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Effects of biochar amendment on rapeseed and sweet potato yields and water stable aggregate in upland red soil

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ABSTRACT

A field experiment was conducted to study the effect of biochar amendment (0, 2.5, 5, 10, 20, 30 and 40 $t \cdot ha^{-1}$) on rapeseed and sweet potato yields, aggregate particle size distribution, aggregate stability, soil organic carbon, total N content and C:N ratio in soil water stable aggregate under a rapeseed–sweet potato rotation system in upland red soil in Jiangxi Province of southern, China. The results were as follows: compared with control treatment (CK), when the amount of biochar was 40 $t \cdot ha^{-1}$, rapeseed and sweet potato yields were increased by 36.02% and 53.77% respectively; the soil water stable aggregate (>0.25 mm) in the 0–15 cm soil layer had a remarkable increase than other treatments, especially the macroaggregate with particle size larger than >2 mm. In the rapeseed harvest season, the mean weight diameter of soil water stable aggregate was enhanced by 28.02% compared to CK with the application rate of biochar being 40 $t \cdot ha^{-1}$. A significant increment in soil organic carbon, total N and C:N ratio was observed in the >2 mm, 2–0.5 mm, 0.5–0.25 mm and <0.25 mm aggregate fractions with respect to the maximum treatment. These results suggest that biochar's incorporation into upland red soil will increase crop productivity and improve soil structure.

1. Introduction

Red soils (equivalent to Ultisols in the Soil Taxonomy System of the United States) cover an area of nearly 2.04×10^6 km^2 in tropical and subtropical regions of southern China (Xu et al., 2003), representing the most important soil resources in this area due to abundant rainfall and high temperature. However, some unfavorable soil properties with inappropriate utilization and management resulted in intensive weathering, thereby the soil is generally characterized by low productivity and high risk of erosion (Zhang et al., 1994). Large demand for food in China makes it urgent to improve the quality and productivity of red soils. Extensive studies have indicated that degraded red soils could be greatly ameliorated through increasing the content of soil organic carbon (SOC) and improving soil aggregation (Huang et al., 2006; Xu et al., 2007; Zhang and Xu, 2005).

Poor soil structural stability is a serious and increasing problem in several areas across the world. An appropriate management of organic matter additions to soils may increase aggregate stability and thus reduce crusting and erosion problems (Abiven et al., 2009). Soil aggregation and structure are important aspects of soil fertility through influencing root distribution and uptake for water and nutrients (Bronick and Lal, 2005a; Pachepsky and Rawls, 2003). In addition, stability of aggregates determines soil resistance to erosion (Barthès and Roose, 2002). But soil aggregation is controlled by soil organic carbon, biota, ionic bridging, clay and silt content, and the presence of carbonates and gypsum (Amézketa, 1999; Bronick and Lal, 2005b). The intrinsic decomposability of the organic product has much influence on aggregate stability dynamics (Abiven et al., 2007). Several models of soil aggregation have been proposed (Goss and Kay, 2005; Six et al., 1999; Tisdall and Oades, 1982). Beare et al. (1994) reported that residue cover in no-till farming method improved soil aggregation and organic carbon content. Lal et al. (1994) reported that no-till improved soil aggregate stability. Hamblin (1980) also found that no-till system could result in a smaller aggregate mean weight diameter (MWD). At the same time polyacrylamide (PAM) penetrates into aggregates and stabilizes exterior surfaces, thereby stabilizing soil aggregates (Mamedov et al., 2007; Wu et al., 2012). Chantigny et al. (1999) observed that the proportion of soil water stable macroaggregates increased with the application of de-inking paper sludge as an organic amendment to agricultural soils.

Biochar is a product of biomass incomplete burning in the absence of limited oxygen. It is usually produced with the intent to be applied in soil, or as a byproduct of thermal pyrolysis of carbon-rich biomass to make biofuel (Laird et al., 2009; Lehmann and Joseph, 2009; Yao et al., 2010). Biochar, rich in C, has received increasing attention because it is believed to store carbon in soil for hundreds to thousands of years, potentially leading to a significant reduction in atmospheric levels of

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greenhouse gases (GHG) (Lehmann, 2007). Moreover, its presence in soils is reported to improve not only soil chemical properties (e.g. pH, CEC, cations) (Oguntunde et al., 2004), physical properties (e.g. soil water retention, hydraulic conductivity) (Asai et al., 2009; Oguntunde et al., 2008) and crop yields (Lehmann et al., 2003; Steiner, 2007), but also soil microbial activity (Steiner et al., 2008). Biochar incorporation into soil has been shown to effectively improve the exchangeable cation status of the soil, in particular for calcium (Jien and Wang, 2013; Lehmann et al., 2003) which is capable to inhibit clay dispersion and the associate disruption of aggregates by the replacement of Na^{+} and Mg^{2+} in clay and aggregates, and thus adding to aggregate stability (Armstrong and Tanton, 1992). Under acidic environments, the hydroxyl groups and carboxylic groups on the oxidized biochar surface could also adsorb soil particles and clays to form macroaggregates (Jien and Wang, 2013). Red soils in subtropical China are poor in soil cation, especially in bivalent Ca^{2+} cation due to strong eluviation. It was hypothesized that biochar addition should exert a positive effect on aggregate stability of upland red soil.

To date, the changes of soil water stable aggregate in upland red soil affected by application of biochar have not yet been investigated. Therefore, the objective of this study was to determine if the combined application of biochar and fertilizer can increase crop yields, improve soil water stable aggregate distribution and mean weight diameter (MWD), and soil organic carbon (SOC) and total N in soil water stable aggregates.

2. Materials and methods

2.1. Study site

The field experiment was conducted at the Institute of Red Soil, Jinxian County (28°37′ N, 116°26′ E, 26 m above sea level), Jiangxi Province, China in 2011. This site was located in a typical subtropical climate zone with a distinct arid (July–September) and humid (March–June) season. The mean annual temperature and rainfall were 17.2 °C and 1549 mm, respectively.

2.2. Biochar amended

Biochar used for the field experiment was produced from wheat straw pyrolyzed at 350–550 °C in a vertical kiln made of refractory bricks in Sanli New Energy Company, Henan Province, China. With such a technology, 30% of wheat straw dry matter would be expected to be converted to biochar (Pan et al., 2011). The biochar amendment had an initial pH of 10.35, SOC of 467.2 $g \cdot kg^{-1}$, total N of 5.9 $g \cdot kg^{-1}$, total P of 14.43 $g \cdot kg^{-1}$, total K of 11.5 $g \cdot kg^{-1}$ and cation exchange capacity (CEC) of 21.7 $cmol \cdot kg^{-1}$.

2.3. Field experiment

Seven treatments (designated as CK, C1, C2, C3, C4, C5 and C6, respectively) were set up according to the application rate of biochar amendment (i.e. 0, 2.5, 5, 10, 20, 30 and 40 $t \cdot ha^{-1}$). The biochar was spread on the surface of red soil, thoroughly mixed with the topsoil by manual plowing, and then tilled to a depth of 15 cm on 22nd September 2011. Replicated (n = 3) trial plots (4 m × 5 m) separated by a protection row of 0.4 m in width were laid out in a randomized complete block design, each with a 0.5 m wide drainage outlet. Two crops, rapeseed and sweet potato, were grown in rotation annually. Rapeseed was planted on 4th October 2011 and was harvested on 15th May 2012, sweet potato on 20th May 2012 and on 28th September 2012 correspondingly. Following the local conventional fertilization, the fertilizer N was applied at 90 kg N ha^{-1} as urea during the rapeseed season, of which 40% was as a base fertilizer prior to seeding, another 60% at the blossom period. During the sweet potato season, N fertilizer input totaled 90 kg N ha^{-1} was broadcasted as urea before transplanting. Both rapeseed and sweet potato received a basal application of 52.5 kg P_2O_5 ha^{-1} and 107 kg K_2O ha^{-1} through calcium superphosphate and potassium chloride, respectively. Additionally, borax was applied at a rate of 15 kg B ha^{-1} before seeding in the rapeseed season.

2.4. Soil sampling and analysis

Soil samples were collected at depths of 0–15 cm and 15–30 cm on 18th May 2012 (after rapeseed harvest, before planting sweet potato) and on 28th September 2012 (between sweet potato harvest and the subsequent rotation) respectively. The samples were sealed in plastic bags and transported to the laboratory within 2 days after sampling. Root detritus was removed and the soil air-dried and ground to pass a 2 mm sieve. Basic soil properties were determined using the methods suggested by Lu (2000). Soil pH (H_2O) was determined with a glass electrode (water–soil ratio of 5:1) (Seven Easy Metter Toledo, China 2008). Soil organic C and total N were measured with an Elementar Vario max CNS Analyzer after soil samples were ground further to pass through a 0.15-mm sieve (German Elementar Company, 2003). The basic properties of upland red soil (0–15 cm and 15–30 cm) are provided in Table 1.

2.5. Aggregate separation

A wet sieving method was used to determine aggregate size distribution (ASD), and mean weight diameter (MWD) which was an index of soil aggregate stability. The method for aggregate fractionation was adopted from Six et al. (2002). Four aggregate-size classes (i.e., >2, 0.5–2, 0.25–0.5, <0.25 mm) were obtained with sieve set of 2, 0.5 and 0.25 mm. Briefly, approximately 100 g air-dried soil sample, without disturbing the aggregates, was put on the first sieve of the set in a water bucket and was gently moistened for 10 min. Care was taken to avoid sudden rupture of the aggregates. The >2 mm aggregates were separated by moving the sieve vertical with a speed of 30 strokes min^{-1} for 5 min after pre-wetting. By the end of wet-sieving, all aggregate-size fractions remaining on each sieve were collected and dried, then sand and aggregates were separated (T. Wang et al., 2012; X. Wang et al., 2012).

The mean weight diameter (MWD, mm) was calculated as follows:

$$MWD = \sum_{i=1}^{n} w_i \cdot \bar{x}_i$$

where $\bar{x}_i$ is the average diameter of the openings of two consecutive sieves, and w_i the weight ratio of aggregates remained on the ith sieve. For the determination of ASD, the weight ratio of aggregates of each sieve (>2, 2–0.5, 0.5–0.25, and <0.25 mm) to the total weight of aggregates was calculated.

2.6. Statistical analysis

One-way analysis of variance (ANOVA) was performed by SPSS 16.0. Means were tested using the multiple comparison performed by least significant difference (LSD) at $P < 0.05$.

3. Results

3.1. Effect of biochar on water stable aggregate distribution

The soil water stable aggregates (>0.25 mm) which accounted for 32.19–69.71% of the dry soil weight made up the largest proportion in both 0–15 and 15–30 cm soil layers, and they decreased with the increase of soil depth (Fig. 1). Compared with control treatment (CK) and other biochar treatments, biochar amendment with the amount of 40 $t \cdot ha^{-1}$ significantly increased the proportion of macroaggregates in the 0–15 cm soil layer ($P < 0.05$, Fig. 1). There existed a significant