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Changes in microstructural behaviour and hydraulic functions of biochar amended soils

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ABSTRACT

Biochar is increasingly used on agricultural soils to enhance productivity and to sequester carbon. However, there is limited research that directly quantifies the underlying mechanisms, particularly those assessing structural changes in amended soils. Also, there is scanty information on the long-term effect of biochar treatment on hydraulic response of soils. Our objective in this study therefore is to determine the effect of biochar treatment on two different soil types and to evaluate the influence on hydrological and mechanical properties that drive aggregate formation and stability. Test substrates were prepared by adding 2, 5 and 10% (by dry mass) of high temperature pyrolysed (HTP) biochar to fine-sand or sandy loamy silt soil material. The repacked cores were exposed to four cycles of wetting and drying in an experiment spanning about 300 days. Changes in the saturated hydraulic conductivity, aggregate sorptivity swelling and shrinkage behaviour, and microstructural stability during desiccation were also investigated. The results indicated that biochar amendment alters the pore structure with the saturated hydraulic conductivity being significantly increased ($p < 0.05$) in the sandy loamy silt. Repeated wetting and drying significantly increased ($p < 0.05$) the repellency index of the amended substrates. Moreover micro structural stability was enhanced as the amount of biochar was increased and at lower matric potential. The partial loss of inter-particle cementation at a given pore water pressure due to increasing biochar amount was compensated by the noticeable addition of organic carbon. The combined effects of pore re-arrangement, enhanced particles surface area and improved microstructural stability in the amended soils produces better soil–plant–water environment. These findings proof that the effects of biochar amendment on pore structure, aggregation and stabilization will depend on the amount of biochar, the texture of the original soil material and the number of wetting and drying (WD) cycles.

1. Introduction

The application of biochar to agricultural soils is gaining more attractions in different parts of the world due to its reported beneficial effects on soil fertility, carbon sequestration and mitigation of greenhouse gas emissions. Accordingly, this has renewed scientific interest on the effect of pyrogenic carbon in soils (Sombroek et al., 2003; Lehmann et al., 2003; Maia et al., 2011).

Biochar is a product of the pyrolysis of biomass, with the intention of using it as soil amendment, carbon storage, or filtration of percolating soil water (Lehmann and Joseph, 2009). Meta-analysis of some field and laboratory trials with biochars produced from different feedstock indicated a statistically significant increase in crop yield with an overall mean increase of 10% (Jeffery et al., 2011). The greatest (positive) effects were found in acidic (14%) and neutral soils (13%). Likewise, yields from coarse and medium textured soils were improved by 10 and 13%, respectively. It was therefore presumed, that two of the main mechanisms responsible for yield increase in biochar amended soils, may be the liming effect of biochar and the improved water holding capacity in the amended soils (Liang et al., 2006; Major et al., 2010; Verheijen et al., 2010; Karhu et al., 2011; Jeffery et al., 2011).

Biochar treatments reduce bulk density, improve aeration, and textural properties of the soil (Lehmann and Joseph, 2009; Sohi et al., 2010; Herath et al., 2013). In addition, when biochar is added to the soil, there is an overall net carbon gain, due to enhancement of the intrinsic soil organic carbon storage capacity and contribution from the carbon stored within the biochar particles itself (Liang et al., 2006; Woolf et al., 2010). This ameliorates the soil organic matter and

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reduces the dependence on the capacity of clay surfaces for several redox processes in the soil (Verheijen et al., 2005).

Amending soils with biochar has also been reported to modify the surface area and bonding patterns of the particles (Karhu et al., 2011; Herath et al., 2013) which again has an important role for micro and meso-scale structure development in the amended soil (Markgraf et al., 2012). Structural changes (meso-scale) in soils have been described as a consequence of mechanical and/or hydraulic stresses (Peng et al., 2007; Horn et al., 2012), whereas microstructural (micro-scale) development is well related to biochemical changes in the soil (Holthusen et al., 2010; Peng et al., 2011; Markgraf et al., 2012; Baumgarten et al., 2012). Structural changes in soils will improve among others aeration, water flux, cation exchange and redox processes (Horn et al., 1994, 2012; Kutilek, 2004; Horn and Smucker, 2005).

Besides, structural changes in biochar amended soils are expected to be dynamic and could be influenced by the alternation of wetting and drying (WD) processes. WD induces swelling and shrinking of soil particles and modify the pore size and shape. During wetting, e.g. the pores are filled by water, but during drying the soil's particles may change their individual orientation and be rearranged. Thus, WD cycles can affect several attributes of amended soils like particle cohesion, internal friction and aggregation. Such modifications may influence aggregate sorptivity, hydro repellency, pore-size distribution, pore number and pore shapes (Rajaram and Erbach, 1998; Pires et al., 2008). Piccolo et al. (1997) in a study on different types of soil amended with coal-derived humic substance (HS) noted that low rates of amendment (equivalent to 100–200 kg ha^{-1}) did not only significantly improve the aggregate stability of all the 3 studied soils, but also substantially reduced the disaggregating effects of WD cycles. They, therefore, proposed the use of these exogenous humic substances as soil conditioners in conservation agriculture aimed at increasing the structural stability of soils . It seems however unclear how long the imports of biochar on soil functions remain and how far structural changes also depend on wetting and intense drying. When a non-rigid soil is continuously desiccated, its structure will change, which can be evaluated from the shrinkage curve (Peng and Horn, 2005; Cornelis et al., 2006; McGarry and Malafant, 1987; Braudeau et al., 1999). These changes due to cycles of WD will affect moisture content dependent properties, like hydraulic conductivity and thermal diffusivity as well as biological activities in the substrates (Dörner et al., 2010). Until now, these effects in biochar amended soils have not been investigated, albeit these processes under in situ conditions have to be quantified in order to predict more precisely the long term behaviour. Therefore, the objective of this study was to determine the effect of biochar treatment on two texturally different soils and to evaluate the influence on hydrological and mechanical properties that drive aggregate formation and stability in these soils.

2. Materials and methods

2.1. Soils

Fine sand (*s*) and sandy loamy silt from calcic Gleysol (*u*) were used as base-materials in this study. The pretreated fine sand (0.13–0.36 mm) sample was procured while the calcic in Germany while Gleysols (sand—74 g kg^{-1}, silt—577 g kg^{-1}, clay—349 g kg^{-1}) are glacial sediments collected from the southern part of Schleswig-Holstein, Germany. The sediment was first air dried, pulverized with a plastic hammer and then passed through a 2.00 mm sieve.

2.2. Biochar

A high temperature pyrolysed (HTP) biochar, prepared by carbonizing hardwood at (500–600 °C) was procured from a commercial producer in Germany (Susterra—nachhaltig pflanzen; www.susterra.de). The biochar was crushed into finer fractions using a centrifugal mill (Retsch) fitted with a 750 μm stainless steel sieve. The pulverized fraction was further passed through a 630 μm sieve before being used to prepare the different substrates.

2.3. Preparation of test substrates cores

The test substrates were prepared by adding biochar at three doses (2, 5 and 10% by dry mass) to the base soil materials (fine-sand or sandy loamy silt). Each substrate was thoroughly homogenized, packed in sealed polythene bags and stored at 10 °C for 30 days before the mixtures were used to prepare the test samples. Test samples were prepared by repacking 100 cm^3 stainless steel cylinders (about 4.00 cm height) with the homogenized substrates. The sandy substrates, *s* (materials prepared from the fine sand) were packed manually to bulk density of 1.65 g cm^{-3} (equivalent of 32, 80, and 160 t ha^{-1} of biochar respectively; 10 replications per treatment). The silty substrates, *u* (materials prepared from the sandy loamy silt) were refilled to bulk densities of 1.45 g cm^{-3} (equivalent of 29, 72.5, and 145 t ha^{-1}of biochar respectively; 20 replications per treatment) and to 1.30 g cm^{-3} (equivalent of 26, 65, and 130 t ha^{-1}, respectively) using an Instron 5569 loading frame (Instron Industrial Products, Norwood MA, USA). Additional 10 samples per treatment were prepared to characterise saturated hydraulic conductivity and aggregation, particularly in the silty substrates. The amount of biochar per hectare, is calculated assuming that the biochar was added up to the upper 10 cm depth. Therefore, the treatments consisted of *s*2, *s*5, *s*10, *u*2, *u*5, and *u*10, where the numbers indicate the proportion of biochar in the substrate's mixture. Unamended samples of the fine-sand −*s*0 and sandy loamy silt -*u*0 samples were similarly packed as controls.

2.4. Moisture retention and shrinkage

The first set of 20 samples prepared to bulk densities of 1.45 g cm^{-3} (silty substrates) and 1.65 g cm^{-3} (sandy substrates) were used to determine the water retention and shrinkage behaviour and the unamended fine sand and unamended sandy loamy silt. They were saturated with water by capillary rise for about 48 h and thereafter equilibrated step-wise to matric potentials −6, −15, −30, and −50 kPa. Desiccation of the samples to −6 kPa was done on a sand bed, while the samples were adjusted to more negative matric potentials on ceramic plates placed inside pressure chambers. The weight of the samples at each matric potential was noted and later used to estimate the gravimetric water content when the samples were oven-dried to 105 °C for 16 h after the last step. The gravimetric water content at permanent wilting point (−1500 kPa) in the substrates, and the control was determined from thoroughly moistened samples packed in very small rings (20 samples per treatment). They were pneumatically drained on ceramic plates, placed within pressure chamber for about 21 days and later oven dried at 105 °C for 16 h .

Possible shrinkage in the samples (used for water retention experiment) due to hydraulic stresses (during the step-wise desiccation process), was checked from height changes on the surface of the samples at 9 consistent points using a special digital caliper (0.01 mm precision). The heights were first measured when the samples were freshly prepared, at saturation (0 kPa), at all pressure step during the desiccation process (−6, −15, −30, −50 kPa) and after the samples were oven dried at 105 °C. The