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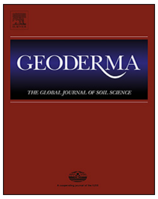

Effect of biochar addition on hydraulic functions of two textural soils

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ABSTRACT

Land degradation reduces soil productivity and exacerbates the problem of food security. Thus, there is an increasing need to look for sustainable farming practices aimed to water and soil conservation. In this regards, conditioning the soil with biochar has been identified as a possible means on improving water conservation and soil biochemical, physical, i.e. mechanical and hydraulic characteristics. Many studies demonstrate these effects of biochar. However, the extended number of variables influencing its impact require further measurements. The objective of this study is to determine the effect of wood-based biochar on two different textured soils and to evaluate their influence on some hydrological properties: water retention, shrinkage behavior and the effect of wetting and drying periods on the hydraulic conductivity. Test samples were prepared by adding 2.5 and 5% (by dry mass) of pyrolyzed mango-wood biochar to a sand and a sandy loam. Soil water retention and soil shrinkage curves were measured. Additionally, extra core samples were exposed to four intense cycles of wetting and drying, by drying the samples at 30 °C for three consecutive days. Biochar amendments increased water retention in the coarse textured sand compared to the unamended soil. Pore size distribution was significantly altered in the sandy substrate, reducing the fraction of wide coarse pores and increasing meso porosity. Repeated wetting and drying cycles enhanced the structural stability of the pore system increasing the saturated hydraulic conductivity. Soil rigidity, especially in the sandy mixtures, was enhanced by the addition of biochar, forming an internal pore structure able to resist better hydraulic deformation due to drying. These results confirm the suitability of biochar to overcome extreme hydrological conditions.

1. Introduction

The exponential demographic growth (United Nations Department of Economic and Social Affairs and Population Division, 2015) imposes challenges to agriculture which faces the requirements of higher productivity to mitigate the threat associated with food security. Thus, farmers are obligated to look for more sustainable land practices and technologies required for an adequate soil management (Verheijen et al., 2010). Degraded land covers approximately 24% of the global land area and the soil organic carbon (SOC) stocks have decreased to 41% in tropical regions, which impacts the resilience of soils to natural disturbances (FAO and ITPS, 2015). Biochar, due to its recalcitrant condition may have a long-term potential impact on the functioning of soils (Spokas et al., 2012; Verheijen et al., 2010) by improving their physical, chemical and hydraulic properties and as a source of carbon sequestration.

The recent trend to use biochar as amendment for soils is mainly based on the findings in the Amazonian region, where the indigenous agricultural management practices lead to the creation of a black soil, called “terra preta do Indio” (Glaser et al., 2001; Sohi et al., 2009). These anthropogenic soils have been identified as fertile and of high quality in comparison to other adjacent soils. The apparent ability of biochar to increase the soil capacity to absorb and store water, makes it a good alternative to protect soils against climate change (Sohi et al., 2009). However, it has been demonstrated that the effect of biochar as soil conditioner is highly related to the quality of the source material, production and postproduction processes, temperature, application rates and soil type to which it is applied (Brewer, 2012; Spokas et al., 2012). Among these parameters, process temperature has the greatest influence on the final biochar composition (Ronsse et al., 2013). Pyrolysis temperatures higher than 500 °C produce biochars with a carbon content > 80%, whereas carbon content at temperatures between 400 and 500 °C ranges between 60 and 80%, and at temperatures lower than 350 °C the carbon content is between 15 and 60% (Laird et al., 2011; Ronsse et al., 2013). Elemental composition of N and S is lost when pyrolysis temperatures increase from 300 °C to 600 °C (Laird et al., 2011). High temperatures (> 550 °C) produce biochars with high surface areas (Joseph et al., 2010; Ronsse et al., 2013) of about > 400 m^2/

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g, high ash content, and recalcitrant to decomposition. Low temperatures ($< 550\,^{\circ}C$) produce biochars with more oxygen-containing and C—H functional groups, producing an amorphous C matrix that promote nutrient retention (Joseph et al., 2010; Laird et al., 2011; Verheijen et al., 2010). However, the hydrophobicity is increased as a negative property (Kinney et al., 2012; Zornoza et al., 2016). The higher the pyrolysis temperature, the higher the pH is due to more alkaline elements in the biochar, although it is highly dependent on the feedstock type, too (Ronsse et al., 2013). In general, Kinney et al. (2012) proposed that ideal pyrolysis temperatures range between 400 °C and 600 °C to promote appropriate hydrological conditions, with high water retention capacity and low hydrophobicity.

In general, biochar as amendment is known to enhance soil chemical properties. It is shown that in infertile soils biochar additions improve cation exchange capacity (CEC) (Liang et al., 2006; Verheijen et al., 2010; Zornoza et al., 2016) enhancing the bounding nutrient-soil conditions and preventing the leachate of nutrients to surface waters and deeper soil regions. Other studies have found that biochar addition may increase pH producing a liming effect (Verheijen et al., 2010) and reduce the risk of some metal toxicity (i.e. aluminum).

Biochar addition enhances physical and hydraulic soil properties by adding porous substances to the soil, modifying water retention, total porosity and pore structure (Burrell et al., 2016; Novak et al., 2012). This has implications in soil aeration, water holding capacity and soil workability (Verheijen et al., 2010). Different effects have been reported relating soil type and biochar dosages without being able to establish a clear trend (Verheijen et al., 2010). Generally, more notable benefits have been observed in soils with coarse grain texture, low pH and generally degraded (Abel et al., 2013; Jeffery et al., 2015). Ajayi et al. (2016) and Ajayi and Horn (2017) reported on coarse grained soil, amended with biochar, an increase in total carbon, specific surface area (SSA), micro porosity, plant available water and total porosity. Ajayi and Horn (2016) also observed that the biochar dosage was positively correlated to the increase of SSA, total porosity, and available water content. They explained these results by a decrease of wide pores. Fine biochar particles transform large pores to medium and fine pores, because of the infilling of the large-sized pores by the small biochar particles (Ajayi and Horn, 2017; Eibisch et al., 2015; Hartge and Horn, 2016). This new relative soil condition makes water available as the soil dries leading to increase plant water availability during dry periods and increase water retention capacity (Ajayi et al., 2016; Ajayi and Horn, 2017; Jones et al., 2010; Verheijen et al., 2010). Biochar particles, due to their fine pore structure, have similar properties like clay particles, raise strength of menisci with decreasing matric potential, and produce a positive contracting force of particles (Ajayi and Horn, 2017).

Finer biochar particles, when added to soils, reduce the saturated hydraulic conductivity due to the formation of narrower pores (Yargicoglu et al., 2015). It has been observed that in coarse grained soils, biochar addition reduces the saturated hydraulic conductivity (Barnes et al., 2014; Lim et al., 2016). Ajayi et al. (2016) also reported that wetting and drying cycles (WD) reduce the saturated hydraulic conductivity in coarse textures and increases it in sandy loam and silty soils. This is attributed to the internal orientation of particles forming aggregates and inter-aggregates cracks.

WD cycles also influence soil shrinkage and swelling. This induces aggregate formation and rearrangement of particles, which make soils less sensitive to soil deformation. The impact of WD cycles on soils is highly dependent on the soil structure and texture (Horn et al., 2017). Peng and Horn (2013) proposed a shrinkage curve model and identified six types of soil shrinkage curves based on four shrinkage zones (structural, proportional, residual, and zero shrinkage). Organic soils have been reported to become more rigid, with less pore changes as soil dries, than mineral soils; presenting less swelling and keeping large pore formation during WD cycles (Peng et al., 2007). Similarly, it has been reported that biochar amended clayey soils are more prompt to reduce the effect of volume changes when wetting or drying, reduce the crack formation and the size at which they are formed compared to unamended clay soils. The wider pore size distribution has been described as the mechanism to improve soil aggregation due to biochar addition (Lu et al., 2014; Zong et al., 2014). Shrinkage and swelling modifications influence the movement of water and flux within the soil matrix affecting the soil hydraulic properties (Horn et al., 2017).

The present study has the objective to assess:

- the physical soil functions (hydraulic conductivity, air permeability),
- water characteristics (pore size distribution, available water content and repellency),
- the shrinkage behavior, and
- the effect of wetting and drying (WD) cycles on the saturated hydraulic conductivity, of two differently grained materials and their amendments when biochar is added as a source of organic carbon in varying proportion.

2. Material and methods

2.1. Sample preparation and characterization

Two materials were used: medium sand (*S*) with grain size diameter mainly between 0.20 and 0.63 mm (99% sand and 1% clay) and a sandy loam soil (*SL*) (54% sand, 13% clay and 33% silt) which was collected in Schleswig-Holstein/Germany. Sediments were first air dried, macerated and passed through a 2 mm sieve. The biochar used was produced from old mango tree (with minimum age of 30 years), and pyrolyzed at a temperature of about 600 °C. It was crushed into finer fractions and passed through a 63 μm sieve.

Test samples were prepared by adding biochar (2.5 and 5% by dry mass) to the two soil materials. Thus the treatments consisted of S0 (control-unamended sand), S2.5 (sand + 2.5% biochar), S5 (sand + 5% biochar), SL0 (control-unamended sandy loam), SL2.5 (sandy loam + 2.5% biochar) and SL5 (sandy loam + 2.5% biochar).

Samples were packed as follows:

a. The first group of 40 replications per treatment was prepared by packing 100 cm^3 stainless steel cylinders (about 4 cm height and 5.6 cm diameter) with the homogenized substrates. The sandy substrates, *S* were packed to an initial bulk density of 1.5 g/cm^3 and the sandy loam substrates, *SL* were refilled to bulk densities of 1.35 g/cm^3 using an Instron 5569 loading frame (Instron, 2008). Water content, sorptivity, air conductivity and shrinkage, at each matric potential were determined
b. 10 samples per treatment (100 cm^3 cylinder) were prepared (to the same bulk densities as in point a.) to characterize saturated hydraulic conductivity after different wetting and drying (WD) cycles.
c. Another 10 ring samples of about 2 cm diameter (ca. 2.6 cm^3), for each treatment, were prepared to quantify the water content by weight at −1500 kPa, which is equivalent to the permanent wilting point.

2.2. Parameter analysis

The dry bulk density (ρ_d) was determined by the soil core method (Soil Survey Staff, 2014). The particle density (ρ_s) was measured with the Pycnometer method. The organic carbon and nitrogen content were determined with a C/N Element-Analyzer. The inorganic carbon fraction was estimated by determining the $CaCO_3$ content during the measurement of the volumetric CO_2 gas produced after adding HCl. Soil texture was analyzed by the combined sieve ($> 63\,\mu m$) and pipette method (Blume et al., 2010) and soil classification was based on the FAO guidelines (Scheffer and Schachtschabel, 2010). pH was measured in a 0.01 M $CaCl_2$ solution and cation exchange capacity (CEC) was determined by the atomic absorption spectrophotometer method