increase of over 91 and 278% for charcoal and charcoal + mineral fertilizer, respectively, on corn yield. Nevertheless, plant growth and dry matter accumulation were affected mainly by the application of the fertilizer.

Dry matter accumulation was not affected by the biochar (Table 4) during the first year. However, in the second year, a positive interaction was found for this parameter at 22 DAS. Madari et al. (2006) observed an increase in the height and dry matter biomass of rice cultivar BRS Primavera in the early stage (until 28 DAS) of crop development with the application of 21 Mg ha⁻¹ biochar, in a clay soil, in a pot experiment. Nehls (2002) reported a 100 to 320% increase in the

dry matter biomass of rice with the application of more than 14 Mg ha⁻¹ biochar.

As there was no correlation between the soil nutrient levels and plant growth or yield, probably there were other ways of biochar affecting rice yield. The increased water retention provoked by the addition of biochar to the soil, especially in coarse textured soils, like the one studied hereby, was reported by Sohi et al. (2010) and Karhu et al. (2011). Additionally, Pereira et al. (2012) reported that biochar positively affected the amount of plant available soil water. This effect of biochar may also have contributed to its positive effect on yield.

Conclusions

1. Eucalyptus biochar improves the fertility properties of sandy loam soil, with a largest effect in the surface soil layer and in the first year after its incorporation.

2. Eucalyptus biochar has a low residual effect on soil chemical attributes.

3. For growth and dry matter accumulation of upland rice, the eucalyptus biochar starts to have a positive

combined effect with the fertilizer in the second year, at the early stage of plant development.

4. Eucalyptus biochar positively affects upland rice yields since the first year of its application.

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