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Modification of chemical and hydrophysical properties of two texturally differentiated soils due to varying magnitudes of added biochar

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ABSTRACT

The potential benefit of biochar as a soil conditioner to improve crop yield and simultaneously sequester carbon in the soil, is a subject of intense discourse. Biochar amendment of agricultural soils is presumed to improve water holding capacity of the soil, and enhance nutrient retention within the root zone. However, there are very few investigations which provide quantitative data and qualitative descriptions concerning the specific mechanisms driving these improvements in the properties of biochar-amended soils. In this study, the effect of different rates of biochar amendment on some chemical, physical and hydraulic properties of fine-sand and sandy loamy silt soils was investigated by adding 20, 50 and 100 g biochar kg^{-1} (by dry weight). In order to evaluate the additional effects of biochar application, the initial hydrophobicity and rheological properties were also examined. The result showed that biochar amendment improved total carbon and aggregate properties. The available water capacity was significantly higher in the amended substrates, particularly in the amended fine sand. Saturated hydraulic conductivity of the sandy loam silt increased between 25% and 119%, but decreased in the fine-sand between 23 and 82%. Moreover, biochar amendment of the sandy loamy silt improved particle to particle bonding and resulted in the development of weaker (compared with the unamended control) but more resilient aggregates which were better structured. With increasing rate of added biochar ($\geq$50–$\leq$100 g kg^{-1}) the added biochar itself now dominated the internal soil strength of the substrate. Adding ($\geq$20 g kg^{-1}) biochar, to the fine-sand induced particle rearrangements, which in combination with possible surface oxidation at the biochar-soil particles interphase, improved bonding in this originally non-cohesive soil. Beyond an amendment rate of 50 g biochar kg^{-1} soil, we observed that most of the positive improvements, associated with the biochar treatment of the soils, were no longer significant and the aggregates became brittle and collapsed more easily. Our results therefore provide more detailed insights into the effect of biochar in agricultural soils depending on texture of the soil and the amount of added biochar.

1. Introduction

The potential benefit of biochar as a soil conditioner, to improve crop yield and simultaneously sequester carbon in the soil, is an on-going topic in environmental research. Biochar in this context is a generic term for the entire continuum of thermally altered organic matter and residue remaining after incomplete combustion of vegetation by pyrolysis. Amending agricultural soils with biochar is commonly reported to improve chemical properties of the soil (e.g. pH, CEC, cations) (Oguntunde et al., 2004; Liang et al., 2006; Peng et al., 2011; Jien and Wang, 2013) and to also increase the capacity of the amended soil to sorb plant nutrients, and thereby, mitigate nutrient leaching and promote nutrient cycling (Liang et al., 2006; Cheng et al., 2008; Laird et al., 2010). Lehmann (2007) and Gaunt and Lehmann (2008) argued that biochar in soils, augments carbon retention and substantially reduces greenhouse gas emissions. Besides, biochar is an effective adsorbent of both nutrients and organic contaminants in soils and can thereby improve plant growth environment and yield (Lehmann et al., 2011; Steiner et al., 2007; Van Zwieten et al., 2010; Laird et al., 2010).

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Biochar also modifies some mechanical and hydraulic properties of amended soils. The bulk density, aggregate stability, erodibility of aggregates and the disaggregating effects of wetting and drying (WD) cycles were reported to be altered in amended soils (Piccolo et al., 1996; Oguntunde et al., 2004; Asai et al., 2009; Obia et al., 2016). Furthermore, hydraulic properties like water retention, hydraulic conductivity (saturated and unsaturated), infiltration capacity, permeability were positively affected by the application of biochar (Busscher et al., 2010; Laird et al., 2010; Zimmerman et al., 2011; Choppala et al., 2012; Mukherjee and Lal, 2013; Sun and Lu, 2014; Zong et al., 2014; Castellini et al., 2015; Obia et al., 2016; Ajayi et al., 2016). Already an application of 1–2% biochar (by wet weight) has been shown to enhance water retention capacity and more importantly, the available water capacity in amended soils (Mukherjee and Lal, 2013). The changes in soil hydraulic functions and air flux that occurred due to added biochar are related, to its highly porous particle structure and the larger inner surface area (Ogawa et al., 2006; Joseph et al., 2013), which modifies the structure of the substrates (Downie et al., 2009; Major et al., 2010; Mukherjee and Lal, 2013; Jien and Wang 2013; Ajayi et al., 2016)

The physical and chemical properties of biochar are related to the feedstock type and the pyrolysis conditions (final pyrolysis temperature and the rate of heating: slow versus fast pyrolysis). High pyrolysis temperature (>500 °C) influences the physical properties of the biochar while a lower pyrolysis temperature (≤400 °C) enhances the sorption capacity of the biochar. As the pyrolysis temperature is increased, the aromaticity of biochar is barely changed, but the polarity decreases and the surface area, while pH and ash contents increase (Novak et al., 2009a; Peng et al., 2011; Mukherjee and Lal, 2013; Lei and Zhang, 2013; Zheng et al., 2013; Yuan et al., 2013). Irrespective of the feedstock, biochar has been shown to influence structural development in amended soil. Lei and Zhang (2013) observed that biochars produced from three different feedstocks (i.e. wheat straw, woodchips, and wastewater sludge) significantly enhanced the formation of macro-aggregates and stability of the aggregates in amended clay soil, at the early stages of the incubation. Similarly, Zong et al. (2014) showed that these biochars, significantly decreased ($p < 0.01$) the coefficient of linear extensibility (COLE), tensile strength and surface area density of cracks of the clay soil. On the other hand, Khademalrasoul et al. (2014) found out in a study based on X-ray visualization of soil aggregates, that biochar increased the tensile strength and the specific rupture energy but decreased the friability index. These observations highlight the need to further investigate the effect of biochar amendment on aggregation and microstructural development of amended soil, so as to fully understand the commonly reported macroscale effects.

Rheometry provides better insight into microstructural development in soils and can help to clarify aggregation and internal strengthening processes of the soil (Ghezzehei and Or, 2001; Mezger, 2006; Markgraf et al., 2006). Rheological parameters such as storage and loss moduli, or loss factor, tan (∂), Integral z values and absolute yield point (cross-over) have been used to characterise the effect of organic matter content, fertilization, salinity, and biochar treatment on microstructural development in soil (Markgraf et al., 2012; Holthusen et al., 2012; Baumgarten et al., 2012, 2013; Ajayi et al., 2016).

Although several aspects of biochar influence on soils are already defined and some chemical and physical reactions proved, there is still the need for more profound analyses of the interactions in amended soils and the consequences for the internal soil properties which define the hydraulic and mechanical properties. The specific mechanism concerning structure formation and aggregate strength vis-a-vis the change in hydraulic functions have not been presented. Thus, this study aims to provide both qualitative and quantitative data which allows a more detailed analysis and explanation of the texture and treatment-dependent changes in properties and functions of soils due to biochar amendment based on Brunauer-Emmett-Teller (BET), rheology and hydraulics characterization.

2. Materials and methods

2.1. Sample preparation

2.1.1. Base soil materials

The amended soil substrates were (i) sandy loamy silt (u) and (ii) fine sand (s). The sandy loamy silt (Sand—0.074 kg kg^{-1}, Silt—0.577 kg kg^{-1}, Clay—0.349 kg kg^{-1}), was sampled from a calcic Gleysols, which developed from glacial sediment in the southern part of Schleswig-Holstein, Germany. Undisturbed soil blocks of the A—horizon were collected in the 0–20 cm depth. The samples were air-dried in the laboratory, homogenized and passed through a 2-mm sieve.

The fine sand material was a commercially available silica sand, with dominant quartz. It was washed to remove all salt and pre-graded into the particle size range 0.13–0.36 mm.

2.1.2. Biochar material

We used a commercially available biochar (Susterra—nachhaltigpflanzen, Germany) manufactured from wood-chips pyrolysed at 500–600 °C, and prepared according to the European biochar standard (Schimmelpfennig and Glaser, 2012). The biochar material was crushed into finer fractions using a “Retsch” centrifugal mill fitted with a 750 μm stainless steel sieve. This reduced fraction was further passed through a 630 μm sieve (because of the intended use in rheological measurements) before being mixed with the soil substrates.

2.1.3. Preparation of test substrates

The test substrates were prepared by adding 20, 50 and 100 g biochar (by dry weight) to every kg of the sandy loamy silt or fine sand. The three mixture ratios were chosen, to evaluate the effects of moderate to very high rates of biochar amendment (based on available data in literature) on some mechanical and chemical properties of the amended soils. Previous studies by Novak et al. (2009b) and Mukherjee and Lal (2013) showed that the application of 1–2% biochar (by wet weight) to some soils was sufficient to influence aggregation and chemical properties. Moreover, there are documented records about the application of extremely high quantities (apparently not practicable on field scale) of biochar (80–900 t ha^{-1}) to improve water retention properties of sandy soils (Tyron, 1948; Gaskin et al., 2007). The six biochar—soil mixes, were manually blended into the various substrates and further sieved (2 mm). Unamended sandy loamy silt and fine sand material were similarly prepared as controls. The substrates were slightly moistened, packed in sealed polyethylene bags and stored at 10 °C for 30 days before they were used to prepare the test samples.

2.1.4. Preparation of test samples

Test samples were prepared by repacking 100 cm^3 (4 cm height, 5.65 cm diameter) stainless steel cylinders with the blended substrates. The sandy substrates (materials prepared from the fine-sand) were packed manually to a bulk density of 1.65 g cm^{-3} (equivalent of 32, 80, and 160 t ha^{-1} of biochar, respectively; 20 replications per treatment). The silty substrates (materials prepared from the sandy loamy silt) were refilled to uniform bulk density of 1.45 g cm^{-3} (equivalent of 29, 72.5, and 145 t ha^{-1} of biochar respectively; 20 replications per treatment) using an Instron 5569 loading frame (Instron Industrial Products, Norwood MA, USA). The respective bulk density values were representative

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