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Effects of Corn Straw Biochar, Soil Bulk Density and Soil Water Content on Thermal Properties of a Light Sierozem Soil

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ABSTRACT

This research aimed to quantify the effects of biochar derived from corn straw on soil thermal conductivity, capacity, and diffusivity. Firstly, the amount of biochar application (w/w) added to light sierozem soil was 0% to 5%, and the mixtures were packed into soil columns at a consistent bulk density (1.20 g.cm^{-3}). Secondly, soil columns with a consistent biochar addition rate (5%) were packed to different bulk densities of 1.30, 1.25, 1.20, 1.15, and 1.10 g.cm^{-3}. Soil thermal characteristics were measured under the control of soil moisture content from 0% to 40%. Under consistent bulk-density conditions, biochar could significantly reduce soil thermal conductivity and diffusivity. Still, there wasn't a significant influence on soil heat capacity in most soil moisture content levels. With the decrease of soil bulk density, soil thermal conductivity, capacity, and diffusion coefficient reduced significantly. As soil water content increased, all the indexes of thermal properties largely improved, and the effects were much more significant than those of biochar amendment and bulk density change on soil thermal performances. This research could supply an implication to evaluate the influence of biochar amendment on soil thermal performances.

INTRODUCTION

Soil thermal properties, including soil thermal conductivity, heat capacity, and diffusivity, are important parameters affecting the soil profile's energy distribution and heat transfer (Liu et al. 2018b). Many studies have shown that soil temperature changes have important effects on soil physicochemical properties and biochemical processes, such as soil hydrothermal coupling transmission (Zhao & Si 2019), soil organic matter decomposition and mineralization (Nieves et al. 2021, Semenov et al. 2022), plant growth (Yang et al. 2022), and greenhouse gas emission (Nsalambi & Stephanie 2018). Precise information on soil thermal properties are widely used in meteorological and industrial applications (Tong et al. 2021), agricultural management (Mendis et al. 2022), soil physical process simulation (Bayat et al. 2020), and many other fields.

Biochar is a carbon-rich material produced through biomass pyrolysis (such as crop residues and wood wastes) in an anoxic environment (Moreira & Feijoo 2017). Biochar application is a new technology, which has been recognized increasingly because of its potential role in carbon sequestration (Papageorgiou et al. 2021), greenhouse gas mitigation (Khan et al. 2022), soil improvement (Shi et al. 2022, Geng et al. 2022), crop productivity enhancement (Melo et al. 2022, Singh et al. 2022). Recently, the physical effects of biochar amendment on surface albedo and soil temperature have attracted extensive attention. The porous black biochar applied to the soil inevitably makes the soil darker and reduces the soil albedo and solar radiation intensity, thus affecting the soil temperature. Oguntunde et al. (2008) detected that the soil color near a charcoal kiln in Ghana is darker than in the distance. This is attributed to the deposition of the escaping charcoal particles, which reduces the surface reflectance by 37.0% and increases the average surface temperature by 4°C. Ding et al. (2019) showed that soil temperature was more sensitive to external temperature changes after the application of biochar. Liu et al. (2018a) showed that applying biochar significantly reduced soil temperature at 5 cm depth and regulated diurnal temperature fluctuations.

Moreover, Zhang et al. (2017) studied seasonal changes in albedo after biochar application on planted and unplanted farmland. It was found that the influence of biochar on the albedo mainly occurred in winter and was related to crop coverage. Therefore, biochar application in soil plays an important role in soil energy balance and temperature distribution.

Soil thermal properties depend on the soil composition of gas, liquid, and solid in a porous medium (Liu et al. 2018b). In contrast, due to its large surface area and low bulk density, biochar can cause changes in soil structure and composition, which in turn can affect the thermal properties of the soil (Usowicz et al. 2016). However, researches on the influences of biochar on soil heat characteristics are particularly scarce (Usowicz et al. 2016), which limits our knowledge to understand the mechanisms of soil temperature change in the presence of biochar. In addition, soil thermal properties are often closely related to atmospheric temperature (Camilo et al. 2022), especially in the arid and semi-arid regions of the Loess Plateau, which are extremely sensitive to climate change, and land-atmosphere interactions in these regions play an important role in the regional climate (Lu et al. 2022). Therefore, considering the effects of changes in soil bulk density and water content on soil thermal properties during biochar application may be important for the potential of biochar to mitigate climate change. We investigated the effects of corn stover biochar, soil bulk density, and water content on soil thermal properties in the loess region's typical light sierozem soil. This study aims to provide a reference for understanding biochar's contribution to soil thermal properties and objectively evaluate biochar's potential role in soil temperature change.

MATERIALS AND METHODS

Materials

The tested soil was sampled from the 0-20 cm soil layer on a hill at Lanzhou Jiaotong University, China, and was classified as light sierozem soil. The soil specimen was naturally dried and sieved with a 2-mm sieve. And the soil belonged to silty loam. The proportions of sand, silt, and clay particles were 78.85%, 19.25%, and 1.9%, respectively. The soil bulk density was 1.35 $g.cm^{-3}$. The organic matter content of the soil was 20 $g.kg^{-1}$.

The corn straw was obtained from Longnan City, Gansu Province, China. The straw was cleaned with running water, stoved at 80°C for 12 h in a drying oven (101-2A, Cangzhou Sansi times equipment Co., Ltd, Cangzhou, China), then triturated with a lapping machine (JM-F50, Jiangsu Banderi Stainless Steel Co., Ltd, Yancheng, China). The fragments were placed in a muffle roaster (XL-2018, Hebi Wanbo Instrument Co., Ltd, Hebi, China) and pyrolyzed at 500°C for 6 h by oxygen-limiting and temperature-controlling methods. The biochar prepared by the above method had 74.5% C, 18.2% O, 2.5% H, and 0.2% N. The BET-N_2 absorption method determined the specific surface area was 60.87 $m^2{\cdot}g^{-1,}$ and the average intraparticle pore size was 3.74 nm. The particle density of biochar was determined to be 1.18 $g.cm^{-3}$ using the pycnometer method. The biochar bulk density was 0.709 $g.cm^{-3}$.

Experimental Design

The experiments consist of two parts. In the first part, biochar was evenly added to the soil according to certain mass ratios (w/w) 0%, 1%, 2%, 3%, 4%, and 5%. Then, 120 g dry soil-biochar mixtures were weighed and put into 6 plastic columns with the same specifications (inner diameter 5cm, volume 100 cm^{-3}). By this means, the bulk density of soil could be calculated as 1.20 $g.cm^{-3}$. In the second part, the biochar application rate was 5%. The soil-biochar mixtures were packed into plastic columns at bulk densities of 1.10, 1.15, 1.20, 1.25, and 1.30 $g.cm^{-3}$ (110, 115, 120, 125, 130 g dry soil-biochar mixtures were weighed and added to 6 plastic columns with the same specifications). There was a movable cover on top of each plastic column. When it was opened, a sensor could be inserted into the soil from the top to measure the thermal properties of the soil. The soil volumetric moisture content was regulated using a syringe to inject different amounts of water into soil-biochar mixtures from the top of the plastic column. Then, those columns were closed and stored at ambient temperature (20°C) for 72 h to obtain a balance for soil thermal property measurements. The volumetric soil water contents were programmed as 0%, 10%, 20%, 30%, and 40%.

Soil Thermal Properties Determination

The soil thermal characteristics, including thermal conductivity, diffusivity, and capacity, were measured by a KD2Pro man-pack soil thermal characteristics analysis meter which is equipped with an SH-1 double-point sensing element (7% accuracy, 1.3 mm diameter, 3 cm long, and 60 mm spacing, Decagon Devices Inc., Pullman, USA).

Data Analysis

The significance of biochar application's influence on soil thermal characteristics was tested by one-way ANOVA analysis (ANOVA). A least significant difference (LSD) test was used in the multiple comparison tests to study the differences between biochar treatments. Statistical analysis was completed with SPSS 22.0 software (IBM, New York, USA), and the significance level was set as 0.05. Origin 8.0 (OriginLab, Northampton, Massachusetts, USA) was used for the data regression and graphing.

RESULTS AND DISCUSSION

Influences of Biochar Addition on Soil Thermal Characteristics

The soil thermal conductivity at constant bulk density with different soil moisture content levels is revealed in Fig. 1.

The values of soil thermal conductivity reduced with the increase of biochar amendment rate. When the amendment rate is 5%, and the soil moisture content is 0%, 10%, 20%, 30%, and 40%, the values of thermal conductivity are 0.154, 0.446, 0.681, 0.841 and 1.09 W.m^{-1}.K^{-1}, which decrease by 15.4%, 24.5%, 15.9%, 24.2%, and 5.2%, respectively, compared with those values of the control sample. Biochar amendment showed remarkable impacts ($p > 0.05$) on thermal conductivity at all kinds of soil water content. The biochar thermal conductivity was determined as 0.055 W.m^{-1}.K^{-1}, which is far below those of water at 20°C (0.594 W.m^{-1}.K^{-1}) and quartz (7.7 W.m^{-1}.K^{-1}) (Lu et al. 2007). Therefore, biochar application was expected to reduce soil thermal conductivity. In addition, biochar application could increase soil organic matter content (Ondrasek et al. 2019). Soil thermal conductivity is inversely associated with soil organic matter content (Mustamo et al. 2019). Therefore, the reduction of soil thermal conductivity may be due to the increase of soil organic matter content from biochar application.

Fig. 2 shows that soil thermal capacity under diverse biochar application rates hadn't marked a difference in most soil water moisture levels. The volumetric heat capacity of biochar particles is 2.9 J.cm^{-3}.K^{-1}, which is higher than that of mineral particles (1.9 J.cm^{-3}.K^{-1}) and soil organic matter (2.5 J.cm^{-3}.K^{-1}) (Liu et al. 2018b). Therefore, biochar application was expected to increase soil thermal capacity. However, Fig. 2 shows that biochar application in this study mostly had no significant effect on soil thermal capacity. Still, Shang et al. (2015) reported that biochar application increased soil thermal capacity when applied at 40-60 t.hm^{-1}. The lack of a significant increase in heat capacity in this study may be due to the large thermal capacity of soil moisture and the small percentage of biochar, and the small amount of biochar was not enough to change the thermal capacity of the soil.

Fig. 3 shows that the values of soil thermal diffusivity decrease with the biochar amendment rate increasing. When the rate is 5%, and the soil moisture content is 0%, 10%, 20%, 30%, and 40%, the values of soil thermal diffusivity are 0.160, 0.339, 0.374, 0.371, and 0.420 mm^2.s^{-1}, which decrease by 3.6%, 15.3%, 14.0%, 24.0%, and 15.7%, respectively, compared with those values of the control sample. The thermal diffusivity of biochar was 0.165 mm^2.s^{-1}, which was approximately equal to that of soil at 0.166 mm^2.s^{-1} (dry soil with a soil density of 1.20g.cm^{-3}). Still, in most cases in this study, the soil thermal diffusivity decreased with increasing biochar application, which may be related to the alteration of soil porosity by biochar (Hardie et al. 2014, Herath et al. 2013). Although the total porosity of the soil didn't significantly change, biochar application can change the pore size distribution of soil and then lead to the enhancement of soil microbial activity and community, which has been indicated in a lot of research (Zhang & Shen

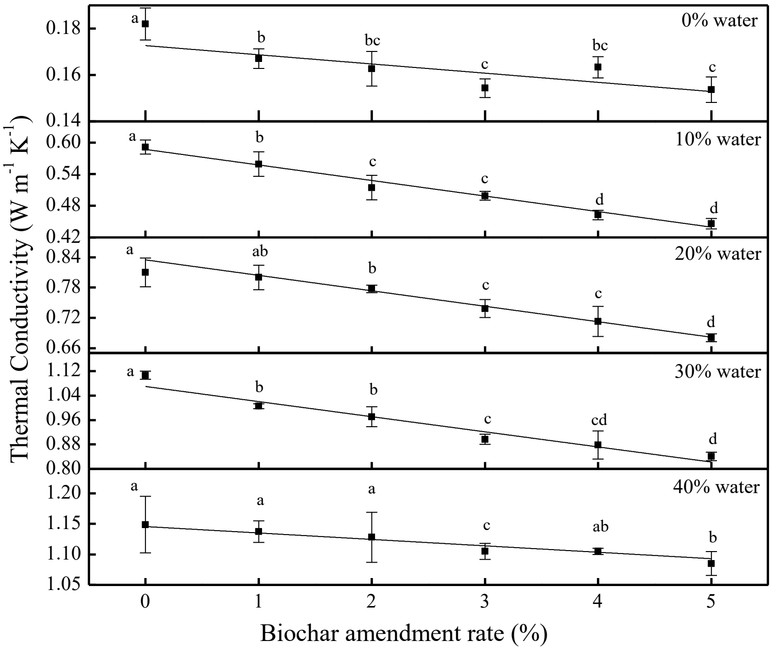

Fig. 1: Influences of biochar addition on thermal conductivity of the soil.

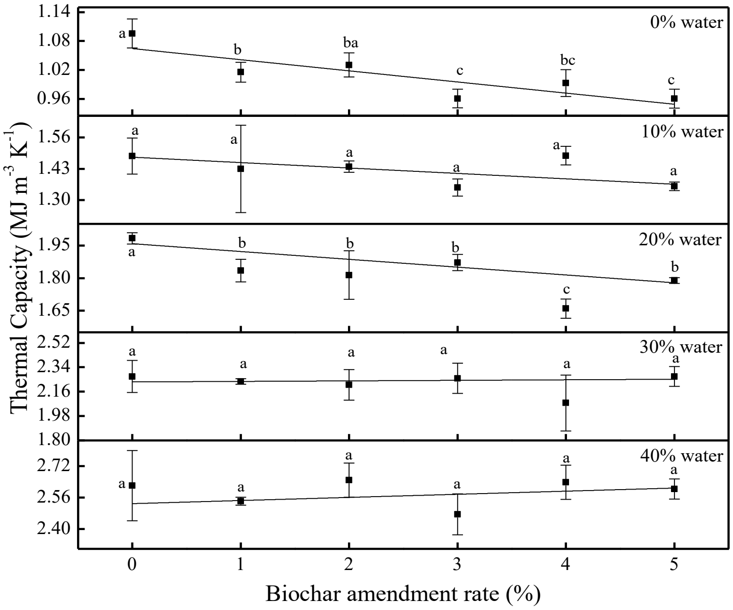

Fig. 2: Influences of biochar addition on soil heat capacity.

2022, Yan et al. 2021). In addition, considering that thermal diffusivity is the ratio of thermal conductivity to thermal capacity when thermal conductivity decreases while thermal capacity remains constant, soil thermal diffusivity inevitably decreases, which is consistent with the values measured in this study.

Influences of Bulk Density on Soil Thermal Characteristics

With soil bulk density reduction, soil thermal conductivity showed the same trend and gradually decreased (Fig. 4). When the water content was kept at 0%, 10%, 20%, 30%, and 40%, soil thermal conductivity decreased from 0.277 to 0.159, 0.555 to 0.480, 0.791 to 0.643, 0.971 to 0.837, and 1.08 to 0.990 W.m^{-1}.K^{-1} with soil bulk density decreasing from 1.30 to 1.10 g.cm^{-3}. Except for the 40% soil water content level, the diverse bulk density gradients in the soil columns had remarkable effects ($p < 0.05$) on soil thermal conductivity. At the same soil water content level, reducing soil bulk density could inevitably lead to increased aerated soil porosity and solid particle reduction. The contact between solid soil particles and water is somewhat isolated, which hinders the heat conduction of the solid and liquid phases. This results in soil thermal conductivity decreasing with soil bulk density reduction. In addition, the air thermal conductivity is only 1% of those of the solid phase and liquid phase in soil, which further hinders heat transfer. Toková et al. (2020) found that the application of biochar significantly reduced soil bulk density (12% reduction) and increased soil porosity (12% increase), while the reduction in soil thermal conductivity was mainly attributed to the biochar-induced reduction in soil bulk density and increase in total porosity (Zhao et al. 2016).

Fig. 5 shows that when the water content was kept at 0%, 10%, 20%, and 30%, the values of soil thermal capacity decreased from 1.22 to 0.948, 1.55 to 1.42, 1.97 to 1.80, and 2.43 to 2.14 MJ m^{-3}.K^{-1} with soil bulk density decreasing from 1.30 to 1.10 g.cm^{-3}. However, when the soil moisture content is 40%, thermal capacity increases with decreasing bulk density, mainly because when the moisture content is too high, water will be abundantly present in the soil pore space, and the lower the bulk density, the higher the soil moisture content, and the greater contribution of moisture to thermal capacity.

Fig. 6 shows that soil bulk density reduction leads to a decrease in soil thermal diffusivity at large. When the water content was kept at 0%, 10%, 20%, 30%, and 40%, the thermal diffusivity of soil decreased from 0.227 to 0.168, 0.343 to 0.328, 0.404 to 0.357, 0.419 to 0.391, and 0.449 to 0.362 mm^{2}.s^{-1} with soil bulk density decreasing from 1.30 to 1.10 g.cm^{-3}.

Influences of Soil Moisture Content on Thermal Characteristics

Soil water content is the most effective and dynamic element, which could affect soil thermal properties (Mengistu et al. 2017, Usowicz et al. 2017). As revealed in Fig. 7,

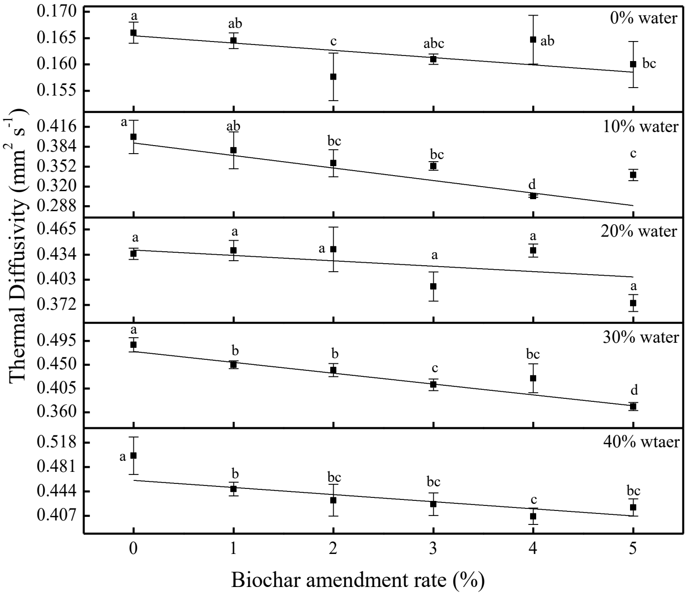

Fig. 3: Influences of biochar addition on soil thermal diffusivity.

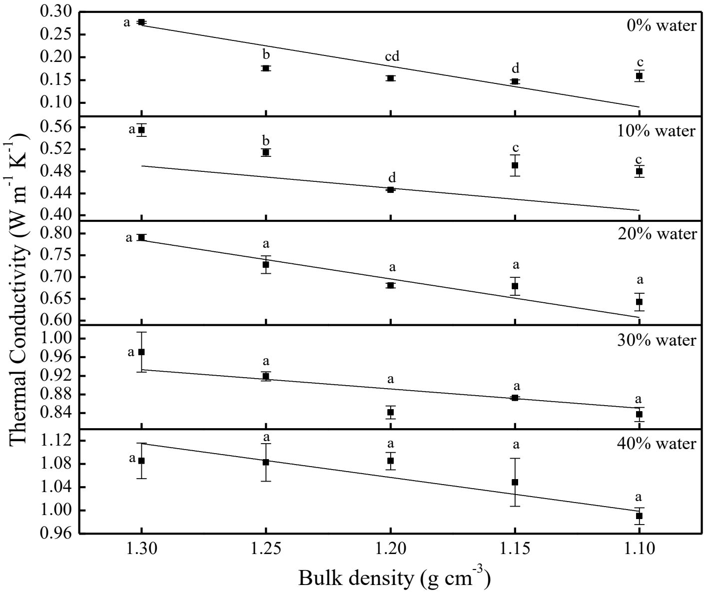

Fig. 4: Effects of biochar addition on thermal diffusivity of the soil.

the influence of soil moisture content on soil thermal characteristics is extremely more significant than those of biochar application and soil bulk density change.

Fig. 7a and Fig. 7b show that soil thermal conductivity increases rapidly with soil moisture content increasing under constant or changing bulk density. Still, with soil water content further increasing, the increasing trend of soil thermal conductivity slows down. When the soil moisture content is 40%, the thermal conductivity values are as high as those of samples with no water amendment. At low soil water content levels, soil thermal conductivity is mainly achieved through the contact between solids. As the water film thickness on the soil particles' surface increases, the contact between soil particles changes from point to surface, and soil thermal conductivity increases instantly. When soil moisture content increases to a certain value (approximately

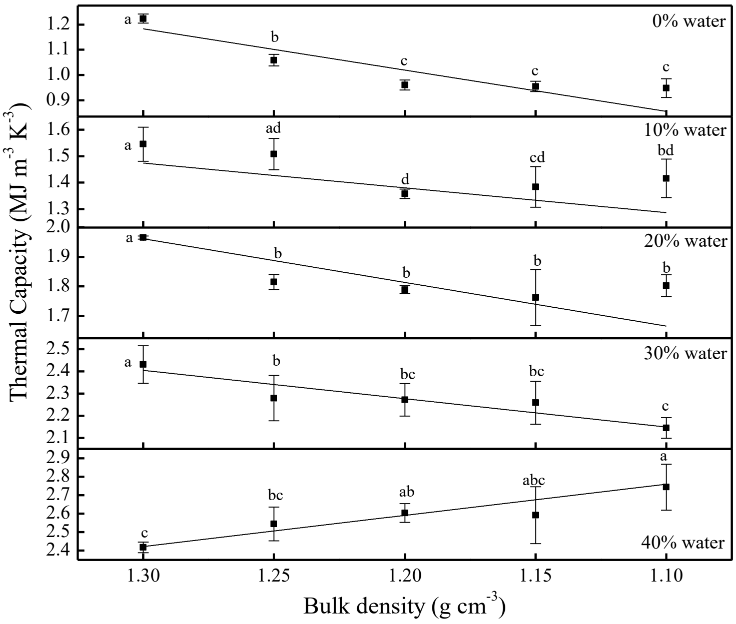

Fig. 5: Effects of bulk density on soil thermal capacity.

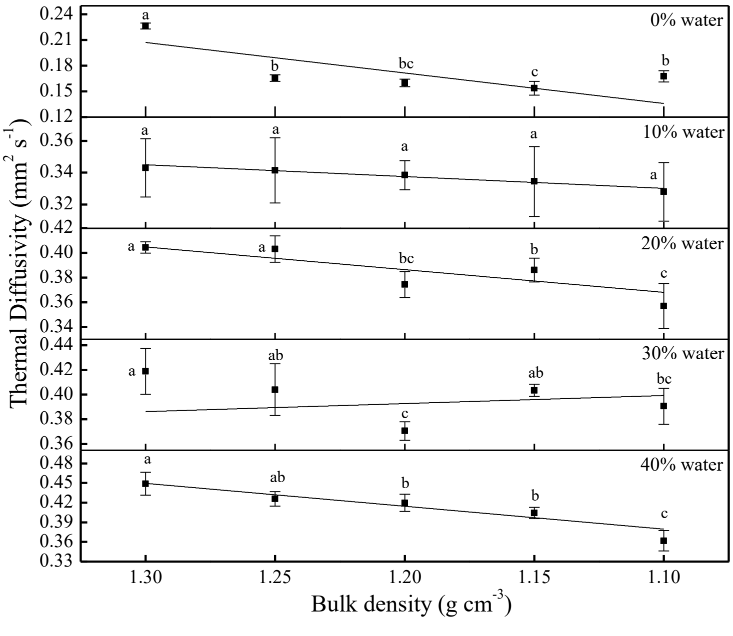

Fig. 6: Effects of bulk density on soil thermal diffusivity.

0.03 $cm^3.cm^{-3}$), the continued increase in moisture mainly exists in capillary water and gravity water. The thermal conductivity increase mainly depends on the volume of water rather than that of air, so the rate of increase is slowed (Fu et al. 2014). The equations reflecting the relation between thermal conductivity and moisture content were obtained by regression with high R^2 values, listed in Table 1.

The soil thermal capacity enhances linearly with soil water content increasing (Fig. 7c and Fig. 7d), mainly because the soil thermal capacity is the sum of the thermal capacities of gas, liquid, and solid phases in soil. The thermal capacity of the water phase in soil increases with soil water content increasing. Although the air content in soil decreases with soil water content increasing, water has a higher heat capacity than air, which makes the decrease in soil thermal capacity caused by the decrease in air content not obvious. The linear equations were obtained and listed in Table 1 with R^2 values more than 0.94.

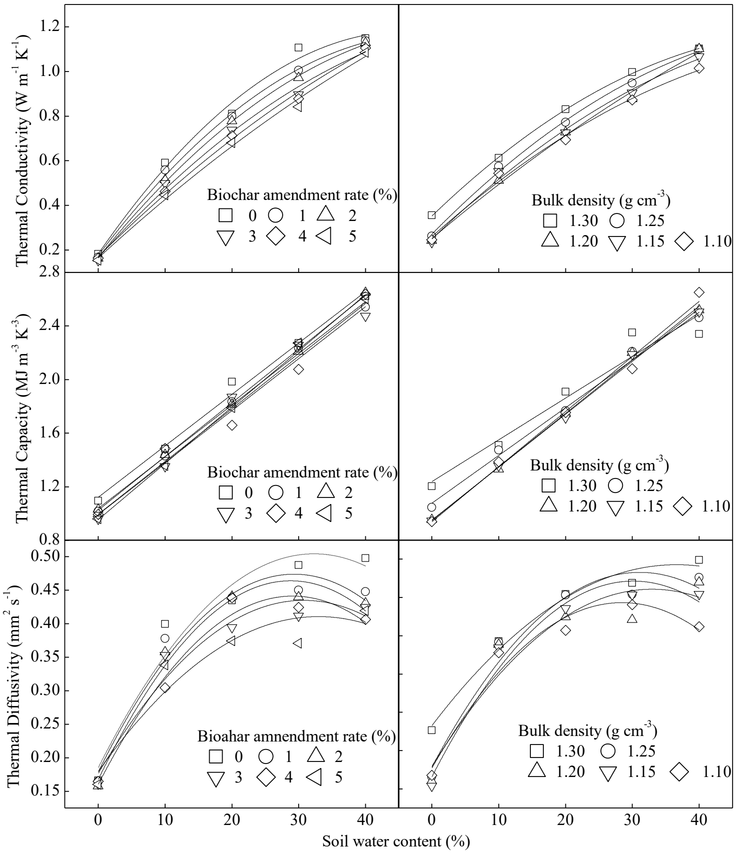

Fig. 7: Influences of soil water content on thermal properties of the soil.

Table 1: Regression results of the relation between the thermal property (y) and moisture content (x).

Runs	Fitting equation											
	Thermal conductivity				Thermal capacity			Thermal diffusivity				
	$y = -ax^2 + bx + c$				$y = ax + b$			$y = -ax^2 + bx + c$				
		a	b	c	R^2	a	b	R^2	a	b	c	R^2
Biochar application rates [%]	0	4.69	0.0432	0.184	0.99	0.0384	1.12	0.99	0.00031	0.0198	0.186	0.95
	1	3.97	0.0397	0.177	0.99	0.0386	1.04	0.99	0.00034	0.0202	0.179	0.97
	2	3.28	0.0370	0.168	0.99	0.0401	1.03	0.99	0.00036	0.0206	0.168	0.98
	3	2.53	0.0293	0.168	0.99	0.0394	0.997	0.98	0.00027	0.0168	0.177	0.95
	4	1.64	0.0295	0.172	0.99	0.0388	0.994	0.98	0.00033	0.0193	0.161	0.98
	5	1.22	0.0275	0.165	0.99	0.0420	0.956	0.99	0.00021	0.0140	0.180	0.91
Bulk density [g.cm^3]	1.30	0.00027	0.0323	0.275	0.99	0.0327	1.26	0.94	1.57	0.0115	0.233	0.98
	1.25	0.00027	0.0329	0.187	0.99	0.0374	1.09	0.99	2.63	0.0164	0.179	0.96
	1.20	0.00012	0.0275	0.165	0.99	0.0420	0.956	0.99	2.13	0.0140	0.1800	0.91
	1.15	0.00024	0.0313	0.163	0.99	0.0415	0.960	0.99	2.81	0.0170	0.167	0.97
	1.10	0.00022	0.0289	0.175	0.99	0.0432	0.947	0.99	2.67	0.0152	0.177	0.97

The relation between thermal diffusivity and moisture content is not a simple linear relationship (Fig. 7e and Fig. 7f). The ratio of thermal conductivity to thermal capacity is thermal diffusivity. Under conditions of low water content, thermal diffusivity rises with moisture content increasing. However, when water content exceeds a certain value (30% v/v), the thermal diffusivity decreases with the moisture content increasing. This occurs because when the soil water content is further increased (the volume ratio is greater than 30%), although the thermal conductivity (numerator) increases, the heat capacity (denominator) increases faster, resulting in the decrease of thermal diffusivity, this is consistent with the study of Liu et al. (2018b). The regression results were also obtained and listed in Table 1 with R^2 values more than 0.91.

CONCLUSIONS

Under constant bulk density conditions, soil thermal diffusivity and conductivity reduced with the increase of biochar application amount. Biochar amendment hadn't an obvious effect on soil thermal capacity. Soil thermal conductivity, capacity, and diffusivity diminished obviously with soil bulk density decrease. However, the influence of water content on soil thermal performances is much more significant than those of biochar application and bulk density change. All soil thermal performance indexes were largely enhanced with soil water content increase.

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