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Mechanisms of biochar effects on thermal properties of red soil in south China

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ABSTRACT

Soil thermal properties play crucial roles in governing heat storage and conduction across soil profiles and affect various soil processes by determining soil microclimate. Biochar has gained wide attention as a soil amendment to affect a series of soil physiochemical properties. However, little information is available on the integrated effects of biochar application on soil thermal properties. Disturbed soil columns with consistent bulk density ($1.3\,g\,cm^{-3}$) were packed using clayey red soil and wheat straw biochar at application rates (w/w) of 0%, 0.5%, 1.0%, 1.5%, 2.0% and 2.5%. Besides, a 2-year field experiment of biochar application at the same application rates with crop rotation was performed in a red soil region in south China. Soil thermal properties, i.e. thermal capacity, conductivity and diffusivity, were measured with heat pulse method for disturbed soil columns and undisturbed soil cores from the field at controlled soil water contents ranging from 0% to 40% at an interval of 5%. Furthermore, soil thermal properties were measured in situ for different biochar treatments under field conditions. For the disturbed soil columns, no significant effect of biochar application on soil thermal properties was detected at most of the soil water content levels. Additionally, it indicated that biochar application cannot directly affect soil thermal properties by changing soil solid substances composition at application rates up to 2.5% w/w. The results from undisturbed soil cores showed significant decreasing effects of biochar application on soil thermal capacity and diffusivity at most of the soil water content levels. The results from in situ measurement showed significant decreasing effect of biochar application on soil thermal capacity, conductivity and diffusivity. Two main underlying mechanisms were identified for the effects of biochar application on soil thermal properties. One is the negative effect of biochar application on soil thermal capacity and conductivity by increasing the soil total porosity, mainly by increase in the meso- and macro-porosity. The other is the positive effects of biochar application on soil thermal properties by increasing the soil water content through improved soil water retention ability. The negative effects through change in the soil structure were the dominant effect under field condition.

1. Introduction

Soil thermal properties, including soil thermal capacity, conductivity, and diffusivity, play crucial roles in governing surface-energy partitioning and heat propagation across soil profile and consequently affect soil microclimate by regulating the spatiotemporal dynamics of soil temperature (De Vries, 1963; Ghauman and Lal, 1985; Chung and Horton, 1987). In addition, soil thermal properties can also affect soil microclimate by affecting the soil water conditions as a result of its effect on the latent heat exchange (Heitman et al., 2008; Xiao et al., 2011). Soil microclimate has great influences on soil chemical and biological processes, such as plant growth (seed germination, seedling emergence, and stand establishment) (Dunlap, 1986; Abu-Hamdeh and Reeder, 2000; Mellander et al., 2004) and microbial activities (soil organic matter turnover and respiration rate) (Karhu et al., 2010; Xu et al., 2012; Wu et al., 2012). Accurate information of soil thermal properties is indispensable in many areas, such as soil physical process modeling, agriculture management, as well as meteorological and industrial applications (Ochsner et al., 2001; Usowicz et al., 2013).

Soil thermal properties are determined by the composition and architecture of the soil solid, liquid and gaseous phases present in the porous media. The solid phrase contains two components, the mineral particle and the soil organic matter (SOM). For a given soil type, its mineralogical composition could only be changed by long-term weathering processes. SOM occupies about 10% (w/w) of the solid phase and would not exhibit large variation in natural ecosystems under equilibrium. However, human activities, such as tillage and organic fertilizing, can greatly alter SOM content within a short period

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(Lal, 2004). Rovdan and Usowicz (2002) discovered that addition of only a few percent of organic matter to mineral soil samples can lead to significant change in soil thermal conductivity. The liquid phase has the highest thermal capacity and moderate conductivity among the three phases. Besides, it is the most variable factor affecting soil thermal properties (Lu et al., 2007), determined by its high spatiotemporal variability at different scales (Hu and Si, 2013). Apart from material composition, soil structure is another important factor affecting soil thermal properties. It determines spatial arrangement and contacts among soil solids, water and air. Soil structure is also a variable factor, which can be altered by human activities, such as tillage and compaction (Pagliai et al., 2004). Increase in bulk density and decreases in porosity would lead to significant increase in soil thermal properties (Potter et al., 1985; Arshad and Azzoz, 1996; Abu-Hamdeh and Reeder, 2000; Dec et al., 2009), and this effect is more pronounced for soils with high water content (Horn, 1994; Usowicz et al., 1996). Furthermore, soil aggregation is an important process that can change soil structure and soil water retention characteristics, consequently having an impact on the soil thermal properties (Horn, 1994; Ju et al., 2011; Usowicz et al., 2013).

Biochar has been used to refer to the solid organic materials converted from a variety of biomass by thermochemical decomposition under limited or oxygen-free conditions (Sombroek, 1966; Meyer et al., 2011). In recent decades, the industrial production of biochar and its land application for soil amelioration and long-term carbon sequestration have aroused widespread concern in the scientific communities (Lehmann, 2007; Woolf et al., 2010; Sohi, 2012). Given its unique physiochemical properties and recalcitrant nature, land application of biochar could lead to a series of irreversible and long lasting ecological and environmental consequences. By far, a large number of studies have been done addressing both the short and long-term effects of biochar on soil chemical and biological processes. Most of them have reported its effective influences on soil fertility and crop productivity (Jeffery et al., 2015; Biederman and Harpole, 2013), nutrient leaching and heavy metal availability (Laird et al., 2010; Rees et al., 2014), soil microorganisms, fauna and plant roots activities (Lehmann et al., 2011), soil organic carbon sequestration and mitigation of non-CO_2 greenhouse gases emission (Lehmann, 2007; Woolf et al., 2010; Cayuela et al., 2014). However, less attention has been given to its effects on soil physical properties and related physical processes in soils (Atkinson et al., 2010). Recently, several studies focused on biochar effects on soil physical properties and their results unanimously indicated biochar amendment can significantly alter soil structural properties (e.g. bulk density, soil porosity and aggregate stability), soil-water retention characteristics (e.g. field holding capacity, plant available water content, and permanent wilting point), and soil hydraulic properties (e.g. saturated and unsaturated hydraulic conductivity, and steady infiltration rate) (Abel et al., 2013; Herath et al., 2013; Hardie et al., 2014; Peake et al., 2014; Ojeda et al., 2015; Castellini et al., 2015; Obia et al., 2016; Novak et al., 2016). Therefore, it is reasonable to speculate that biochar application can affect soil thermal properties in an integrated manner by changing the soil material composition, porosity, and soil water condition. However, there is a dearth of literature addressing the effects of biochar amendment on soil thermal properties and soil energy balance. Usowicz et al. (2016) discovered significant effects of biochar application on soil thermal properties under two different land use types. After > 5-year successive application (4.5 t ha^{-1} $year^{-1}$ and 9.0 t ha^{-1} $year^{-1}$) of corncob biochar, Zhang et al. (2013) and Zhao et al. (2016) reported significant decreases in soil thermal conductivity and diffusivity in a sandy loam agriculture soil in North China Plain and the changes in thermal properties reduced the diurnal fluctuation of surface soil temperature at both daily and seasonal scales. However, the underlying mechanisms of biochar amendment on soil thermal properties remain unclear.

Red soils cover about 22% of the total national land area of China. Subjected to intensive weathering and leaching, red soils are characterized by clay or loamy clay texture, low soil organic matter and available nutrients, poor soil structure and available water storage efficiency, high acidity and aluminum toxicity (Zhang et al., 2004; D'Angelo et al., 2014). Given its low bulk density, high porosity and high pH, biochar is considered as an effective soil amendment in improving soil quality and crop yield for red soils in China (Peng et al., 2011; Jien and Wang, 2013). Previous studies have shown that biochar application can significantly affect soil bulk density, porosity, soil water retention, hydraulic conductivity, and aggregate stability of red soils (Asai et al., 2009; Peng et al., 2011; Jien and Wang, 2013; Demisie et al., 2014; Peng et al., 2016; Novak et al., 2016).

Therefore, the objectives of the current study were (1) to investigate the effects of biochar application on soil thermal properties of red soil in south China, and (2) to discover the underlying mechanisms.

2. Materials and methods

2.1. Field experimental design

The study area is located in Liu Jia Zhan Town, Yingtan County, Jiangxi Province in south China. This region is dominated by a warm and humid subtropical monsoon climate. The annual precipitation is 1795 mm and the average annual temperature is 17.8 °C. Soils in this region are mainly derived from Quaternary red clay parent material, and are classified as Ultisols (Soil Survey Staff, 2010). The dominant clay mineral is kaolinite. The soil is clay in texture with 30.2% sand (2–0.02 mm), 20.8% silt (0.02–0.002 mm), and 49.0% clay (< 0.002 mm). Soil organic carbon (SOC) and total nitrogen (TN) content was 5.41 g kg^{-1} and 0.73 g kg^{-1}, respectively. Soil pH was 5.34 and cation exchange capacity was 11.2 cmol kg^{-1} (Peng et al., 2016).

The field experiment site was on an upland cultivated area, about 2 km away from the Red Soil Ecological Experimental Research Station, Chinese Academy of Sciences (28°15′ N, 116°55′ E). Prior to the experiment setup, the top 0–20 cm surface soil was tilled and mixed using a gyrotiller to achieve flat topography and uniform soil material. There were six biochar application treatments (w/w): control 0% (BC0), 0.5% (BC1), 1.0% (BC2), 1.5% (BC3), 2% (BC4), and 2.5% (BC5). Biochar was applied to the top 0–20 cm surface soil. Taking 1.3 g cm^{-3} as the average soil bulk density, these six biochar treatments were equivalent to 0 t ha^{-1} (BC0), 13 t ha^{-1} (BC1), 26 t ha^{-1} (BC2), 39 t ha^{-1} (BC3), 52 t ha^{-1} (BC4) and 65 t ha^{-1} (BC5). Each treatment was carried out in triplicates. All the replicates were arranged to 18 plots following a random complete block design. Each plot had an area of 16 m^2 (4 m × 4 m). The plots were separated by cement slabs (100 cm length × 50 cm height × 8 cm width) with 30 cm inserting into the soil and 20 cm left aboveground to avoid surface soil loss from erosion during stormy rains. Different amounts of biochar (dry mass), i.e. 0 kg (BC0), 20.8 kg (BC1), 41.6 kg (BC2), 62.4 kg (BC3), 83.2 kg (BC4) and 104 kg (BC5) were spread on the soil surface within the corresponding plots and mixed thoroughly with the soil by manual plowing to a depth of 20 cm in October 2014. There was no successive biochar application. Two local crops, rapeseed and sweet potato, were grown in rotation in the experimental field. The rapeseed was planted in early October and harvested in mid-May and sweet potato was planted in June and harvested in late September. The number of rapeseed and sweet potato plants was fixed to 105 (7 rows, 15 lines) in each plot. Compound fertilizer (N-P_2O_5-K_2O, 15-15-15) was applied at a rate of 750 kg ha^{-1} as basal fertilizer and additional N fertilizer was applied as urea at a rate of 150 kg ha^{-1} according to the local agronomic practice.

2.2. Biochar properties

The biochar used in the current study was a commercial biochar produced by LiuHe Qinfeng Straw Technology Company in Jiangsu Province of China. The feedstock was wheat straw. The pyrolysis temperature was between 450 and 550 °C. Details of biochar production