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Properties of a sandy clay loam Haplic Ferralsol and soybean grain yield in a five-year field trial as affected by biochar amendment

Beata E. Madari[a,*,1], Mellissa A.S. Silva[a,b], Márcia T.M. Carvalho[a], Aline H.N. Maia[c], Fabiano A. Petter[b,1,2], Janne L.S. Santos[b], Siu M. Tsai[d,1], Wesley G.O. Leal[a], Walmes M. Zeviani[e]

[a] Embrapa Arroz e Feijão, Rodovia GO-462, Km 12, CEP 75375-000 Santo Antônio de Goiás, GO, Brazil
[b] School of Agronomy and Food Engineering, Federal University of Goiás, Campus Samambaia, Rodovia GO-462, Km 0, CEP 74001-970 Goiânia, GO, Brazil
[c] Embrapa Meio Ambiente, Rodovia SP-340, km 127.5, Tanquinho Velho, CEP 13820-000 Jaguariúna, SP, Brazil
[d] University of São Paulo (USP/CENA), Av. Centenário, 303, CEP 13400-970 Piracicaba, SP, Brazil
[e] Fedral University of Paraná, Rua XV de Novembro, 1299, Centro, CEP 80060-000 Curitiba, PR, Brazil

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ABSTRACT

Biochar may increase soil fertility and crop yield by enhancing soil organic carbon (SOC), nutrient availability and water retention. However, the mechanisms through which biochar effects crop yield at field scale and the time span over which biochar can affect soil properties and crop yield are still little known. The aim of this study was to evaluate the effect of wood biochar as soil amendment, combined with the application of synthetic fertilizer in a zero-tillage system, on soil physical-chemical properties and soybean grain yield in a 5-year field trial settled on a sandy clay loam Haplic Ferralsol of the Brazilian savannah. Immediately after biochar application (year 0), soil pH and plant available water (PAW) increased and Al^{3+} and bulk density (BD) decreased linearly with biochar application rate. Later, in year 5, biochar had no effect for PAW and BD increased with biochar rates. The SOC was not affected until the third year after application, but increased linearly with biochar rates at 4 and 5 years after its application. Macro-porosity (MAC) was affected in a quadratic manner reaching a maximum at 8 Mg ha^{-1} biochar rate in years 0 and 2, however in year 5 it decreased with increasing biochar rates. Soybean grain yield increased with biochar rates until the third year after its application. There was almost no interaction effect of biochar and synthetic fertilizer; except for potassium (K^+) availability and grain yield in year 3. Possible control mechanisms of biochar effect on soybean grain yield through its effect on soil fertility and physical-hydraulic properties are discussed. The effect of biochar on soybean yield depended on multiple independent factors that included soil and environmental variables. Because of this its effect on yield was variable through the years, which makes it rather unpredictable. Biochar, however, may have an important contribution to sustainable production through enhancing the effect of conservation soil management, like the use of green manure or mulching, on SOC accumulation.

1. Introduction

Synthetic fertilization can represent 30% of the total costs of grain production in Brazil (CONAB, 2015). Nutrient prices are especially prohibitive for small or family producers. The lack of adequate soil fertilization results in low yields and deterioration of soil quality. Using local or alternative sources of nutrients or amendments in order to improve or maintain soil fertility through improving soil quality could be a reasonable way for sustainable intensification of smallholders' agricultural activities.

Biochar is any source of biomass that was previously heated in the absence, or at low concentrations, of oxygen with the purpose of application to the soil in order to improve its production potential (Sohi et al., 2010). Due to the process of pyrolysis, biochar has proportionally increased carbon (C) content compared to the initial feedstock, which is partially recalcitrant (Crombie et al., 2013). The recalcitrant C content suggests a relatively long persistence of a fraction of this material in the soil. However, its other fractions may be readily decomposable. The relative content of stable and decomposable C in biochars largely depends on the charring conditions, including temperature (Sohi et al.,

* Corresponding author.
E-mail address: beata.madari@embrapa.br (B.E. Madari).
[1] Fellow for productivity in research of the National Council for Scientific and Technological Development of Brazil (CNPq).
[2] Present address: Federal University of Mato Grosso, Av. Fernando Corrêa da Costa, 2367, Bairro Nova Esperança, CEP 78060-900 Cuiabá, MT, Brazil.

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2010). Lower temperatures result in less fixed C, lower stability characteristics, including lower C:N and higher H:C and O:C ratios as well as a lower proportion of aromatic compounds compared to labile structural elements (Trompowsky et al., 2005). Besides, biochar, due to its physical and surface properties, potentially enhances soil porosity, soil water retention, adsorption of soluble compounds and serves as shelter to microorganisms (Joseph et al., 2010), which are mechanisms to enhance soil quality and productive potential.

Biochar application to soils can lead to an increase in crop yields of a wide variety of plant species (Jeffery et al., 2011). However, the comparison of research findings is difficult because different biomass sources and charring conditions result in biochars of different properties (Novotny et al., 2015). Also, there is still relatively limited information that originates from field experiments and the outcomes are often contradictory. For example, 33% increase was observed in biomass and yield of durum wheat in a Fluvaquentic Dystroxerepts (43% silt, 50% sand) in two consecutive growing seasons after a single application of coppiced woodlands (beech, hazel, oak and birch) biochar (Vaccari et al., 2011). Increased maize and soybean yields were measured during four consecutive years in a kaolinitic typic Haplustox (40–44% clay) after single application of wood biochar made at about 300 °C (Major et al., 2013). In contrast, although pronounced effects on the retention of exchangeable cations such as K^+ and Ca^{2+} was observed with walnut shell biochar (made at 900 °C) applied in a silt loam soil (49% sand, 29% silt), compared to unamended or compost added soils, no effect on crop yields was found (Suddick and Six, 2013).

In the Brazilian Savannah, a single application of biochar made of eucalyptus wood (at about 450 °C) improved the yield of aerobic rice over two consecutive years in a sandy Dystric Plinthosol (Petter et al., 2012). However, no effect of the same biochar on rice yield was observed in a clay Rhodic Ferralsol (Carvalho et al., 2016). The cause for the different effect of the same biochar on rice yield could be a consequence of the different original soil properties, among which, in this case, soil texture was the most evident (Carvalho et al., 2016).

Regardless of the increasing number of studies published on biochar over the past two decades, there is still a large knowledge gap to be explored (Tammeorg et al., 2016). Among other aspects, i) the mechanisms of the effect of biochar on crop yield at field scale, including the processes that govern the interactions between biochar and soil and ii) the time span over which biochar can affect soil properties and crop yield, is little known.

The aim of this study was to evaluate the effect of wood biochar as soil amendment, combined with the application of synthetic fertilizer (P, K), on soil physical-chemical properties and soybean grain yield in a 5-year field trial settled on a sandy clay loam Haplic Ferralsol of the Brazilian savannah. We postulate that wood biochar, alone or through its interaction with synthetic fertilizer, would improve soil fertility via enhancement of nutrient availability, soil physical-hydraulic properties and organic carbon. Soybean grain yield would also increase with biochar rate. Our study was carried out within a soil management system that included cover crop in the off-season and zero-tillage.

2. Material and methods

2.1. Site characteristics and design of the field experiment

The field experiment was established on a sandy clay loam Haplic Ferralsol (62% sand, 31% clay, 7% silt) in a transition zone between the Brazilian Savannah (also called Cerrado) and the Amazon ecosystems (Elias et al., 2013), in Nova Xavantina, Mato Grosso State, Brazil (14° 35′ 36″ S and 52° 24′ 04″ W). The experimental site featured plain topography. The local climate is classified as Aw according to the Köppen-Geiger climate classification (Peel et al., 2007). The monthly precipitation and average temperature within the evaluated soybean growing seasons of the field experiment is shown in Fig. 1.

The area where the field experiment was established had been cultivated with soybean (*Glycine* max) under zero-tillage for about 10 years. The soybean received 35 kg ha^{-1} phosphorus (P) and 66 kg ha^{-1} potassium (K) each year in the form of synthetic fertilizer (400 kg ha^{-1} NPK, 00-18-18) at sowing. Pearl millet (*Pennisetum glaucum*) was planted in March or April each year as cover crop with no addition of fertilizer. Dolomitic lime (3 Mg ha^{-1}) was applied in September 2004. The field experiment was established in September 2006, when the wood biochar was incorporated into the soil. The design of the studied field experiment is shown in Fig. 2.

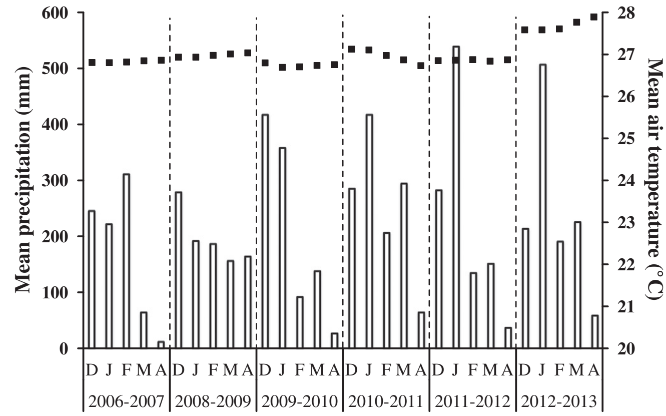

Fig. 1. Monthly total precipitation (white bars) and mean air temperature (black squares) within soybean growing seasons (from December to April) from immediately (2006/2007) to five (2011/2012) years after wood biochar application in the sandy clay loam Haplic Ferralsol of the Brazilian Savannah located at Nova Xavantina, Mato Grosso State, Brazil.

The biochar was ground to pass through a 2-mm sieve and incorporated into the 0–15 cm soil layer using a rotary hoe. It was applied only once, September 29, 2006, at five application rates (0, 2, 4, 8 and 16 Mg ha^{-1}), randomized within each of the four blocks in plots measuring 40 m^2 (4 m × 10 m). The synthetic fertilizer NPK (00-18-18) was applied annually, at the moment of sowing, in strips across the blocks at 0, 100, 200, 300 or 400 kg ha^{-1}, equal to 0, 8.75, 17.50, 26.25, 35 kg ha^{-1} P and 0, 16.5, 33.0, 49.5, 66.0 kg ha^{-1} K. In each plot, nine rows of 10 m were sown, with 45 cm between rows and 12 seeds per meter. The seeds of soybean, genetically modified for glyphosate resistance, were inoculated with *Bradyrhizobium japonicum* to stimulate root nodulation and so enhance biological nitrogen fixation. The soybean was sown during six growing seasons. Out of the six growing seasons five were evaluated: 2006/2007, 2008/2009, 2009/2010, 2010/2011 and 2011/2012. These years represent growing seasons from immediately (three months) to five years after the wood biochar application. Therefore, they were identified as Y0 (year 0 - 2006/2007), Y2 (year 2 - 2008/2009), Y3 (year 3 - 2009/2010), Y4 (year 4 - 2010/2011) and Y5 (year 5 - 2011/2012). We were not able to assess the growing season 2007/2008 (Y1) due to low establishment of the rice plant.

The applied soil management was zero-tillage with cover crop (Table 1). After the incorporation of the biochar (Y0), pearl millet (*Pennisetum glaucum*) was sown in September to form mulch. Fifteen kilograms of seeds per hectare were planted and no chemical fertilizer was applied. The millet was dessicated, using glyphosate and 2,4-D acid 2 days before the soybean was sown in December 2006. In Y1 aerobic rice (*Oryza sativa*) was sown in December. Cover crop was not planted. From Y2, soybean was sown every year in December, followed by *Brachiaria* grass (*Urochloa ruziziensis*) as cover crop in the off-season. Ten kilograms of seed (*U. ruziziensis*) was sown per hectare and no chemical fertilizer was applied to the cover crop. Glyphosate acid (1080 g ha^{-1}) and 2,4-D acid (242 g ha^{-1}) were applied as pre-emergent herbicides, two days before sowing soybean. Chemical control for disease and pests during the crop cycle was applied when necessary, using a mixture of trifloxystrobin + cyproconazole (66 + 28 g ha^{-1})