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The effect of biochar application on thermal properties and albedo of loess soil under grassland and fallow

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ABSTRACT

There is sparse peer-reviewed literature on the biochar effects on the thermal properties of soils although they play an important role in the soil energy balance and resulting temperature distribution. The objective of this study was to quantify the effect of biochar from wood off cuts on the thermal conductivity, heat capacity, thermal diffusivity, albedo, water content, and bulk density of loess soil under grassland (G) and fallow (F) in the temperate climate of Poland. The biochar at an amount of 0, 10, 20, and 30 $\mathrm{Mg\,ha^{-1}}$ was incorporated to a depth of 0–15 cm under F and remained on the surface under G. All field measurements were done on 24 occasions from spring to autumn in 2013–2014. Additional laboratory measurements of the thermal properties in water saturated (Wet) and dry (Dry) states. Incorporation of biochar under the F led to reduced soil bulk density and particle density from 1.18–1.20 $\mathrm{Mg\,m^{-3}}$ and 2.48–2.55 $\mathrm{Mg\,m^{-3}}$ under F0 and F10 to 1.00 $\mathrm{Mg\,m^{-3}}$ and 2.20 $\mathrm{Mg\,m^{-3}}$ under F30, respectively. The field measured average water contents were greater under F while the minimum ones were lower in biochar-amended than control soil without biochar. In general, the average thermal conductivity and thermal diffusivity and values of thermal conductivity at the saturation and dry state under F in general decreased with the increasing biochar application rate. After biochar addition, the albedo decreased with the increasing biochar application rate and was considerably greater under F than G. After rain, there was substantial reduction of the albedo under F in contrast to G, where it was increased. Changes in the soil thermal properties in response to biochar application were most pronounced under F and those in albedo under G. Irrespective of the biochar application rate, the average thermal conductivity and water content were greater under G than F. The daily soil temperature amplitude in biochar amended plots decreased under G and increased under F. The use of the statistical-physical model showed that the rate of the increase in the thermal conductivity and thermal diffusivity with increasing soil water content was greater in soil with greater rather than lower bulk density. The relatively wide range of variations suggests that biochar application can be an important factor in regulation of the thermal soil properties and albedo as well as climate change.

1. Introduction

Biochar is charcoal obtained by the pyrolysis of biomass, i.e., by incomplete thermal decomposition of organic material under a limited supply of oxygen at temperatures between 300 and 1000 °C (Verheijen et al., 2013; Hardie et al., 2014; Castellini and Ventrella, 2015). Unlike charcoal and similar materials, biochar is produced with the aim of being used as a soil amendment to improve soil nutrient status, C storage and/or filtration of percolating soil water (Lehmann and Joseph, 2009; Paz-Ferreiro et al., 2014). Different organic feedstocks such as wood chips, crop residues, biomass crops, and straw as well as animal manure, sewage sludge or urban waste (Gul et al., 2015) are used for biochar production.

The greater intrinsic stability of carbon in biochar materials than other organic matter enhances soil C sequestration. Lehmann et al. (2006) in their review reported that transformation of biomass to biochar C leads to sequestration of ca. 50% of the initial C compared to the low amounts retained after burning (3%) and biological decomposition (<20% after 5–10 years). Hence, biochar

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application has been proposed as a promising strategy to increase the stable C pool while concurrently improving soil fertility and crop yields (Woolf et al., 2010; Genesio et al., 2015) and restraining the development of atmospheric CO_2 concentration (Lehmann et al., 2006; Muter et al., 2014).

There have been numerous studies examining biochemical and microbial effects of biochar amended soils. They revealed that biochar was an effective acid-neutralizing material and had the potential to increase the availability of most major cations for plants (Lehmann et al., 2003; Zhu et al., 2015) due to negative surface charged area and increasing both the overall net surface area (Chan et al., 2007) and the cation exchange capacity or direct nutrient contributions (Liang et al., 2006; Nabavinia et al., 2015). Further, as shown in a review paper (Gul et al., 2015), biochars produced from various feedstocks consistently increase the abundance and alter the community structure of microorganisms in a vast number of soils. Due to its adsorptive and sorptive properties, biochar has been used for multiple applications in soil remediation of soil contaminated by pesticides or metals (Lu et al., 2015) and as a "supersorbent" for persistent organic pollutants in soils, which affect many important environmental processes (Koelmans et al., 2006; Zhang et al., 2013a). The application of biochar has aroused a growing interest as a sustainable technology to improve highly weathered or degraded tropical and subtropical soils (Paz-Ferreiro et al., 2015; Zong et al., 2015). However, to date, there is sparse peer-reviewed literature that shows on the role of biochar in the modification of different physical properties in agricultural soils (Hardie et al., 2014; Castellini and Ventrella, 2015). Particularly scarce information is available on biochar impact on the soil thermal properties although they play an important role in the soil-energy balance and resulting temperature distribution (Logsdon et al., 2010; Genesio et al., 2012; Meyer et al., 2012). The thermal properties are largely influenced by bulk density (Abu-Hamdeh and Reeder, 2000; Usowicz et al., 2013) water content or air-filled porosity (Usowicz et al., 2006a) and organic matter content (Dec et al., 2009) that can be altered by biochar's application (Paz-Ferreiro et al., 2014). The alterations can be associated with the high organic matter content as well as the surface area and low bulk density of biochar (Lehmann and Joseph, 2009; Ścisłowska et al., 2015).

A recent study by Zhang et al. (2013b) under warm monsoon climate in China showed that biochar application moderated diurnal variability in soil temperature due to the combined effects of soil albedo (reflectivity) and thermal conductivity. Therefore, modifying soil surface albedo in a biochar-amended soil may have important implications for biochar climate change mitigation potential, considering the proposed widespread application thereof. This issue needs urgent field studies including modeling the biochar impact with consideration of spatial and temporal variability (Verheijen et al., 2013).

The objective of this study was to quantify the effect of surface and incorporated treatments under grassland and fallow, respectively, on soil thermal properties, including thermal conductivity, capacity and diffusivity, and albedo of the loess soil in the temperate climate of Poland. We tested the hypothesis that biochar addition modifies the thermal properties by different ways depending on the types of land use.

2. Materials and method

Before the start of the field experiment, measurements of thermal conductivity, heat capacity and thermal diffusivity of pure biochar were done in the laboratory using a KD2 Pro meter (Decagon Devices). The biochar used in this study was produced from wood offcuts at pyrolysis temperature 350–400 °C by a local company (Fluid SA, Sedziszow, Poland) according to the technology developed by Bis and Nowak (Patent, Coll. Bis/W. Nowak No. P204294 dated 28.11.2003). The following five different textured fractions of the biochar were used: <0.5, 0.5–1, 1–2, 2–5 and >5 mm along with a mix of all the fractions. Various size fractions are often used for testing the performance of biochar.

The studies were carried out in grassland (G) and fallow (F) fields (51°15′N, 22°35′E, Lublin, Poland) on a Haplic Luvisol (according to the IUSS Working Group WRB., 2006) derived from loess material. The soils derived from loess occupy approximately 10% of the world's surface and are considered to be very productive (Catt, 2001). The fallow land had been left unseeded after being tilled (to a depth of 20 cm) and harrowed for 10 years. Such land use is used by farmers to regenerate naturally soil fertility on typically cultivated field. During the experiment the fallow plots were maintained without plants. The grassland was established at least 35 years ago and managed through cutting. Both under G and F fields of 20 m^2 (4×5 m), the dry biochar was uniformly surface applied in sub-plots at an amount of 0 (control, G0 and F0), 10 (G10 and F10), 20 (G20 and F20) and 30 (G30 and F30) Mg ha^{-1} in spring 2013. Then it was incorporated to a depth of 0–15 cm in the fallow using a rototiller and left on the surface in the grassland. The grass height under G during biochar application was ca. 6 cm.

Field measurements included measurements of the thermal properties using the same meter as for the pure biochar and the volumetric water content using TDR (Easy Test) at 0–10 cm depth. Field measurements were done on 24 occasions, for 8 plots from spring to autumn in 2013–2014, which in total are ca. 1000 measurements of all examined properties. The field data collected is presented as mean values (Ave) with standard deviations, as well as minimum (Min) and maximum (Max) values for each of the 8 sub-plots. Soil temperature at a depth of 2 cm was measured on all plots by thermocouples every 10 min and recorded on a data logger for the period from 9 to 30 August 2013. The data were given as the average daily minimum and maximum values and average from all data for this period and standard deviations. Albedo was determined with Net Radiometers (Kipp & Zonen) on the 1 m height of sensor placement at noon in 3 replicates. The measurements were done at four occasions: immediately after biochar application (at grass height 6 cm under G); one day after rain (16 mm) and biochar application at grass height 6 cm under G; at grass height 10–15 cm under G and one day after heavy rain (85 mm) and at grass height 15–50 cm under G.

Additional measurements of the thermal properties for water-saturated (Wet) and dry (Dry) soil were done in the laboratory using soil cores of 100 cm^3 taken from 0 to 10 cm depth in 4 replicates. The same cores were used to determine dry bulk density and gravimetric volumetric water content. Under separate study using the same soil with and without biochar it was found that the volumetric water content from TDR and gravimetric (grav.) methods were well agreed. Corresponding regression equations were (TDRbiochar = 0.932 grav. + 0.0045; R2 = 0.844 and TDR = 0.912 grav. + 0.0168; R2 = 0.790). Therefore we used data from both methods in our study. Saturated and dry states were obtained by capillary rise and oven drying, respectively. Particle density of soil was calculated using total porosity (corresponding to the water content at saturation) and that of biochar was estimated from the equation given by Brewer et al. (2014).

To better understand how the soil components affect the thermal properties, we used the statistical-physical model of soil thermal conductivity (Usowicz, 1992; Usowicz et al., 2006b). This model is based on the terms of heat resistance (Ohm's law and Fourier's law), two Kirchhoff's laws, and multinomial distribution (Eadie et al., 1971). The volumetric unit of soil in the model consists of solid particles, water and air, and is treated as a system made up of elementary geometric figures; in this case, spheres that form overlapping layers. It is assumed that connections between the

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