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Emissions intensity and carbon stocks of a tropical Ultisol after amendment with Tithonia green manure, urea and biochar

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ABSTRACT

Biochar has been shown to reduce soil emissions of CO_2, CH_4 and N_2O in short-term incubation and greenhouse experiments. Such controlled experiments failed to represent variable field conditions, and rarely included crop growth feedback. The objective of this study was to assess the effect of biochar, in comparison to green manure and mineral nitrogen, on greenhouse gas Emissions Intensity (EI = emissions in CO_2 equivalents per ton of grain yield) in a low-fertility tropical Ultisol. Using a field trial in western Kenya, biochar (0 and 2.5 t ha^{-1}; made from Eucalyptus wood) was integrated with urea (0 and 120 kg N ha^{-1}) and green manure (*Tithonia diversifolia*; 0, 2.5 and 5 t ha^{-1}) in a factorial design for four consecutive seasons from October 2012 to August 2014. Compared to the control, biochar increased soil CO_2 emissions (9–33%), reduced soil CH_4 uptake (7–59%) and reduced soil N_2O emissions (1–42%) in each season, with no seasonal differences. N_2O emissions increased following amendment with *T. diversifolia* (6%) and urea (13%) compared to the control. Generally, N_2O emissions decreased where only biochar was applied. The greatest decrease in N_2O (42%) occurred where all three amendments were applied compared to when they were added separately. EI in response to any of the amendments was lower than the control, ranging from 9 to 65% (33.0 ± 3.2 = mean ± SE). The amendments increased SOC stocks by 0.1–1.2 t ha^{-1} $year^{-1}$ (mean ± SE of 0.8 ± 0.09 t ha^{-1} $year^{-1}$). The results suggest decreased net EI with biochar in low fertility soils mainly through greater net primary productivity (89% of the decrease).

1. Introduction

The search for climate-smart agricultural production technologies is directing research to identify innovations that address multiple benefits such as crop productivity, carbon sequestration and mitigation of soil-atmosphere greenhouse gas (GHG) emissions. Addition of biochar (pyrogenic organic matter) to agricultural soils as a management strategy has reportedly increased crop yields in several studies but has shown variable effects on GHG fluxes (Knoblauch et al., 2011; Cayuela et al., 2014). Biochar may affect fluxes of GHGs such as CO_2, CH_4 and N_2O by a variety of mechanisms, including: (i) the turnover rate of soil organic matter (SOM), which in turn determines the availability of C and N, the precursors for GHG production or consumption, (ii) soil physical properties (e.g. gas diffusivity, aggregation, water retention) (Quin et al., 2014); (iii) soil chemical properties (e.g. pH, Eh, availability of organic and mineral N and dissolved organic C, organo- mineral interactions); and (iv) soil biological properties (e.g. microbial community structure, microbial biomass and activity, macro-fauna activity, N cycling enzymes) (Van Zwieten et al., 2010).

Biochar may also change the effects of adding easily mineralizable organic matter as well as mineral N fertilizers on GHG emissions from soil. Additions of legume materials as a fertilizer provide both N and C that typically lead to greater GHG emissions from soils (Gentile et al., 2009). Similarly, the amount of fertilizer N additions is considered proportional to the N_2O emissions (Manzoni and Porporato, 2009; Mori and Hojito, 2011). It is not clear, if simultaneous addition of biochar

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with either fertilizer N or legume mulch or a combination if the two may result in GHG emission reductions. Uncertainty also exists whether any emission reductions would persist over several cropping seasons.

It is not clear what role possible feedback through enhanced crop growth plays to the GHG budget. Greater crop growth and presumably greater C return to soil have been found where the pH is increased by biochar to neutral values (Jeffery et al., 2015) and this feedback would therefore be expected to be greatest in acid tropical soils. Whereas Spokas (2013) suggested that biochar has mainly shorter-term GHG mitigation effect (few days to several weeks) after application, Lentz et al. (2014) indicated that the effects may be long-lived. As such, questions remain concerning the long-term implications in cropping periods particularly for field-based biochar studies. Zimmerman et al. (2011) observed that native SOM mineralization was higher during the early incubation stage (first 90 days) and low during the later incubation stage (250–500 days). Maestrini et al. (2014) also reported pyrogenic OM (PyOM) to have promoted native OM mineralization during the first 18 days and inhibited it afterward (up to 150 days).

The objectives of this study were to determine the effect of biochar on (i) GHG fluxes (CO_2, CH_4 and N_2O), (ii) Emissions Intensity (EI; the net CO_2-equivalent for CH_4 and N_2O per ton of grain yield), and (iii) changes in soil organic carbon (SOC) and ecosystem carbon balance of a low-fertility tropical agricultural soil when integrated with organic and mineral N inputs. The overall hypothesis is that biochar is responsible for controlling the release of labile N and C from high N mineral and organic amendments and an accompanying reduction in CO_2, CH_4 and N_2O emissions. Specifically, we hypothesize that compared to unamended soil, biochar (i) reduces availability of N from both organic and mineral sources such as *T. diversifolia* and urea to thereby reduce N_2O emission resulting from interactions of N_2O with biochar; (ii) increases availability of easily mineralizable C from both soil and organic amendment to reduce the CH_4 soil sink; (iii) affects emissions of CH_4 and N_2O early on, but not in later seasons as active surfaces get saturated with time; and (iv) increases plant growth as a result of biochar additions that are more important than changes in other soil processes affecting GHG emissions.

2. Materials and methods

2.1. Study site

The field experiment was established in September 2012 at Kapsengere on the southern Nandi hills in western Kenya (00′ 09′ 34″N and 34′ 57′ 37″E). The site receives ~2000 mm mean annual rainfall in a bimodal distribution, with two growing seasons per year, March–July and September–January. The mean annual temperature is 26 °C. The soils are classified as Typic Kandiudults (USDA, 1999) developed on biotite-gneiss parent material. The experimental field was divided into three blocks. Soil properties before the experiment were determined by taking two samples from each block (six composite samples in total). The composite sample was obtained by mixing soil taken at four random locations. These were assumed to adequately represent the entire field where the experiment was established. The soil samples were analyzed using methods described in Fungo et al. (2014); in addition, particle size distribution was determined by the hydrometer method (Soil Texture Unit 1067; LaMotte Co., Chestertown, MD, USA) (soil properties in Table 1). The natural vegetation is composed of tropical rainforest of the Guineo-Congolian type. The experiment was conducted for four consecutive maize growing seasons: September–December 2012; March–August 2013; September–December 2013; March–August 2014. The seasons are henceforth referred to as Short Rains 2012 (SR2012); Long Rains 2013 (LR2013); Short Rains 2013 (SR2013) and Long Rains 2014 (LR2014), respectively.

Table 1
Physical-chemical properties of the soil (0–0.2 m) and the amendments used in the field trial in western Kenya (n = 6 replicates for soil; triplicate measurements for amendments; means with standard errors in brackets).

Property	Biochar		Soil		Green manure (T. diversifolia)		
					Property		
pH	6.3	(0.1)	6.0	(0.1)	N (mg kg^{-1})	21.5	(0.5)
C (g kg^{-1})	868	(11)	23.3	(0.1)	P (mg kg^{-1})	2.3	(0.1)
N (g kg^{-1})	27.0	(0.9)	21.0	(0.9)	K (mg kg^{-1})	43.2	(1.2)
P (mg kg^{-1})	135	(3.7)	9.30	(0.2)	Ca (mg kg^{-1})	13.6	(0.2)
K (mg kg^{-1})	1490	(14)	223	(10)	Na (mg kg^{-1})	72.7	(0.9)
Ca (mg kg^{-1})	1920	(17)	1950	(10)	Fe (mg kg^{-1})	951	(10)
Na (mg kg^{-1})	180	(7.3)	15.9	(0.6)	Zn (mg kg^{-1})	89.7	(1.6)
Mg (mg kg^{-1})	150	(4.5)	312	(9.4)	Mg (mg kg^{-1})	2.6	(0.0)
Al (mg kg^{-1})	559	(9.8)	939	(16)	S (mg kg^{-1})	2.5	(0.0)
S (mg kg^{-1})	36.5	(1.4)	14.0	(0.8)	Mn (mg kg^{-1})	264	(5)
Fe (mg kg^{-1})	164	(5.7)	67.2	(1.6)	Cu (mg kg^{-1})	11.0	(0.2)
Zn (mg kg^{-1})	108	(2.4)	13.5	(0.4)	B (mg kg^{-1})	53.2	(1.6)
Mn (mg kg^{-1})	188	(4.9)	782	(14)	Mo (mg kg^{-1})	1.3	(0.0)
Cu (mg kg^{-1})	0.77	(0.1)	1.97	(0.1)			
B (mg kg^{-1})	1.07	(0.0)	0.33	(0.0)			
C.E.C (meq 100 g^{-1})	18.2	(0.6)	16.2	(0.5)			
EC (S mm^{-1})	196	(6.5)	88.0	(1.2)			
Silt (%)	nd		17.5	(0.3)			
Sand (%)	nd		10.7	(0.4)			
Clay (%)	nd		71.6	(2.0)			

nd = not determined.

2.2. Biochar and green manure

Biochar was produced from eucalyptus wood by chopping and grinding to pass through a 2-mm sieve. The ground material was pyrolyzed to a maximum temperature of 550 °C using a thermostat-regulated kiln with continuous agitation to provide homogeneous charring conditions and retained at this temperature for one hour before cooling to room temperature. Green manure from *T. diversifolia* was prepared by cutting leaves from the field and chopping them into 50-mm lengths, air-drying and grinding to pass through a 2-mm sieve before field application. The physical and chemical characteristics of the soil were analyzed following the same procedures as in Fungo et al. (2014) and are presented in Table 1.

2.3. Experimental design

The experiment was laid out in a randomized complete block design with three replicates. Treatments included the following: two levels of biochar (0 and 2.5 t ha^{-1}); three levels of *T. diversifolia* green manure (0, 2.5 and 5 t ha^{-1}); and two levels of urea application (0 and 120 kg N ha^{-1}) in a full factorial design (Table 2). Treatments were indicative of the range of conventional management practices of many small-holder farmers in integrated soil fertility management systems. Each treatment was established in 2 × 2-m plot separated by a one meter distance within and between rows.

2.4. Management of experiment

Precipitation and air temperature were monitored throughout the experiment with the help of a weather station on site. Application of biochar was done only once at the start of the first season in October 2012. The same amounts of green manure (2.5 or 5.0 t ha^{-1}), were applied to each plot once at the start of each season (four applications in total). Mineral N (Urea; 261 kg ha^{-1}) was applied in two splits at a total of 120 kg N ha^{-1} per season; 40% at planting and 60% at 30 days-after planting. Due to the inherently low fertility of the soil, 30 kg ha^{-1}