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Biochar improves fertility of a clay soil in the Brazilian Savannah: short term effects and impact on rice yield

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Abstract

The objective of this study was to report single season effects of wood biochar (char) application coupled with N fertilization on soil chemical properties, aerobic rice growth and grain yield in a clayey Rhodic Ferralsol in the Brazilian Savannah. Char application effected an increase in soil pH, K, Ca, Mg, CEC, Mn and nitrate while decreasing Al content and potential acidity of soils. No distinct effect of char application on grain yield of aerobic rice was observed. We believe that soil properties impacted by char application were inconsequential for rice yields because neither water, low pH, nor the availability of K or P were limiting factors for rice production. Rate of char above 16 Mg ha $^{-1}$ reduced leaf area index and total shoot dry matter by 72 days after sowing. The number of panicles infected by rice blast decreased with increasing char rate. Increased dry matter beyond the remobilization capacity of the crop, and high number of panicles infected by rice blast were the likely cause of the lower grain yield observed when more than 60 kg N ha^{-1} was applied. The optimal rate of N was 46 kg ha^{-1} and resulted in a rice grain yield above 3 Mg ha^{-1}.

Keywords: aerobic system, carbonised biomass, Ferralsol, nitrogen, *Oryza sativa*, Oxisol

1 Introduction

Aerobic rice (*Oryza sativa*) based cropping systems (ARS) are typically rain fed, where rice is grown on well drained soils. Compared to rice paddy cultivation, less demand for labour, mechanization and effective water usage are important advantages of ARS (Pinheiro *et al.*, 2006). However, grain yield of aerobic rice in the Brazilian Savannah (BS) can be 60 % lower than in continuously waterlogged soil (Fageria, 2001). Crop yield constraints of ARS in the BS are: water limitation due to rainfall variability, high weed infestation, rice blast (*Magnaporthe grisea*), low soil organic matter (SOM) content and poor soil nutrient availability.

Approximately 46 % of the total area in the BS is covered by Ferralsol (Embrapa, 2006), which have, in their original condition, favourable physical properties,

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such as fine texture, good structure and high water conductivity. Chemically, however, those soils are highly weathered, acid, with low SOM (Fageria *et al.*, 2004). The SOM level is about 2 % within 0.2 m soil depth. Under such soil conditions, nitrogen (N) is often the most yield-limiting nutrient. Management options that could increase N use efficiency would probably lead to increased aerobic rice yields in the BS.

One promising management option is the use of 'biochar' as soil amendment, although so far there are still no conclusive field studies that quantify the effect of biochar application on grain yield of aerobic rice in the BS. Pieces of charcoal produced from timber, worthless for industrial or domestic uses, could be recycled as soil amendment. It is such material that we refer to as 'biochar', a substance rich in resistant (pyrogenic) carbon (70–80 % of the material) that might improve soil fertility. According to Jeffery *et al.* (2011), the main positive effects of biochar on crop yield are via increased soil water retention, reduced soil acidity and increased soil nutrient availability (in particular K). Using sprinkler irrigation and applying K and P fertilizer to all treatments, enabled us to focus on the potential interaction effect between biochar application and synthetic N fertilization on grain yield and yield components in ARS.

Some effects of biochar on ARS have been reported showing that the dominant effects are on soil chemical properties rather than on crop yield and that the positive effect of biochar on crop yield might be dependent on the application of organic or synthetic fertilizer (Haefele *et al.*, 2011; Asai *et al.*, 2009; Steiner *et al.*, 2007). Further, Haefele *et al.* (2011) and Asai *et al.* (2009) reported some negative effects of biochar applications on aerobic rice growth and yield due to decreased N availability. To investigate the effect of wood biochar in combination with synthetic N on grain yield and on soil properties in ARS in areas of the BS, two field experiments were established: one on a clayey Rhodic Ferralsol featuring favourable soil conditions and with possibility for sprinkle irrigation and another on a less favourable sandy loam Dystric Plinthosol (non-irrigated). The short-term effects of wood biochar on ARS in the sandy loam Dystric Plinthosol were reported by Petter *et al.* (2012). The objective of our study was to report short-term effects of wood biochar application on soil chemical properties and on aerobic rice growth and grain yield on the clayey Rhodic Ferralsol in the BS.

2 Materials and methods

2.1 Experimental design and agronomic details

A field experiment was established in June 9, 2009, on a clayey Rhodic Ferralsol at the National Rice and Beans Research Centre, in Santo Antônio de Goiás, Goiás, Brazil (16°29'17" S and 49°17'57" W). The soil texture consisted of clay (574 $g\,kg^{-1}$), silt (100 $g\,kg^{-1}$), and sand (326 $g\,kg^{-1}$). Sixty four experimental plots of 40 m^2 (4 m $\times$ 10 m) were arranged in four replications, with wood biochar (0, 8, 16, 32 $Mg\,ha^{-1}$) and synthetic N (0, 30, 60, 90 $kg\,ha^{-1}$), each applied at four levels. At the establishment of the field trial, biochar was incorporated into 0–0.15 m soil depth using a harrow. On November 3, 2009, following a crop of irrigated common beans (*Phaseolus vulgaris*), aerobic rice (*Oryza sativa*), cultivar 'BRS Primavera', was sown. Rice was sown in seven rows of 10 m in each plot, with a row spacing of 0.4 m and a plant density of 100 seeds m^{-1}. Plots were located under a centre pivot. A total of 78 mm of water was applied by sprinkler irrigation in amounts of around 13 mm each time, throughout the growing season. Rates of 120 $kg\,ha^{-1}$ of P and 60 $kg\,ha^{-1}$ of K and 50 % of the total N (urea) were applied to all plots and incorporated into the soil together with the rice seeds using a no-till planter. The remaining 50 % of N was broadcasted at 33 days after sowing. Total rainfall during the growing season was 871 mm, average temperature was 24 °C, and average daily radiation was 18.5 $MJ\,m^{-2}$. Rice was harvested on 22nd of February, 2010.

2.2 Biochar properties

The source of biochar applied was charcoal produced from plantation timber (*Eucalyptus* sp.) by slow pyrolysis, at around 400–550 °C. Pieces of charcoal ($\leq$ 8 mm) were obtained from a commercial producer of charcoal in the region. It was milled to pass a 2 mm sieve before soil application. Chemical analysis showed that the biochar contained around 76 % C, 0.8 % N, 0.0002 % P, 0.003 % K, 0.0002 % Cu+Fe+Mn+Zn, 0.05 % Ca, and 0.009 % Mg. This accounts for 77 % of the biochar mass. The remaining mass of biochar comprises mainly O (ca. 20 %). Biochar has a labile fraction, around 6 % of the total C, which was determined via oxidation of biochar with dichromate by the Walkley-Black method (Walkley & Black, 1934). Total C and N were determined in a PerkinElmer 2400 Series II CHNS/O Elemental Analyser. Extractable P, K, Cu, Fe, Mn, and Zn were determined using a Mehlich 1 solution (Mehlich, 1953); and available Ca and Mg were determined using a 1 mol L^{-1} KCl solution (Gavlak *et al.*, 2003). Extraction was followed by determination via atomic absorption spectrometry (Embrapa, 2009).

2.3 Soil measurements

Soil chemical properties were determined using one 500 g composite sample for each plot collected in the 0–0.2 m layer at 70 days after sowing (DAS). Available P, K, Cu, Fe, Mn, Zn, Ca and Mg were quantified using same methods as described previously. The pH was determined using a 1:1 soil:water solution (Bates, 1973); potential acidity (H + Al) using a solution of calcium acetate (0.5 mol L^{-1} at pH 7.1–7.2) followed by titration with NaOH (0.025 mol L^{-1}) using phenolphthalein (10 g L^{-1}) as indicator (Embrapa, 2009); and soil organic carbon (SOC) using the Walkley-Black method with sulphuric acid (H_2SO_4) to create internal heat for reaction (Nelson & Sommers, 1996). Cation exchange capacity (CEC) was calculated as the sum of Ca, Mg, K and Al.

Soil moisture, ammonium (NH_4^+) and nitrate (NO_3^-) concentrations were frequently measured throughout the growing season in the 0–0.1 m soil layer; three subsamples were collected to get a 30 g soil sample in each plot. Around 10 g of soil was weighed before and after drying in an oven for 24 hours at 105 °C. The available NH_4^+ and NO_3^- were extracted by shaking 20 g of soil with 60 mL of 1 mol L^{-1} KCl solution for 60 minutes (Mulvaney, 1996). Extraction was followed by determination via flow injection analysis (Ocean Optics, USA). The final result was given in mg L^{-1}. To estimate mineral N [mg (kg soil)$^{-1}$] the soil moisture [(g water) (g soil)$^{-1}$] at the moment of sampling was taken into account.

2.4 Plant measurements

Total shoot dry matter (TDM) and leaf area index (LAI) were determined at 72 DAS; plants from a 0.5 m row (area of 0.2 m^2) were collected in each plot. Leaf area of 10 tillers was measured by using a LI-COR equipment (Lincoln, NE, USA). The total number of tillers in a 0.5 m row was counted and used to calculate LAI. All plants were dried in an oven at 75 °C for 48 hours and weighed to determine TDM. At 94 DAS, 20 panicles were collected to determine the number of panicles infected by rice blast (*Magnaporthe grisea*) in each plot. The number of infected panicles was visually determined. At 110 DAS, yield (weight of grains dried to 13 % moisture) and yield components (total dry matter, number of tillers, panicles, grains, empty grains and full grains) were determined from an area of 2.4 m^2 (2 rows of 3 m). Spikelet fertility was expressed as the ratio between number of filled grains per panicle and total number of grains per panicle. Harvest index was calculated as the ratio between weight of dried grains and weight of TDM (including grains).

2.5 Statistical analysis

We adopted a generalized linear mixed model (GLMM) to estimate functional relationships (response surface) between soil and plant response variables and predictors (N and biochar). The GLMM allows the estimation of response surface parameters via restricted maximum likelihood method, accounting for spatial autocorrelation among plots via information on random effects. In our study, rows and columns (coordinates of plots) were included as random effects, and predictors were included as fixed effects. We started with a complete quadratic response surface model in which all predictors were included. To select the appropriate response surface model, we followed a backward criteria in which predictors with highest p-value ($p > 0.10$) were progressively excluded, subject to the hierarchical criteria of retaining the corresponding linear terms whenever interactions or quadratic terms were present (for further details see McCullagh & Nelder, 1983). Considering the expected high residual variance for most of the outcomes as consequence of the large experimental set, we adopted $p \leq 0.10$ as our threshold to safeguard against high type II error. Analyses were performed using the SAS/STAT® MIXED procedure (SAS Institute Inc., 2008).

3 Results

3.1 Soil chemical properties

Soil pH, Ca, Mg and CEC increased linearly with biochar rate, whereas for Al a linear decrease was observed (Table 1). The effect of biochar on potential acidity (H+Al) followed a quadratic trend with peak around 16 Mg ha^{-1}. The effect of biochar on K was dependent on the N application rate: the higher the rate of N, the more biochar was required to achieve same K concentration. There was no effect of biochar on both P and soil organic carbon (SOC) level. The SOC increased linearly with N application. A linear relationship was also observed between N rate and both nitrate (NO_3^-) and ammonium (NH_4^+) concentrations. Concentration of NO_3^- increased linearly with biochar applications. Among micronutrients, Manganese (Mn) increased linearly with biochar application. There was no effect of biochar on Zn and Cu. Zn increased with N rate above 60 kg ha^{-1} and Cu above 53 kg ha^{-1}. There was no effect of N and biochar on Fe concentration.

Table 1: *Fitted response surface models to represent the quantitative effects of wood biochar (char) and synthetic nitrogen (N) rate on soil chemical properties of a clayey Rhodic Ferralsol cultivated with aerobic rice in the Brazilian Savannah, growing season 2009/2010*[†]

Variables	*Fitted models*	R^2
P (mg kg^{-1})	$32.64 - 0.4390\,\mathrm{N}^{**} + 0.005883\,\mathrm{N}^{2\;***}$	0.49
K (mg kg^{-1})	$59.37 + 1.3705\,\mathrm{char}^{***} - 0.1011\,\mathrm{N}^{\mathrm{ns}} - 0.0127\,\mathrm{char} \times \mathrm{N}^{**}$	0.78
Cu (mg kg^{-1})	$2.55 - 0.01241\,\mathrm{N}^{**} + 0.000118\,\mathrm{N}^{2\;**}$	0.35
Mn (mg kg^{-1})	$10.79 + 0.1103\,\mathrm{char}^{***} - 0.1052\,\mathrm{N}^{***} + 0.000827\,\mathrm{N}^{2\;**}$	0.79
Zn (mg kg^{-1})	$4.94 - 0.04723\,\mathrm{N}^{**} + 0.000391\,\mathrm{N}^{2\;*}$	0.51
Ca (mmol$_c$ kg^{-1})	$10.09 + 0.0879\,\mathrm{char}^{**} - 0.04146\,\mathrm{N}^{*}$	0.60
Mg (mmol$_c$ kg^{-1})	$3.26 + 0.02292\,\mathrm{char}^{*} - 0.01213\,\mathrm{N}^{\mathrm{ns}}$	0.61
pH (water)	$5.06 + 0.005716\,\mathrm{char}^{**} - 0.00312\,\mathrm{N}^{**}$	0.70
H+Al (mmol$_c$ kg^{-1})	$60.49 + 0.31082\,\mathrm{char}^{\mathrm{ns}} + 0.08002\,\mathrm{N}^{*} - 0.01299\,\mathrm{char}^{2\;*}$	0.66
Al (mmol$_c$ kg^{-1})	$3.41 - 0.04703\,\mathrm{char}^{***} + 0.01561\,\mathrm{N}^{*}$	0.67
SOC (g kg^{-1})	$15.56 + 0.00894\,\mathrm{N}^{*}$	0.15
CEC (mmol$_c$ kg^{-1})	$18.47 + 0.08376\,\mathrm{char}^{*} - 0.04542\,\mathrm{N}^{*}$	0.53
N-NH$_4^+$ (mg kg^{-1})	$16.83 + 0.06349\,\mathrm{N}^{***}$	0.67
N-NO$_3^-$ (mg kg^{-1})	$43.85 + 0.5002\,\mathrm{char}^{***} + 0.3357\,\mathrm{N}^{***}$	0.91

[†] Rate of char (0, 8, 16, 32 Mg ha^{-1}) and N (0, 30, 60, 90 kg ha^{-1}); SOC: soil organic carbon; CEC: capacity to exchange cations; R^2: squared Pearson correlation coefficient between observed and predicted values for each char × N treatment (n = 4).
Nominal significance level of tests for effects: *** $p \leq 0.01$, ** $p \leq 0.05$, * $p \leq 0.10$, $^{\mathrm{ns}}$ not significant.

Table 2: *Fitted response surface models to represent the quantitative effects of wood biochar (char) and synthetic nitrogen (N) rate on growth, grain yield and yield components of aerobic rice on a clayey Rhodic Ferralsol in the Brazilian Savannah, growing season 2009/2010*[†]

Variables	*Fitted models*	R^2
LAI at 72 DAS (m^2 m^{-2})	$3.83 + 0.08097\,\mathrm{char}^{**} - 0.00276\,\mathrm{char}^{2\;**}$	0.27
TDM at 72 DAS (Mg ha^{-1})	$3.67 + 0.08908\,\mathrm{char}^{\mathrm{ns}} + 0.02041\,\mathrm{N}^{**} - 0.00329\,\mathrm{char}^{2\;*}$	0.81
TDM at 110 DAS (Mg ha^{-1})	$5.63 + 0.05018\,\mathrm{N}^{*} - 0.00048\,\mathrm{N}^{2\;*}$	0.53
Grain yield (Mg ha^{-1})	$2.07 + 0.03718\,\mathrm{N}^{**} - 0.00036\,\mathrm{N}^{2\;**}$	0.40
Harvest Index (Mg ha^{-1})	$0.44 - 0.00221\,\mathrm{char}^{*} - 0.00072\,\mathrm{N}^{\mathrm{ns}} + 0.00004\,\mathrm{char} \times \mathrm{N}^{**}$	0.28
Weight of 1000 grains (g)	$21.91 - 0.01586\,\mathrm{N}^{**}$	0.36
Spikelet Fertility × 100 (%)	$0.72 + 0.00201\,\mathrm{N}^{*} - 0.00003\,\mathrm{N}^{2\;**}$	0.52
Healthy Panicles × 100 (%)	$0.59 + 0.00348\,\mathrm{char}^{*} - 0.0016\,\mathrm{N}^{*}$	0.45

[†] Rate of char (0, 8, 16, 32 Mg ha^{-1}) and N (0, 30, 60, 90 kg ha^{-1}); R^2: squared Pearson correlation coefficient between observed and predicted values for each char × N treatment (n = 4). DAS: days after sowing. Nominal significance level of tests for effects: ** $p \leq 0.05$, * $p \leq 0.10$, $^{\mathrm{ns}}$ not significant.

3.2 Plant growth, grain yield and yield components

The influence of biochar on leaf area index (LAI) and total shoot dry matter (TDM) at 72 DAS followed quadratic trends with a peak around 16 Mg ha^{-1} (Table 2). Predicted LAI (m^2 m^{-2}) varied from 4.4 ± 0.49 (16 char) to 3.6 ± 0.51 (32 char), regardless of N. Predicted TDM (Mg ha^{-1}) varied from 6.1 ± 0.54 (16 char; 90 N) to 3.1 ± 0.61 (32 char; 0 N). There was no effect of biochar on grain yield of aerobic rice. Rates of N above 60 kg ha^{-1} tended to negatively affect grain yield, even though the higher the rate of N, the higher the TDM at 72 DAS. Predicted grain yield (Mg ha^{-1}) varied from 2.99 ± 0.32 (60 N) to 2.07 ± 0.38 (0 N) (Fig.1). As observed for grain yield, the influence of N on TDM at 110 DAS and on spikelet fertility (SF) also followed a quadratic trend, with predicted TDM (Mg ha^{-1}) at 110 DAS varying from 6.9 ± 0.55 (60 N) to 5.6 ± 0.63 (0 N). Predicted SF varied from 0.75 ± 0.02 (30 N) to 0.65 ± 0.02 (90 N). Weight of 1000-grains decreased linearly with N rate. Predicted weight of 1000-grains varied from 21.91 ± 0.42 (0 N) to 20.48 ± 0.45 (90 N). There was, however, an effect of the interaction biochar × N on harvest index (HI), whereby the higher the rate of biochar applied, the more N was required to achieve the same HI. In treatments without N application, biochar rate had a negative effect on HI; and in treatments without biochar application, N rate had a negative effect on HI. Predicted HI (Mg Mg^{-1}) varied from 0.44 ± 0.03 (0 char; 0 N) to 0.37 ± 0.03 (32 char; 0 N). Ratio of healthy panicles (HP) increased linearly with biochar rate, whereas N rate linearly decreased HP ratio (Fig.1). Predicted HP varied from 0.70 ± 0.07 (32 char; 0 N) to 0.45 ± 0.06 (0 char; 90 N).

4 Discussion

We found no observable effect of biochar on grain yield of aerobic rice, even though biochar application led to improvements on soil chemical properties, mostly related to the acidity neutralizing capacity of biochar. We postulate that the observed improvements in soil properties due to biochar application did not increase grain yield because (i) there was no limitation of water, K or P in our study and (ii) aerobic rice is an acid tolerant crop (Fageria *et al.*, 2004). For this study we expected N to be the most important yield-limiting factor. Soil nitrate concentration increased with biochar applications without influencing plant growth, except at very high levels of biochar (> 16 Mg ha^{-1}) that reduced TDM and LAI at 72 DAS. Similarly, Asai *et al.* (2009) observed that application of 16 Mg ha^{-1} wood biochar reduced chlorophyll concentration in rice leaves. The cause for a negative effect on plant growth was not clear in our study. Possibilities are discussed below.

Throughout the growing season, nitrate was the predominant form of mineral N in the soil with the presence of biochar. If there was an excess of nitrate in soil, then sporadic losses via denitrification were prone to occur, especially under irrigated systems (Bouwman, 1990). Complementary, due to the high C/N ratio of the wood biochar and its labile C (ca. 6 % of the total C), soil microbial activity is likely to raise leading to a decrease in N availability to the crop. In an Amazon Ferralsol amended with wood biochar, Lehmann *et al.* (2003) reported a decrease in total soil N availability and Steiner *et al.* (2008) detected an increase in microbial activity with increasing wood biochar rate. If there was an effect

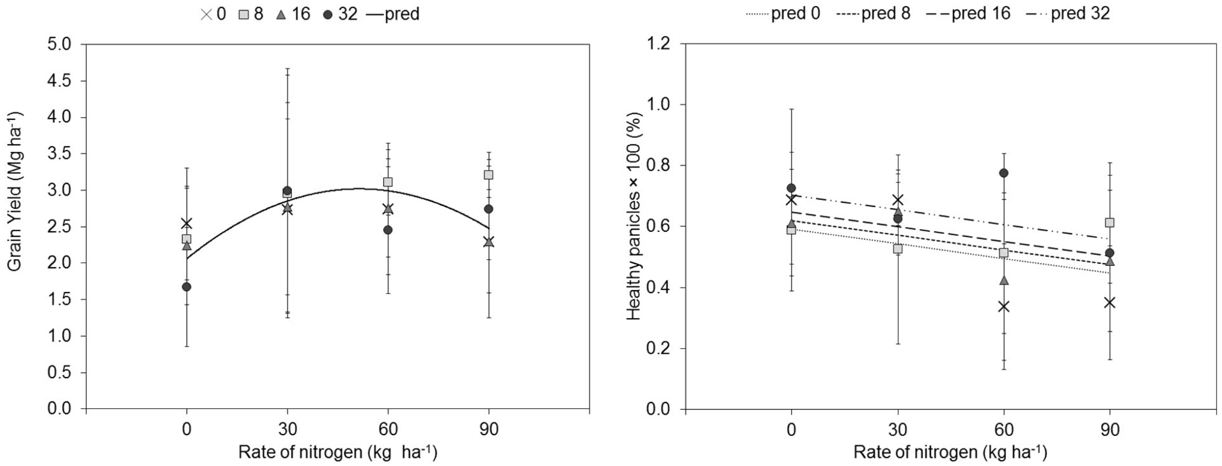

Fig. 1: *Response surfaces for the effect of wood biochar (× 0, □ 8, △ 16, and ○ 32 Mg ha^{-1}) and synthetic nitrogen (0, 30, 60, and 90 kg ha^{-1}) rate on grain yield and percentage of healthy panicles of aerobic rice cultivated on a clayey Rhodic Ferralsol during 2009/2010 growing season in the Brazilian Savannah. Dots represent means for each char × N treatment. Bars represent standard deviation of means (n=4). Lines correspond to predicted values (pred) given by fitted models presented in Table 2.*

of biochar on decreasing N availability to the crop, then it was temporary, since no effect of biochar on TDM and yield at crop maturity was detected in this study. Conversely, surplus fertilization with synthetic N increased TDM at 72 DAS but lowered yields because it could result in an amount of dry matter that exceeded the capacity of the rice variety to remobilize stored carbohydrates to fill grains. This capacity limitation is more usually found in modern varieties, such as the 'BRS Primavera' used in this study, than in traditional aerobic rice varieties (Pinheiro *et al.*, 2006).

For our study and according to our model, the optimal rate of N was around 46 kg ha^{-1} resulting in a grain yield above 3 Mg ha^{-1} (Fig. 1). In a less favorable area (76 % sand, non-irrigated) in the Brazilian Savannah, Petter *et al.* (2012) found that grain yield of aerobic rice was increased by 3 % per Mg ha^{-1} biochar amendment, with the rice sown one month after wood biochar application. This finding suggests that short-term effects of biochar application on grain yield of aerobic rice can be more prominent under less favorable (Petter *et al.*, 2012) than favorable (this study) conditions in the Brazilian Savannah. Clay soils naturally have higher water holding capacity and CEC than sandy soils. In sandy soils, wood biochar is likely to act as an extra fertilizer, as well as increasing water holding capacity as reported by Tryon (1948).

Apart from the positive effects of biochar on improving soil fertility, we observed that biochar applications decreased the number of panicles infected by rice blast (*Magnaporthe grisea*), whereas N rate increased the severity of the disease. While leaf blast can indirectly reduce grain yield via reduction of green leaf area (Bastiaans, 1993), rice blast in panicles directly affects the number and weight of grains (Silva-Lobo *et al.*, 2012) as was observed in this study. The effect of biochar on increasing the number of healthy panicles might be associated with Manganese (Mn). Manganese plays an important role for the resistance to rice blast (Thompson & Huber, 2007; Primavesi *et al.*, 1972). We observed that biochar application increased soil Mn concentration, but we did not find an observable direct effect of soil Mn on healthy panicles, spikelet fertility or harvest index (data not shown). This suggests that the effect of biochar on reducing rice blast in panicles has probably other causes than Mn alone. Elad *et al.* (2010), for example, has reported a systemic resistance to foliar fungal pathogens induced by soil-applied wood biochar. Since rice blast is one of the most yield-limiting factors of aerobic rice in Brazil, the potential positive effect of biochar on resistance to rice blast requires further investigation. The negative effect of rate of $N > 60$ kg N ha^{-1} on grain yield can have two causes: increased dry matter beyond the remobilization capacity of the crop; and increased number of panicles infected by rice blast. Effects of biochar on soil properties may change with time, leading to different responses than the ones observed in this study.

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