SOIL ORGANIC MATTER OVER 4 GROWING SEASONS OF AEROBIC RICE ON A CLAY AND SANDY SOIL AMENDED WITH HARDWOOD BIOCHAR IN THE BRAZILIAN SAVANNAH

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ABSTRACT: In the Brazilian savannah (Cerrado), soils are highly weathered, acidic, with low soil organic matter (SOM) levels, requiring additions of lime and fertiliser for agricultural use. In these soils, improving quantity and quality of SOM is pivotal for efficiency and sustainability gains in crop production. However, building SOM under tropical conditions is challenging due to the fast decomposition of organic material. Here we investigated if SOM levels under aerobic rice systems in the Cerrado could be enhanced through the addition of hardwood biochar, a by-product of bioenergy production rich in resilient, pyrogenic C (70-80% of its weight). The aim of this study was to test the effect of hardwood biochar (char) rates combined with different rates of synthetic N on SOM over 4 growing seasons of aerobic rice after a single application of char to a sandy and a clay soil in the Cerrado. The SOM increased with 0.07% per Mg ha^{-1} of char, at 0.1 year after applying char to the sandy soil. In the clay soil, SOM increased with 0.26 and 0.23% per Mg ha^{-1} of char at 2.5 and 3.5 years after char application, respectively. The increase in SOM is likely to be related to the porosity of char, where SOM can be absorbed and physically protected. Residue added via crop rotation was likely to be the main source of organic material related to an increase in SOM in the clay soil over seasons, the opposite of what was observed in the sandy soil, where no extra source of organic matter, other than char, was added to soil after establishment of field trial.

KEY WORDS: soil amendment, pyrogenic C, char, Ferralsol, Plinthosol, *Oryza sativa*

INTRODUCTION: In the Brazilian savannah (Cerrado), soils are highly weathered, acidic, with low soil organic matter (SOM) levels, requiring additions of lime and fertiliser for agricultural use. In these soils, improving quantity and quality of SOM is pivotal for efficiency and sustainability gains in crop production. Beneficial effects of SOM are increased water and nutrient retention (Fageria, 2001). In the Cerrado, one common strategy to increase organic C levels is the no-tillage system with grass-legume rotation (Barreto et al., 2009). However, building SOM under tropical conditions is challenging due to the fast decomposition of organic material. Also in the Cerrado, around 20-40% of total soil organic C under areas of soybean-based crop rotation and pasture has been regarded as of pyrogenic origin and resilient due to charred material (Roscoe et al., 2001; Jantalia et al., 2007). Here we investigated if SOM level under aerobic rice systems in the Cerrado can be improved through the addition of hardwood biochar, a by-product of bioenergy production rich in resilient, pyrogenic C (70-80% of its weight). Pieces of charcoal made of *Eucalyptus* sp. timber by slow pyrolysis (450-550 °C) which are smaller than 8 mm are not suitable for industrial or domestic uses and could be recycled as soil amendment. High specific surface areas, microporosity (such as presented in Figure 2), and ion-charge characteristics can make biochar very efficient sorbent for a range of organic chemicals which are of agronomic and environmental importance; but such characteristics may change over time due to a myriad of biogeochemical interactions that biochar is likely to undergo in soil (Kookana et al., 2011). Addition of organic material with high C/N ratio, such as hardwood biochar, also requires addition of extra N fertiliser, in order to enhance positive effects on SOM. The aim of this study was to test the effect of rates of hardwood biochar (char) combined with rates of synthetic N on SOM over 4 growing seasons of aerobic rice after a single application of char to a sandy and a clay soil in the Cerrado.

MATERIAL AND METHODS: In December 2008, a permanent field trial was established without irrigation on a sandy Dystric Plinthosol (17% clay, 76% sand, 7% silt) at Estrela do Sul Farm, in Nova Xavantina, Mato Grosso, Brazil. Before the establishment of the field trial, the area was used as pasture for around 15 years, without synthetic fertilization or rotation, covered with brachiaria (*Urochloa ruziziensis*) as the dominant species of grass. After the establishment of the field trial, rice (*Oryza sativa*) was cultivated during summer, followed by fallow during winter. A similar experiment under center pivot irrigation was established in June 2009 on a clayey Rhodic Ferralsol (57% clay, 33% sand, 10% silt) at Embrapa Rice and Beans, Capivara Farm, in Santo Antônio de Goiás, Goiás, Brazil. Before the establishment of the field trial, the area had been cultivated with corn (*Zea mays* L.) + brachiaria (*Urochloa* sp.) (summer) in succession with irrigated common beans (*Phaseolus vulgaris*) (winter) since 2001. After the establishment of the field trial, irrigated common beans was cultivated as the first crop. Over seasons, rice was always cultivated during summer in rotation with irrigated common beans during winter, with an additional crop in 2009 and in 2010, when rice and millet, respectively, were cultivated immediately after harvesting rice. Rice was direct seeded. Crop residues and weeds were controlled using herbicide. Every plot received the same rate of P and K together with the seed, and synthetic N amounts were always fractioned for use in three applications: at sowing and around 25 and 45 days after emergence (DAE). Biochar (char) was applied only once: in December 5, 2008 to the sandy soil; and in June 9, 2009 to the clay soil. Char was milled to pass a 2-mm mesh sieve, spread manually on the soil surface, and incorporated within 0.15 m soil depth using a harrow. Soil organic matter (SOM) was quantified from 500-g samples collected in 3 points within each plot between rows of rice during the flowering stage (around 75 DAE). The SOM was determined by the Walkley–Black method (Nelson and Sommers, 1996), without external heating, using sulphuric acid to generate internal heat for the reaction. On both sites combinations of 4 rates of char (0, 8, 16, 32 Mg ha^{-1}) and synthetic N (0, 30, 60, 90 kg ha^{-1}) were tested. Char rates were randomly allocated to plots of 40 m^2 within four blocks. On the sandy soil, N rates were applied in sequential strips across each of the four blocks every growing season. On the clay soil, some plots had to be placed out the track of pivot wheels resulting in incomplete blocks, and N rates were applied in sequential strips across the four blocks every growing season. Due to incomplete randomization of N rates, which was an unavoidable operational feature in these field trials, the linear mixed model was used to analyse data. Mixed model accounts for potential spatial autocorrelation among plots via the restricted maximum likelihood method (Litell et al., 2006). Location of plots were included as random effects (rows and columns in the clay soil, and blocks and rows within blocks in the sandy soil), and the predictors (char, N, interaction and respective quadratic terms) were included as fixed effects. To identify continuous patterns of response of SOM to char and N rates, surface responses were fitted to the data. A complete quadratic surface response model in which all predictors (char, N, interaction and respective quadratic terms) were included was the start point. To select the appropriate surface response model, predictors with the highest *p*-value (for $p > 0.10$) were progressively excluded. Linear terms were retained whenever interactions or quadratic terms were significant (MacCullagh and Nelder, 1983). Analyses were performed using the mixed procedure (Proc MIXED) of the statistical software SAS/STAT® (SAS Institute Inc., 2008).

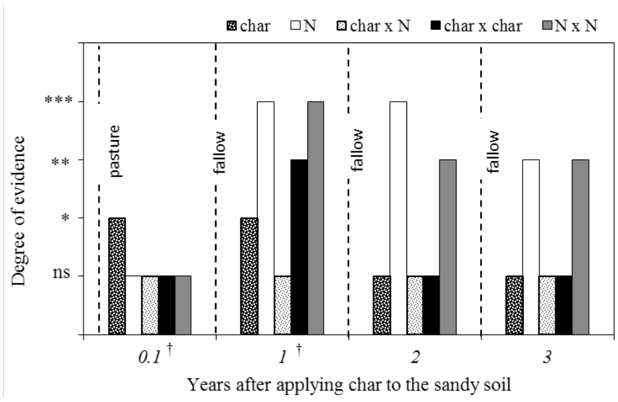
RESULTS AND DISCUSSION: There was no interaction effect of biochar (char) with the synthetic N on SOM for both soil types over growing seasons. In the sandy soil, in 2008, SOM increased with 0.07% per Mg ha^{-1} of char applied; in 2009, SOM increased in a quadratic trend with char rates higher than 16 Mg ha^{-1}; in 2010 SOM increased in a quadratic trend with N rates higher than 60 kg ha^{-1}; and in 2011 SOM increased with N rates up to 60 kg ha^{-1}. In the clay soil, in 2009, SOM increased linearly with N rates; in 2010, SOM increased in a quadratic trend with char rates higher than 16 Mg ha^{-1}; and in 2011 and 2012, SOM increased linearly with char rates, with 0.26 and 0.23% per Mg ha^{-1} of the char applied, respectively (Table 1).

Table 1. Parameter estimates (± standard error) for fitted surface response models representing the quantitative effect of rates of hardwood biochar (char) and synthetic nitrogen (N) on soil organic matter (SOM, g dm^{-3}) at 0.2 m soil depth in a clayey Rhodic Ferralsol and in a sandy District Plinthosol over 4 growing seasons (years after applying char) of aerobic rice in the Brazilian savannah.

Seasons	Fitted models	R^2
	Sandy soil	
2008† (0.1 yr)	12.45 (0.10) + 0.008246 (0.004631) char	0.21
2009† (1 yr)	7.46 (0.31) - 0.0528 (0.0299) char + 0.0393 (0.0103) N + 0.0019 (0.0009/ char^2 - 0.0003 (0.0001) N^2	0.79
2010 (2 yr)	9.92 (0.70) - 0.0684 (0.0255) N + 0.00068 (0.00027) N^2	0.50
2011 (3 yr)	9.65 (1.53) + 0.1925 (0.0768) N - 0.00204 (0.00082) N^2	0.38
	Clay soil	
2009 (0.6 yr)	15.56 (0.32) + 0.00894 (0.00497) N	0.15
2010 (1.5 yr)	25.39 (1.16) - 0.1338 (0.09956) char + 0.005224 (0.002874) char^2	0.12
2011 (2.5 yr)	25.50 (0.67) + 0.06684 (0.03388) char	0.16
2012 (3.5 yr)	29.87 (0.64) + 0.06892 (0.03291) char	0.37

Biochar rates: 0, 8, 16, 32 Mg ha^{-1}, N rates: 0, 30, 60, 90 kg ha^{-1}; values between brackets correspond to standard error of estimate; significance values for estimates presented in Figure 1; R^2: squared Pearson correlation coefficient between observed and predicted values. †Adapted from Petter et al. (2010).

The temporal dynamics in the sandy soil showed a positive response of SOM to char rates at 0.1 and 1 year after applying char, followed by no response to char rates at 2 and 3 years after applying char. To the contrary, the temporal dynamics in the clay soil showed no response of SOM to char rates at 0.6 years after applying char, followed by a positive response of SOM to char rates at 1.5, 2.5 and 3.5 years after applying char (Figure 1). Effects on SOM due to char application might be related to the intrinsic absorption capacity of char, and a consequence of the different agronomic management adopted on the sandy and clay soil over seasons. The SOM decreased around 22% in the sandy soil, whereas increased around 92% in the clay soil under control treatments (0 char, 0 N) after 4 growing seasons (Table 1). The combination of char with fresh organic matter (added via crop residues) seemed to be the key component related to an increase in SOM in the clay soil over seasons, the opposite of what was observed in the sandy soil, where no extra source of organic matter, other than char and rice residues, was added to the soil. Particles of SOM can be physically protected within pores of char, whose size is around 5 μm (Figure 2). In the sandy soil, SOM response to char rates was positive immediately after establishment of the field trial in 2008 (0.1 year after applying char), when the area was converted from pasture to agriculture; and in 2009 (1 year after applying char), probably as a result of the lasting effect of the organic material added to the soil after conversion. Since rice was cultivated followed by fallow, no input of crop residues or other source of organic material was added to the soil, therefore no effect of char rates on SOM was observed after 1 year of its application to the sandy soil. In the clay soil, to the contrary, a positive response of SOM to char rates was continuously observed from the second season on (1.5, 2.5 and 3.5 years after applying char). The remaining positive effect of char on SOM raises the question whether the physical interaction of char with SOM is influencing size of aggregates and C accumulation within aggregates in the clay soil.



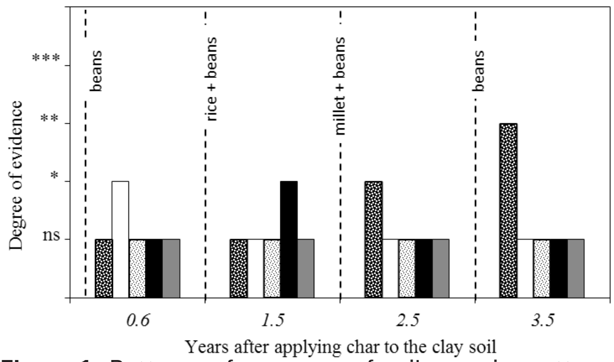


Figure 1. Patterns of response of soil organic matter to hardwood biochar (char) and synthetic nitrogen (N) rates over 4 growing seasons of aerobic rice on a sandy District Plinthosol and clayey Rhodic Ferralsol in the Brazilian savannah. Patterns were represented by the degree of evidence (*0.05 < $p \leq 0.10$, **0.01 < $p \leq 0.05$, *** $p \leq 0.01$, ns $p > 0.10$) on fitted linear, interaction and quadratic effects as presented in Table 1. Dotted lines represent rotations between growing seasons of rice. †Adapted from Petter et al. (2010).

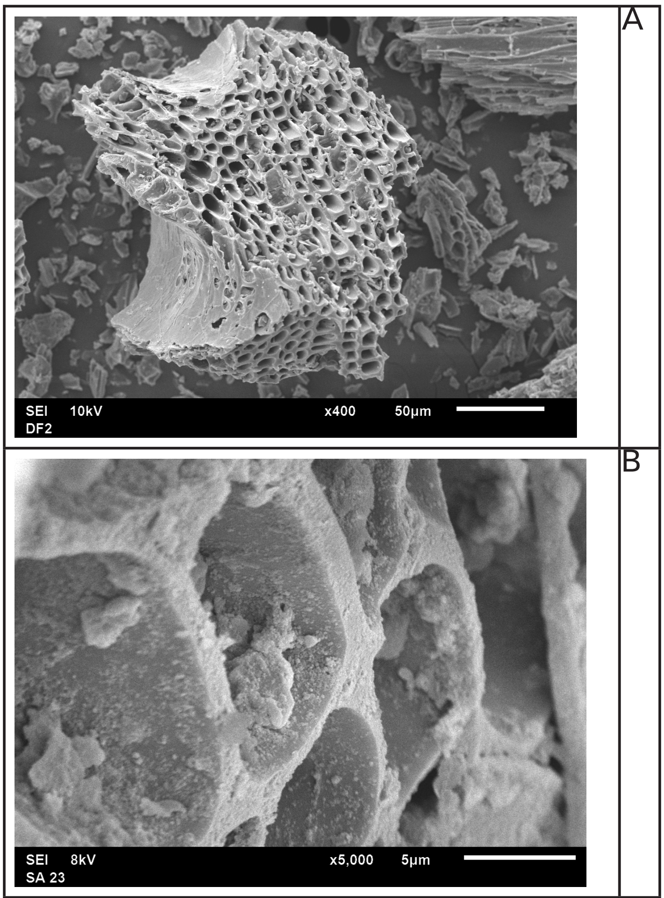


Figure 2. High resolution images of hardwood biochar: the intrinsic porosity (400x) (a); and the interaction with soil particles 1.5 years after application into a clay soil (5000x) (b).

CONCLUSIONS: SOM increased with 0.07% per Mg ha^{-1} of char, at 0.1 year after applying char to the sandy soil. In the clay soil, SOM increased with 0.26-0.23% per Mg ha^{-1} of char at 2.5 and 3.5 years after char application, respectively. The increase in SOM is likely to be related to the porosity of char, where SOM can be absorbed and physically protected. Residue added via crop rotation was likely to be the main source of organic material related to an increase in SOM in the clay soil over seasons, the opposite of what was observed in the sandy soil, where no extra source of organic matter, other than char and rice residues, was added to the soil after establishment of the field trial.

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