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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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layers of the spheres and the layers between neighboring spheres will be represented by the serial and parallel connections of thermal resistors, respectively. The thermal conductivity of soil λ($\mathrm{W\,m^{-1}\,K^{-1}}$) was calculated according to the equation (Usowicz, 1992):

$$\lambda = \frac{4\pi}{u\sum_{j=1}^{L}\frac{P(x_{1j},\ldots,x_{kj})}{x_{1j}\lambda_{1}(T)r_1+\ldots+x_{kj}\lambda_{k}(T)r_k}} \tag{1}$$

where: u is the number of parallel connections of soil particles treated as thermal resistors, L is the number of all possible combinations of particle configuration, x_1,x_2, . . . , x_k—a number of particles of individual particles of a soil with thermal conductivity λ_1, λ_2, . . . , λ_k and particle radii r_1, r_2, . . . , r_k, where $\sum_{i=1}^{k} x_{ij} = u$, j = 1,2, . . . ,L, $P(x_{ij})$—probability of occurrence of a given soil particle configuration calculated from the multinomial distribution (Eadie et al., 1971):

$$P(x_{1j},\ldots,x_{kj}) = \frac{u!}{x_{1j}^{!}\ldots x_{kj}^{!}} f_1^{x_{1j}}\ldots f_k^{x_{kj}}. \tag{2}$$

The condition: $\sum_{j=1}^{L} P(X = x_j) = 1$ must also be fulfilled. The probability of selecting a given soil constituent (particle) f_i, i = s, c, g, in a single trial was determined based on fundamental physical soil properties. In this case, f_s, f_c, and f_g are the contents of individual minerals and organic matter—$f_s = 1 - \phi$, liquid—$f_c = \theta_v$ and air—$f_g = \phi - \theta_v$ in a unit of volume, ϕ—soil porosity, θ_v—water content.

Heat capacity was calculated using de Vries formula (1963) based on the content of quartz (f_q) and other minerals (f_m), organic matter content, and biochar concentration (f_o):

$$C_v = \left(2.0 \times \left(f_q + f_m\right) + 2.51 f_o + 4.19\theta_v\right) \times 10^6 \tag{3}$$

The thermal diffusivity (α) was calculated from $\alpha = \lambda / C_v$.

3. Results

3.1. Biochar and soil characteristics

The biochar used in the field study as a mix of fractions had 70% carbon, nitrogen ~0.4%, pH ~ 8.0, bulk density ~0.33 $\mathrm{Mg\,m^{-3}}$, and particle density 1.41 $\mathrm{Mg\,m^{-3}}$. As can be seen from Table 1, the bulk density of the biochar decreased from 0.27 to 0.17 $\mathrm{Mg\,m^{-3}}$ with the increasing fraction size whereas it increased up to 0.33 $\mathrm{Mg\,m^{-3}}$ with the mix of the fractions. The thermal conductivity ranged from 0.08 to 0.1 $\mathrm{W\,m^{-1}\,K^{-1}}$ for all the individual fractions and increased to 0.13 $\mathrm{W\,m^{-1}\,K^{-1}}$ for the mix of the fractions. The highest thermal conductivity of the mix is consistent with the maximum bulk density, possibly because the smaller particles partially fill in the spaces between the larger particles. Likewise, heat capacity in the individual fractions varied within a relatively narrow range (0.53–0.62 $\mathrm{MJ\,m^{-3}\,K^{-1}}$) and increased up to 0.91 $\mathrm{MJ\,m^{-3}\,K^{-1}}$ in the mix of fractions. As to the thermal diffusivity, the fraction >5 mm had the maximum value (0.18 $\mathrm{mm^2\,s^{-1}}$) that was noticeably lower and similar in all the other fractions and the mix of the fractions (0.13–0.15 $\mathrm{mm^2\,s^{-1}}$).

Particle size distribution and soil organic matter under F and G are presented in Table 2. The soil under F compared to G has slightly less of the coarse fraction (2–0.02 mm) and more of the fine fraction (0.02–< 0.002 mm). The soil organic matter contents at the 0–15 cm and 15–30 cm were under F 0.9 and 0.7%, respectively. The corresponding values under G were by 78 and 43% greater.

3.2. Bulk density, particle density and water contents

Incorporation of the biochar into the fallow 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 (Fig. 1a,b). The changes in both bulk density and particle density in response to biochar under G were relatively lower than under F due to the surface application in the former. Under F, the average and maximum saturated soil water contents were greater, while the minimum contents were lower in the biochar-amended than control soil. However, under G, there was no noticeable effect of the biochar addition on all the soil water contents. Irrespective of the biochar application rate, the standard deviations for the average water content were greater under G than F. The reductions in bulk density in the biochar-amended plots under F corresponded in general with the increases in saturated soil water contents (Fig. 1a and c).

3.3. Thermal properties

In general, the minimum and average thermal conductivities and those in dry soil (Dry) and after saturation with water (Wet) under F decreased with the increasing biochar application rate (Fig. 1d). However, in the case of the maximum thermal conductivity (Max), the inverse was true. In general, changes in the thermal conductivity in response to biochar were largely influenced by bulk density, which decreased with the increasing biochar application rate. The wide range of variations in the thermal conductivity from 0.18 up to 1.35 $\mathrm{W\,m^{-1}\,K^{-1}}$ indicates that

Table 2
Soil physical data used for calculation of thermal conductivity of soils.

Soil	Plot/depth	Sand*	Silt	Clay	Organic matter**	f_q	f_m	f_o
	Grass	%			%	$\mathrm{m^3\,m^{-3}}$		
	0–15 cm	77	14	9	1.62	0.716	0.258	0.026
Haplic Luvisol	15–30 cm	72	15	13	1.20	0.708	0.272	0.020
	Fallow							
	0–15 cm	66	23	11	0.91	0.624	0.361	0.015
	15–30 cm	67	22	12	0.71	0.686	0.302	0.012

[*] Cassagrande areometer method (Polish Standard PN-R-04032, 1998).
[**] Tiurin digestion and titration method (Angelova et al., 2014).

Table 1
Thermal properties and bulk density of pure biochar for single textured fractions and mix of all fractions.

Diameter, mm	Thermal conductivity, $\mathrm{W\,m^{-1}\,K^{-1}}$	Heat capacity, $\mathrm{MJ\,m^{-3}\,K^{-1}}$	Thermal diffusivity, $\mathrm{mm^2\,s^{-1}}$	Bulk density, $\mathrm{Mg\,m^{-3}}$
$0.5 < \phi$	0.079	0.592	0.134	0.267
$0.5 < \phi < 1$	0.080	0.550	0.147	0.212
$1 < \phi < 2$	0.078	0.530	0.148	0.174
$2 < \phi < 5$	0.080	0.545	0.146	0.169
$\phi > 5$	0.104	0.615	0.180	0.167
All fractions	0.132	0.913	0.145	0.334

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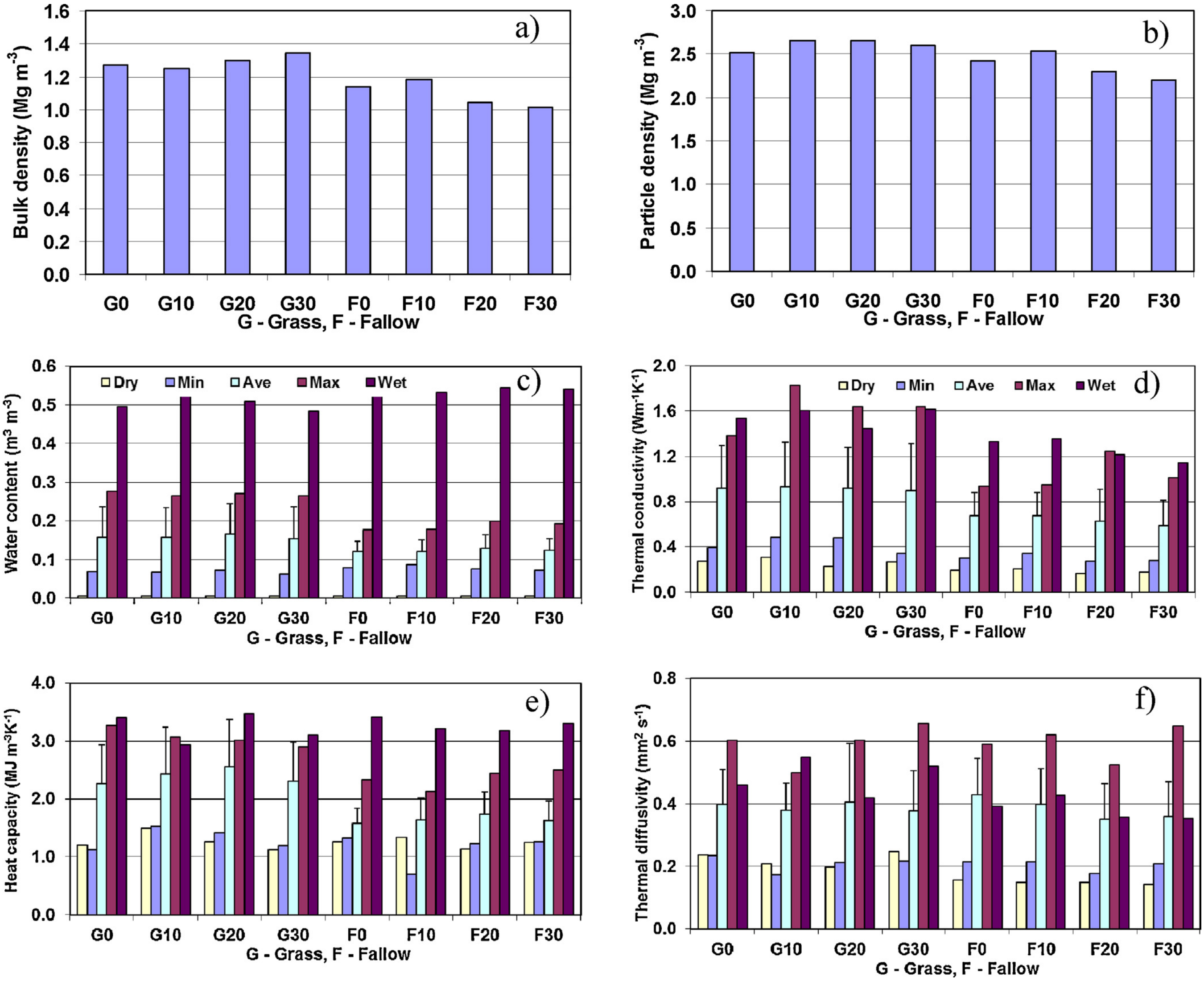

Fig. 1. Bulk density (a), particle density (b), water content (c), thermal conductivity (d), heat capacity (e) and thermal diffusivity (f) of the grassed (G) and fallow (F) soil with 0 (F0 and G0), 10 (F10 and G10), 20 (F20 and G20), and 30 (F30 and G30) Mg ha^{-1} of biochar. Dry and Wet refer to the laboratory and Min, Ave and Max to the field measurements.

biochar application in the fallow can be an important factor in regulation of the thermal conductivity. There was no discernible effect of surface-applied biochar on the soil thermal conductivity under G. Irrespective of the biochar application rate, both the average thermal conductivity and the standard deviations (Fig. 1d) were greater under G than F (Fig. 1a,c).

Changes in heat capacity in response to the biochar application were rather small and difficult to interpret under both G and F. The average field measured values of heat capacities as well as standard deviations were greater under G than F. Maximum heat capacity under F, compared to G, was substantially lower and the minimum values were similar. It is worth noticing that the maximum heat capacities of the soil under G were almost equal to those in water-saturated soil, whereas they were much lower under F. Irrespective of land use and the biochar application rate, heat capacity ranged from 0.7 to 3.5 MJ m^{-3} K^{-1} and increased with the increasing water content (Fig. 1). Similar to thermal conductivity, the standard deviations were greater under G than F.

There was a slight decrease in the average (Ave) thermal diffusivity with the increasing quantity of biochar application under F (Fig. 1f). Under G, no noticeable effect of biochar application on the diffusivity was observed. The diffusivities in the dry state (Dry) and minimal (Min) values were similar under G and F. Irrespective of the biochar application rate and land use, the thermal diffusivity ranged from 0.14 to 0.66 mm^2 s^{-1}. The maximum thermal diffusivity of the soil (Max) was in a majority of cases considerably greater than the diffusivity in the water saturated soil (Wet) (Fig. 1f). The results indicate that higher thermal diffusivities occurred already at the soil water content below the saturated water content in contrast to the thermal conductivity and heat capacity, which increased with the increasing soil water content up to saturation.

3.4. Albedo

Shortly after biochar addition, the albedo decreased with the increasing biochar application rate under G and F (Fig. 2a,b). The albedo values before the first rain after the application of biochar were considerably greater under F than G at all the biochar rates compared (Fig. 2a). After the rain, there was considerable reduction of the albedo in all the biochar treatments under F in contrast to those under G, where it was even slightly increased (Fig. 2b). The decrease on the fallow was associated with an increase in surface soil compactness and smoothing following the

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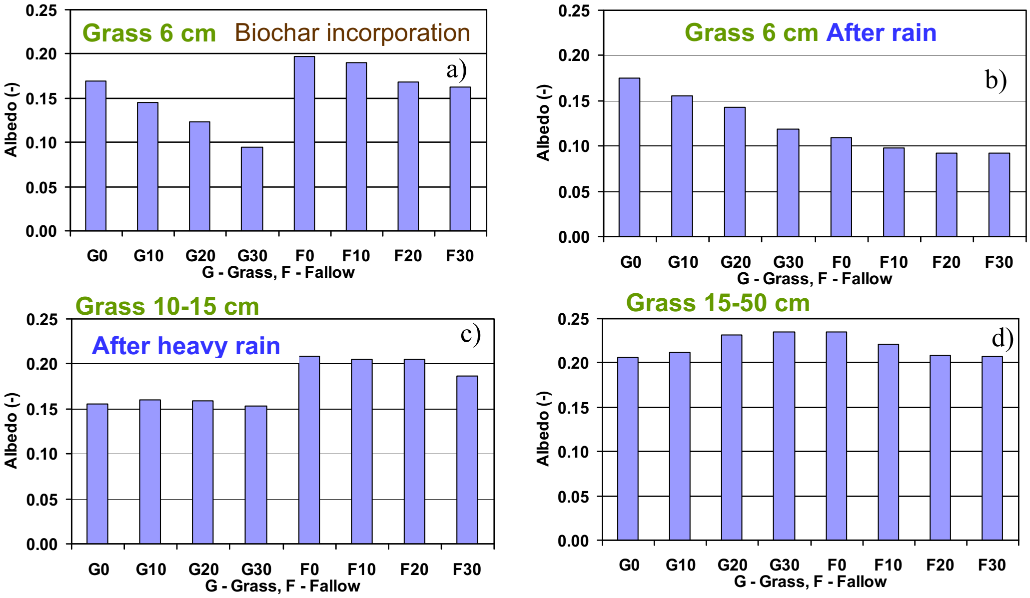

Fig. 2. Albedo of the grassland and fallow with and without biochar at various grass height before and after rains (rain = 16 mm, heavy rain = 85 mm).

rain. However, after heavy rain when the grass height was 10–15 cm, the albedo was similar in all the biochar treatments under G and F, with greater values under F (Fig. 2c). At grass height 15–50 cm the albedo in the grassed soil tended to increase with the increasing biochar rate and to decrease on the fallow (Fig. 2d). Irrespective of land use and the biochar application rate, the albedo varied in the range from ca. 0.1–0.23.

3.5. Soil temperature

Addition of biochar led to a decrease and increase of the daily soil temperature amplitude under G and F, respectively (Fig. 3). In biochar amended plots the soil under G warmed up less during the daylight (lower maxima) and cooled less at nighttime (higher minima) and under F inverse responses were observed. Average soil temperatures were similar irrespective of land use category and biochar application rate whereas the temperature dispersion in biochar amended decreased under G and increased under F.

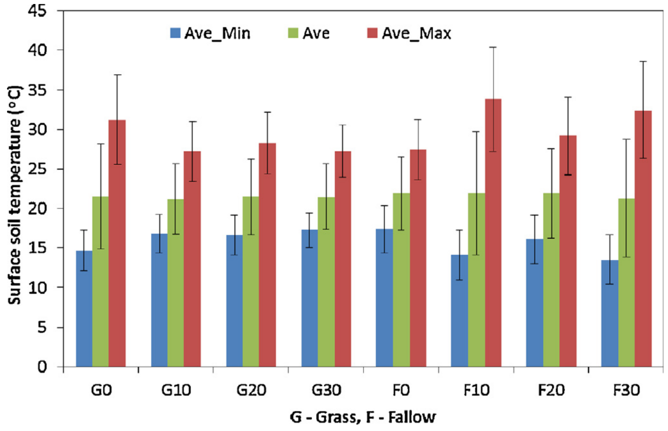

Fig. 3. Average daily minimum (Ave_Min) and maximum (Ave_Max), average (Ave) soil temperatures at depth 2 cm under the grassland and fallow for the period from 9 to 30 August 2013. The bars represent standard deviations.

3.6. Model-predicted thermal conductivity

The results shown in Fig. 4 indicate that the measured thermal conductivities and diffusivities in soil with and without biochar were in most cases within the curves calculated with the statistical-physical model. Some measurement results that are beyond the model-predicted curves may correspond to places with higher or lower soil bulk densities than those used in the model input data. The model data revealed that the rate of the thermal conductivity increase with the increasing soil water content was greater in soil with greater rather than lower bulk density (Fig. 4). The model-predicted thermal conductivity of pure biochar was considerably lower than that for the biochar-amended soil at all the soil water contents. The response of the thermal diffusivity of the biochar-amended soil to the increasing soil water content had a non-linear shape and was more sensitive in the dense than loose soil (bulk density 1.4 vs. 1.0 Mg m^{-3}). It is worth noting that a characteristic maximum of the thermal diffusivity occurs at lower soil water content for the soil with greater rather than lower bulk density.

4. Discussion

4.1. Effect of biochar on soil bulk density

Addition of 20 and 30 Mg ha^{-1} of the biochar under F caused a considerable decrease in soil bulk density and particle density. This can be attributed to soil structure modification and the physical dilution effect of a low bulk density biochar amendment. The decline in the densities was accompanied by the increasing saturated volumetric water content and thus total soil pore volume. The increase in the saturated soil water content can be associated with additional external macropores. Based on findings of hydraulic conductivity, drainable porosity, and soil water content at low tensions (suctions), Hardie et al. (2014) revealed that an increase in the soil pore volume after biochar addition resulted from the formation of large macropores from 300 to 1200 μm. An increase in macroporosity in biochar-amended soil was also reported in other studies (Herath et al., 2013). Formation of macropores was attributed to settling biochar particles between the particles of the soil matrix and earthworm burrowing (Herath

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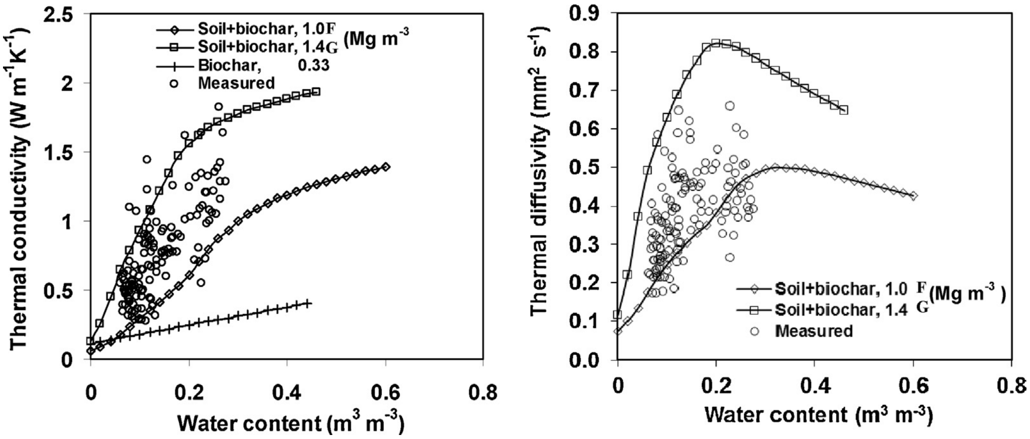

Fig. 4. Thermal conductivity and diffusivity of biochar-amended soil as a function of water content. Soil + biochar with bulk density 1.0 Mg m^{-3} under fallow (F) is indicated by the solid line with the rhombus; soil + biochar with bulk density 1.4 Mg m^{-3} under grassland (G)—by the solid line with squares; pure biochar with bulk density 0.33 Mg m^{-3}—by the solid line with crosses, and the measured data—by open circles.

et al., 2013; Hardie et al., 2014). Some studies have also suggested that the increase in the total soil pore space can be partly due to the contribution of the internal porosity of biochar itself (Liang et al., 2006; Ścisłowska et al., 2015). However, in the study of Hardie et al. (2014), where the internal porosity was removed, the calculated bulk density was significantly lower in the biochar-amended than unamended control soil. This result indicates that the contribution of the internal biochar porosity to the greater total soil pore volume is not obvious. Irrespective of the mechanisms by which biochar influences soil structure, the observed increase in soil porosity and thus the decrease in bulk density in general improves growth conditions for crop production (Hamza and Anderson, 2005) and alters other soil physical characteristics such as soil water content (Conte et al., 2013).

4.2. Effect of biochar on soil thermal properties and temperature

The effect of biochar on the soil thermal properties was related to the type of land use, the form of biochar application, and the type of the thermal property. Bulk density and soil water status are considered to be main factors influencing the thermal properties of a given soil (e.g. Usowicz et al., 2013). Addition of 20 and 30 Mg ha^{-1} biochar under F in our study caused a considerable decrease in the bulk density and, thus, an increase in total porosity along with a slight increase in the soil water content. This suggests that the effect of biochar on reduction of the thermal conductivity and diffusivity can be exerted through increasing soil porosity and content of air, which displays considerably lower thermal conductivity and diffusivity than other soil components. There was no sizeable effect of the biochar on the thermal properties under G, where biochar was applied on the soil surface.

However, the effect of biochar under G was most pronounced in the albedo, especially at short grass cover (6 cm). Decreasing the albedo and thus decreasing the reflectivity in the biochar-amended soil can be due to the dark color of biochar itself, which was further enhanced by the greater water content. Similar albedo values before and after the rain under G suggest that the biochar effect on the soil reflectivity is more persistent in contrast to that under F, where it was substantially decreased following the rain, particularly in plots with the highest biochar rates (F20 and F30). The decrease under F can be a result of mostly darkening as well as smoothing due to rainfalls. During later measurement occasions, including that after the heavy rain, the differences in the albedo between the biochar treatments under G and F diminished possibly due to soil surface protection by taller plants under the former and increased bulk density by an earlier raindrop impact and soil subsidence under the latter. It is worth noting that irrespective of biochar treatment, one day after heavy rain there was observed nearly a 100% increase in the albedo under F, that can be ascribed to sealing, reduction of shading by aggregates and darkening due to solar radiation and drying of surface soil (Genesio et al., 2012; Meyer et al., 2012, Verheijen et al., 2013). However, under G it was reduced under G0 and increased under G30. The results indicate that the effects on albedo are largely mediated by the type of land use and the surface and incorporated biochar application, respectively, under G and F as well as by the biochar application rate. The diverse albedo responses can result in spatial and temporal variability of the surface energy balance and evaporation rate. Using a first-order global energy balance model, Verheijen et al. (2013) showed that the field studies on biochar-albedo relationships are of importance in assessing the biochar climate change mitigation potential and spatiotemporal modeling.

Our results indicate that the thermal conductivity and heat capacity of the mix of all the fractions were greater by 27–33% and 48–68%, respectively, compared to each of the individual fractions in the range from <0.5 to >5 mm. This substantial increase can be caused by the fact that the smaller particles partially fill in the spaces between the larger particles and result in a greater number of contacts between the particles and thus lesser content of air, which has much lower thermal conductivity and heat capacity than organic matter. This explanation can be supported by the greater bulk density of the mix of the fractions from 25% relative to fraction <0.5 mm up to 200% compared to fraction >5 mm. This observation suggests that application of the biochar as mulch in untilled environments in the form of a mix of various biochar fractions may show different thermal performance compared to single size fractions. This aspect needs research under field conditions.

A decrease of the daily soil temperature amplitude in biochar amended plots under grassland can be due to changes in albedo (Fig. 2c,d), interception of the solar radiation and reduced the back-radiation from the soil by vegetation, low thermal conductivity and heat capacity of the biochar (Table 1) and associated slow heat conduction to- and from the soil. The opposite trend of the soil temperature amplitude in of the bare fallow soil can be associated with a decreased albedo (darker soil after addition of biochar) (Fig. 2) and the greater absorption of solar radiation in the surface soil during the daylight and increased heat output at night.

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4.3. Model-predicted thermal properties

The simulations made with the statistical-physical model showed that the soil thermal conductivity and thermal diffusivity increments with the increasing water content of biochar-amended soil were smaller in the soil with low than high bulk density. Reduction of soil bulk density was mostly observed under F due to the addition and incorporation of biochar along with loosening by tillage and the increase in air capacity. These may have resulted in a lower number of contacts between the soil particles and, thus, reduced heat transfer by conduction as the thermal conductivity of air was approximately 24-fold lower than that of water and substantially lower compared to other soil components.

5. Summary and conclusions

The effect of biochar addition on the soil thermal properties and albedo was influenced by the type of land use i.e. grassland and fallow, and the form and rate of biochar application. Biochar amendments to fallow were effective at decreasing bulk density, particle density, thermal conductivity and thermal diffusivity. There was no discernible effect of surface-applied biochar on the soil thermal conductivity and thermal diffusivity under grassland. The changes in heat capacity in response to biochar application were rather small and inconsistent.

Biochar amendments caused reduction of albedo under both grassland and fallow, but increasing grass cover under grassland masked the effect of the biochar. Under fallow the changes in albedo were associated with structure and color of surface soil due to changes in bulk density and soil water content. The daily soil temperature amplitude in biochar amended plots decreased under G and increased under F.

The thermal conductivity, thermal diffusivity and bulk density of the five different textured fractions (<0.5, 0.5–1, 1–2, 2–5 and >5 mm) of pure biochar were substantially lower compared to the mix of all the fractions. The results should be validated under a field study to determine how realistic seasonal fluctuations in temperature and precipitations might influence the effect of particular fractions.

Using a statistical-physical model it was shown that the increase in the thermal conductivity and thermal diffusivity in the biochar-amended soil with increasing soil water content was stronger in the soil with greater than lower bulk density.

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