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Biochar-Induced Changes in Soil Resilience: Effects of Soil Texture and Biochar Dosage

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ABSTRACT

Biochars are, amongst other available amendment materials, considered as an attractive tool in agriculture for carbon sequestration and improvement of soil functions. The latter is widely discussed as a consequence of improved physical quality of the amended soil. However, the mechanisms for this improvement are still poorly understood. This study investigated the effect of woodchip biochar amendment on micro-structural development, micro- and macro-structural stability, and resilience of two differently textured soils, fine sand (FS) and sandy loam (SL). Test substrates were prepared by adding 50 or 100 g kg^{-1} biochar to FS or SL. Total porosity and plant available water were significantly increased in both soils. Moreover, compressive strength of the aggregates was significantly decreased when biochar amount was doubled. Mechanical resilience of the aggregates at both micro- and macro-scale was improved in the biochar-amended soils, impacting the cohesion and compressive behavior. A combination of these effects will result in an improved pore structure and aeration. Consequently, the physicochemical environment for plants and microbes is improved. Furthermore, the improved stability properties will result in better capacity of the biochar-amended soil to recover from the myriad of mechanical stresses imposed under arable systems, including vehicle traffic, to the weight of overburden soil. However, it was noted that doubling the amendment rate did not in any case offer any remarkable additional improvement in these properties, suggesting a further need to investigate the optimal amendment rate.

Key Words: aggregate stability, amendment material, compressive strength, rheometry, shear properties, total porosity

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Biochar is a fine-grained charcoal, rich in recalcitrant organic carbon and produced from controlled pyrolysis (zero or low oxygen environment) of biomass. Its application to agricultural soils has been well argued as a means to sequester carbon (C), improve soil functions (Lehmann, 2007; Laird, 2008; Mukherjee and Lal, 2013), and enhance crop yield (Glaser *et al.*, 2001; Oguntunde *et al.*, 2004; Graber *et al.*, 2010). Moreover, biochar amendment has been proposed as a way to reduce fertilizer need in agriculture, since it decreases nutrient leaching from the root zone and improve fertilizer use efficiency (Liang *et al.*, 2006; Mukherjee and Lal, 2013). Furthermore, biochar application to soil can mitigate greenhouse gas emissions due to positive improvement of the soil's physical environment, which in turn inhibits or decreases anaerobic denitrification, CO_2 flux, and CH_4 production (but increases CH_4 oxidation) (van Zwieten *et al.*, 2010; Karhu *et al.*, 2011; Troy *et al.*, 2013; Mukherjee and Lal, 2013). The improved physical properties in biochar-amended soils have been related to the lower particle density of biochar, in comparison with soil minerals and the prevalence of micro-pores in biochar (Lehmann *et al.*, 2011; Abel *et al.*, 2013).

Additionally, biochar amendment improves infiltration and water-holding capacity mainly in coarse-textured soils or the soils with large amounts of macropores (Busscher *et al.*, 2010; Sun and Lu, 2014; Obia *et al.*, 2016). Some studies have equally reported a similar improvement in fine textured soils (*i.e.*, clay soils) (Kameyama *et al.*, 2012; Castellini *et al.*, 2015). Biochar amendment enhances aggregation, improves aggregate stability, and decreases penetration resistance and soil strength (Ekwue and Stone, 1995; Piccolo *et al.*, 1997; Sun and Lu, 2014). In a pot trial with a hard-setting Chromisol (Alfisol in the USDA classification), Chan *et al.* (2007) observed that tensile strength (initial biochar-free value of 64.4 kPa) was decreased by 52% and 72%, respectively, in a soil amended with 50 and 100 t ha^{-1} of green waste biochar material.

Overall, it appears that most of the improvements in biochar-amended soils are connected principally to

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modifications of pore configuration and aggregate and surface properties in the amended soils (Piccolo *et al.*, 1997; Oguntunde *et al.*, 2004; Kameyama *et al.*, 2012; Sun and Lu, 2014; Castellini *et al.*, 2015; Ajayi *et al.*, 2016; Obia *et al.*, 2016). These modifications affect several soil processes and transform the soil-plant environment. Lehmann *et al.* (2011) observed that the differences between the physical structure of biochar and soils alter the tensile strength in a soil-biochar mixture.

It has been well discussed in literature that the physico-chemical properties of biochar, which define its influence in soil, depend on the feedstock and pyrolysis conditions (final pyrolysis temperature and rate of heating) (Lei and Zhang, 2013; Yuan *et al.*, 2013; Zheng *et al.*, 2013). For example, biochar produced at a high pyrolysis temperature ($\geq$ 500 °C) is more likely to improve soil physical properties, due to its higher aromaticity, surface area, pH, and ash contents (Novak *et al.*, 2009; Busscher *et al.*, 2010; Mukherjee and Lal, 2013), while that produced at lower pyrolysis temperature ($<$ 500 °C) will contribute more to the changes in nutrient status (Novak *et al.*, 2009; Spokas *et al.*, 2012; Mukherjee and Lal, 2013; Lei and Zhang, 2013; Yuan *et al.*, 2013; Zheng *et al.*, 2013).

Although the differences in bonding, aggregation, and strengthening process at the micro- (particle-to-particle) and macro-scale are critical to understanding of the mechanisms behind the commonly reported improvement in physical properties of biochar-amended soils, there is no conceptual perspective on the effect of different rates of biochar amendment on soil mechanical parameters. Similarly, there are very scanty quantitative data describing the effect of biochar amendments on these parameters. Therefore, the objective of this study was to investigate the effect of biochar treatment at two different rates on soil pore configuration, aggregate characteristics, shear strength at micro- and macro-scale, precompression stress, and some other parameters that define the internal strengthening of amended soils. Moreover, the mechanisms underpinning the changes in biochar-amended soils were investigated.

MATERIALS AND METHODS

Soils and biochar

In this study, a medium-textured soil (sandy loam, SL) and a coarse-textured soil (fine sand, FS) were amended. The choices of these soils and their texture range were informed by two reasons. Firstly, meta-analysis has shown that biochar amendment has the greatest (positive) effects on the soils with medium or coarse texture (Jeffery *et al.*, 2011). Secondly, medium to coarse textured soils often undergo extreme drought stress and provide only a very limited ion sorption capacity, with consequences to further leaching and groundwater pollution. The SL soil (sand 57.8%, silt 27.4%, and clay 14.8%) was collected *in situ* from the B horizon (18–35 cm depth) of a Calcic Chernozem (IUSS Working Group WRB, 2014) within the Inner Mongolian Grassland Ecosystem Research Station, Chinese Academy of Sciences (43°38′ N, 116°42′ E, 1 270 m above sea level). The soil was ungrazed for more than 30 years. The undisturbed soil samples were air-dried, carefully homogenized, and then passed through a 2-mm sieve. The FS material is commercially pre-graded to 0.13–0.36 mm and consists of 100% quartz with negligible cation exchange capacity. Commercially available biochar (Susterra Inc., Germany) was used, which was produced from woodchips by controlled pyrolysis at 500 to 600 °C, according to the European biochar certificate (Schimmelpfennig and Glaser, 2012). The biochar material was crushed into finer fractions using a centrifugal mill (Retsch, Germany) fitted with a 750-μm stainless steel sieve. The specific surface area and micro-porosity of the biochar and the amended soil particles were determined with the Brunauer-Emmett-Teller (BET) method (Ajayi and Horn, 2016).

Sample preparation

Two sets of test substrates based on soil types were prepared. Each set consisted of the soil amended with 50 and 100 g kg^{-1} biochar, which was thoroughly mixed by hand. The experimental setup, therefore, comprised of 2 soil types (SL or FS) and 2 biochar treatments (50 and 100 g kg^{-1}), labelled as SL5B, SL10B, FS5B, and FS10B, respectively. The unamended samples with 0 g kg^{-1} biochar (labelled as SL0B and FS0B) were prepared as the controls. The rates of amendment were selected based on several previous experiments, in which equivalent and even higher amounts of biochar have been added to medium- and coarse-textured soils and resulted in significant changes of soil physical properties and hydraulic functions (Herath *et al.*, 2013; Sun *et al.*, 2014; Zong *et al.*, 2014; Ajayi *et al.*, 2016). The substrate from each treatment was slightly moistened and incubated in sand bags at about 10 °C for over 100 d prior to analysis.

Determinations of water retention and pore size distribution

The water retention characteristics of different sub-