



Aggregate size distribution in a biochar-amended tropical Ultisol under conventional hand-hoe tillage



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ABSTRACT

Biochar (or pyrogenic organic matter) is increasingly proposed as a soil amendment for improving fertility, carbon sequestration and reduction of greenhouse gas emissions. However, little is known about its effects on aggregation, an important indicator of soil quality and functioning. The aim of this study was to assess the effect of Eucalyptus wood biochar (B, pyrolyzed at 550 °C, at 0 or 2.5 t ha⁻¹), green manure (T, from *Tithonia diversifolia* at 0, 2.5 or 5.0 t ha⁻¹) and mineral nitrogen (U, urea, at 0, or 120 kg N ha⁻¹) on soil respiration, aggregate size distribution and SOC in these aggregate size fractions in a 2-year field experiment on a low-fertility Ultisol in western Kenya under conventional hand-hoe tillage. Air-dry 2-mm sieved soils were divided into four fractions by wet sieving: Large Macro-aggregates (LM; >1000 μm); Small Macro-aggregates (SM, 250–1000 μm); Micro-aggregates (M, 250–53 μm) and Silt + Clay (S + C, < 53 μm). We found that biochar alone did not affect a mean weight diameter (MWD) but combined application with either *T. diversifolia* (BT) or urea (BU) increased MWD by 34 ± 5.2 μm (8%) and 55 ± 5.4 μm (13%), respectively, compared to the control ($P = 0.023$; $n = 36$). The B + T + U combination increased the proportion of the LM and SM by 7.0 ± 0.8%, but reduced the S + C fraction by 5.2 ± 0.23%. SOC was 30%, 25% and 23% in S + C, M and LM/SM fractions, and increased by 9.6 ± 1.0, 5.7 ± 0.8, 6.3 ± 1.1 and 4.2 ± 0.9 g kg⁻¹ for LM, SM, M and S + C, respectively. MWD was not related to either soil respiration or soil moisture but decreased with higher SOC ($R^2 = 0.37$, $P = 0.014$, $n = 26$) and increased with greater biomass production ($R^2 = 0.11$, $P = 0.045$, $n = 33$). Our data suggest that within the timeframe of the study, biochar is stored predominantly as free particulate OC in the silt and clay fraction and promoted a movement of native SOC from larger-size aggregates to the smaller-sized fraction in the short-term (2 years).

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1. Introduction

Biochar (pyrogenic organic matter) has shown promise for contributing to the triple benefit of improving soil productivity (Biederman and Harpole, 2013; Qian et al., 2015), sequestering soil carbon (Lehmann, 2007; Schneider et al., 2011; Lorenz and Lal,

2014) and reducing an emission of greenhouse gasses (i.e. CO₂, CH₄ and N₂O) in agricultural soils (Cayuela et al., 2013; Fungo et al., 2014). According to Woolf et al. (2010), sustainable global implementation of biochar projects can potentially off-set 12% (1.8 Pg CO₂-C_e per year) of current anthropogenic CO₂-C equivalent emissions. However, the rate and scale of soil organic matter (SOM) turnover following biochar amendment depends on complex associations among biochar as well as soil properties (pH, native SOM, texture, mineralogy), agro-ecological conditions (precipitation and temperature), and management interventions such as use of manure and mineral fertilizers, tillage and irrigation.

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Soil aggregation is a good indicator of soil quality because it mediates microbial feedbacks of C and N cycling in soils (Kapkiyai et al., 1999; Jimenez et al., 2011; Demisie et al., 2014). Biochar incorporation into soil can improve soil aggregate stability (Liu et al., 2014; Zhang et al., 2015; Obia et al., 2016) by increasing exchangeable cation status of the soil, such as calcium (Enders et al., 2012; Jien and Wang, 2013), thereby inhibiting clay dispersion and associated disruption of soil aggregates. Biochar can also affect aggregation by the replacement of Na^+ and Mg^{2+} in clay and aggregates through adsorption on its surfaces (Kwon and Pignatello, 2005). Under acidic environments such as those in highly weathered soils of the humid tropics, the hydroxyl and carboxylic groups on the oxidized biochar surface could also adsorb clay particles to increase macro-aggregate formation (Jien and Wang, 2013). However, the location of SOC within the aggregates and its chemical characteristics, which affect the rate of its decomposition (Balesdent et al., 1998; Christensen, 1996; Luo et al., 2014) and thus is sequestration potential, have not received much attention.

The effect of biochar on soil aggregation is disputed (c.f. Busscher et al., 2010; Peng et al., 2011; Zhang et al., 2015). Whereas an increase in soil aggregate sizes as a result of an increase in SOC when synthetic fertilizers are applied to the soil has been widely reported (Halvorson et al., 1999; Plaza-Bonilla et al., 2012), some evidence of the reverse trend has also been observed (Sainju et al., 2003; Khan et al., 2007; Le Guillou and Angers, 2011; Plaza-Bonilla et al., 2012). Biochar is expected to increase aggregation because it can act as a nucleus of aggregation, similar to other particulate organic matter or microorganisms, especially because biochar increases microbial biomass (Lehmann et al., 2011). Furthermore, increased OM input by roots and microbial mucilage following biochar amendment would increase aggregation (Abiven et al., 2015). Hence, it is unclear how N fertilizers in combination with biochar can affect both soil aggregate size distribution and the resultant physical protection of SOC.

When biochar is applied with green manure as *Tithonia diversifolia*, there is likely a greater amount of microbial activity (Li et al., 2012) and concomitant production of metabolites which, through a variety of bonding mechanisms, may contribute to aggregate build-up. Mechanisms of interaction between biochar and the soil matrix that may result in soil stabilization include (1) occlusion in aggregates (Bachmann et al., 2008), (2) formation of biochar-cation complexes (interactions with polyvalent cations of soil minerals), or (3) interactions via polyvalent cations with soil mineral surfaces (OM-mineral associations) (von Lützwow et al., 2007). Thus, biochar can be a binding agent for aggregate formation and stabilization. However, our understanding of these effects on aggregation of soil remains speculative. Understanding the effect of introducing biochar in such a system will aid predicting the long-term effects of these cropping practices on soil quality and C storage.

The objectives of the study were to determine the effect of biochar on (i) size and distribution of soil aggregates, (ii) changes in the content of SOC in different soil fractions, and (iii) relationships among aggregation, SOC, soil respiration (CO_2 emission) and biomass production under integrated soil fertility management on an Ultisol of the humid tropics. We hypothesized that under conventional hand-hoe tillage practices, (i) biochar would increase soil aggregation because over time, biochar gets more oxidized (Cheng et al., 2008), so there may be more cation bridges between clay and biochar (increasing its ability to form organo-mineral and Biochar-SOM interactions), (ii) soil aggregation increases with an increased amount of easily mineralizable organic matter inputs (such as *T. diversifolia* manures) because of the increased microbial activity and therefore mucilage, but might decrease with addition of mineral N fertilizer (such as urea) because of increased

decomposition of easily mineralizable SOM, and (iii) increased soil respiration is related to SOM increases and larger aggregates.

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. The sites receive ~2000 mm mean annual rainfall in a bimodal distribution, with two rainy seasons per year (March–July and September–January) with a mean annual temperature of 26 °C. Precipitation and air temperature were monitored throughout the experiment with the help of a weather station located near the experimental field. The soil is classified as Typic Kandiodults (USDA, 1999) developed on biotite-gneisses parent material. The natural vegetation is composed of tropical rainforest of Guineo-Congolian species. The trial was conducted for four consecutive maize rainy seasons (September 2012–August 2014).

2.2. Preparation of the biochar and *T. diversifolia*

The biochar was produced by chopping and grinding Eucalyptus wood so as to pass through a 2-mm sieve. The sieved material was then pyrolyzed at a ramp of 5 °C min^{-1} to a maximum temperature of 550 °C and retained for one hour before cooling to room temperature. In the laboratory, the resultant biochar was characterized for pH, surface area, CEC, elemental composition. *T. diversifolia* was prepared by cutting leaves from the field and chopping them into 50-mm lengths, air-dried and ground to pass through a 1-mm sieve before field application. The chopping and grinding were to ensure uniform application in the field and reduce effects on soil physical properties. The physical and chemical characteristics of the above materials are presented in Table 1.

2.3. Experimental design

The treatments were selected to represent presence and absence of biochar as well as low and high input of *Tithonia* green manure, with and without mineral nitrogen (N) fertilizer. This arrangement represented a range of conventional management practices of many small-holder farmers in integrated soil fertility

Table 1

Physical-chemical properties of the soil at start of the experiment and the amendments used in the field trial (nd = not determined).

Biochar and soil Property	Green manure (<i>T. diversifolia</i>)	
	Biochar	Soil
C (g kg^{-1})	868	23.3
N (g kg^{-1})	27	21.0
pH	6.31	6.01
EC (S mm^{-1})	196	88.0
K (mg kg^{-1})	1490	223
Ca (mg kg^{-1})	1920	1950
Mg (mg kg^{-1})	150	312
Mn (mg kg^{-1})	188	782
S (mg kg^{-1})	36.5	14.0
Cu (mg kg^{-1})	0.77	1.97
B (mg kg^{-1})	1.07	0.33
Zn (mg kg^{-1})	108	13.5
Na (mg kg^{-1})	180	15.9
Fe (mg kg^{-1})	164	67.2
P (mg kg^{-1})	135	9.30
Al (mg kg^{-1})	559	939
C.E.C ($\text{meq } 100 \text{g}^{-1}$)	18.2	16.2
Silt (%)	nd	17.5
Sand (%)	nd	10.7
Clay (%)	nd	71.6

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