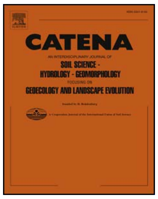
Catena 162 (2018) 29–39

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena



Effects of biochar addition on evaporation in the five typical Loess Plateau soils

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ARTICLE INFO

Keywords:
Biochar
Soil evaporation
Biochar particle size
Loess Plateau soils
Biochar addition amount

ABSTRACT

Soil evaporation is the main route of soil moisture loss and often exceeds precipitation in the arid and semi-arid regions of the Loess Plateau. This study was conducted to determine whether biochar addition could reduce soil evaporation in drylands. We measured the evaporative loss in five typical topsoils (0–20 cm) from the Loess Plateau, Shaanxi, China, that differed in texture (Eum-Orthic Anthrosol, Isohumisol, Loess, Sandy loess, and Aeolian sand) with five different biochar addition amounts (0, 10, 50, 100, and 150 g-biochar/kg soil) and three biochar particle sizes (2–1 mm, 1–0.25 mm, and < 0.25 mm). The results showed that biochar addition generally increased the soil average water content (by 35.6% in biochar treatments and 33.5% in control treatments) and effectively reduced soil cumulative evaporation (by 322.64 g in biochar treatments and 326.68 g in control treatments). In addition, the inhibition of evaporation was enhanced with increases in biochar particle size and addition amount. Biochar addition had contrasting effects in the two evaporation stages: Biochar decreased evaporation through capillary flow during the first stage of evaporation but increased evaporation during the second, diffusion-limited vapour transport stage, particularly in the Aeolian sandy soil. When expressed on a mass basis, the effect of biochar addition amount on the cumulative evaporation (CE) was dependent on biochar particle size. In the larger sized (2–1 mm and 1–0.25 mm) biochar treatments, the final CE decreased as the addition amount increased, but for < 0.25 mm particles, increasing the biochar addition amount increased the final CE due to the creation of micropores. However, biochar addition decreased the ratio of evaporative loss in all soils proportional to the biochar addition amount. Soil texture and biochar particle size were the main factors affecting soil evaporation. Biochar application has the potential to improve soil water availability in semi-arid lands, but the results will depend on the biochar particle size and addition amount.

1. Introduction

According to a report by the National Ministry of Agriculture of China, growing plants and crops is difficult in large areas of China due to water shortages (Zhang et al., 2016). Soil moisture is fundamental to agricultural construction and a key factor in determining the structure and functioning of ecosystems, particularly in arid and semi-arid regions where strong associations exists among the ecosystem productivity, surface energy balance, and water availability (Wu et al., 2014; Ma and Zhang, 2016; Liu and Shao, 2016). Severe drought may result in further soil degradation, i.e., sandification and desertification, which permanently increases evaporative water loss and decreases soil water retention in these lands. To improve the water use efficiency and soil structure characteristics, enhance soil water retention, and prevent desertification, soil amendments have been widely applied to soil (Agegnehu et al., 2015).

Traditionally, China is an agricultural country and has rich forest resources. Huge agricultural and forestry waste, such as crop straw, sawdust, branches and fruit, are produced by agricultural and forestry activities, representing not only a waste of energy (inefficient burning) but also a disaster to the local environment (Zhang et al., 2016). Therefore, how to renewable use of these waste has been a research hotspot. One method involves pyrolysis them and application of the products (i.e., biochar) to soils.

Abbreviations: CE, cumulative evaporation; CRP, constant rate period or stage I; FRP, falling rate period or stage II; final CE, total cumulative evaporation amount including the evaporation in stages I and II; initial CE, cumulative evaporation amount in stage I

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https://doi.org/10.1016/j.catena.2017.11.013
Received 15 December 2016; Received in revised form 29 October 2017; Accepted 8 November 2017

Table 1
Physical properties of experimental soils.

Soil type	Sampling site	Sand content (2–0.02 mm)/%	Silt content (0.02–0.002 mm)/%	Clay content (< 0.002 mm)/%	Soil texture	Soil bulk density (g/cm^3)
Eum-Orthic Anthrosol	Experimental field of ISWC,CAS Yangling county	32.55	35.08	32.36	Loamy clay	1.48
Isohumisol	Experimental field of Agricultural ecological experimental station, Changwu county	36.38	33.27	30.35	Loamy clay	1.48
Loess soil	Experimental field of soil and water conservation experimental station, Ansai county	60.61	20.51	18.88	Sandy clay loam	1.22
Sandy loess	Farmland of Mizhi village, Mizhi county	70.14	16.41	13.45	Sandy loam	1.25
Aeolian sand	Forest land in Liudaogou watershed, Shenmu county	92.15	4.52	3.34	Sand	1.56

Biochar is a carbon-rich product of the thermal decomposition of organic materials under a limited oxygen supply and at a relatively low temperature (< 700 °C) (Lehmann et al., 2006; Yan et al., 2010; Wang et al., 2017). The application of biochar as a soil amendment or slow-release fertilizer carrier or for carbon sequestration has recently attracted substantial attention (Marris, 2006; Lehmann, 2007) because biochar has a complex structure, extensive porosity, and a large specific surface area with rich organic functional groups that can improve the physical and chemical properties of soil (Sohi et al., 2009; Lehmann et al., 2011; Li et al., 2011). Increasing numbers of researchers have reported a significant increase in the water holding capacity of soil after biochar addition (Baronti et al., 2014; Zhang et al., 2016). Furthermore, biochar may enhance agricultural production due to its ability to absorb and retain nutrients in soil (Lentz and Ippolito, 2012), reduce the soil bulk density and increase the diversity and abundance of the soil biological community (Herath et al., 2013; Gong et al., 2008; Gomez et al., 2014; Kolb et al., 2009; Warnock et al., 2007). Biochar can also enhance soil porosity and water permeability, thus improving the soil water holding capacity (Herath et al., 2013; Kumari et al., 2014). Biochar has a moisture absorption capacity that is 1–2 orders of magnitude higher than that of soil organic matter (Accardi-Dey and Gschwend, 2002). The potential of biochar to improve water-holding capacity has been widely recognized (Asai et al., 2009; Lehmann and Joseph, 2009; Zheng et al., 2012; Akhtar et al., 2014; Wong et al., 2017).Therefore, biochar may play an important role in improving soil water relationships in agricultural systems, particularly the systems in the Loess Plateau.

The addition of biochar to soil will inevitably alter the physical and chemical properties of the soil (Liu et al., 2012; Herath et al., 2013), thereby affecting soil moisture and evaporation processes. Evaporation is a catenary physical process in which soil moisture flows through the soil surface in the form of water vapour into the atmosphere, and it is an essential part of the transformation of water from soil to surface water vapour in the soil-plant-atmosphere system (Zhao and Wu, 2004; Novák, 2012). In semi-arid environments, soil evaporation can exceed precipitation and limit normal vegetative growth (Alizai and Hulbert, 1970; Onder et al., 2009; Van Wesemael et al., 1996). Reducing soil evaporation is essential to maintaining agricultural production in arid areas (Raz-Yaseef et al., 2010).

Soil evaporation is characterized by two periods (Lehmann et al., 2008). A period with an initially high and relatively constant rate is termed stage I evaporation, which is supported by internal capillary flow (the constant rate period, CRP) (Yiotis et al., 2006). After a certain period (or mass loss), this CRP is followed by a period with a lower and gradually decreasing evaporation rate (stage II), reflecting a transition to diffusion-limited vapour transport (the falling rate period, FRP) (Bond and Willis, 1969; Or et al., 2013). Recently, increasing numbers of researchers have begun to consider the influence of biochar characteristics, such as the feedstock, pyrolysis temperature, particle size, amount added, intra-particle porosity, shape, and plasticity on soil evaporation (Eibisch et al., 2015; Hardie et al., 2014). Ibrahim et al. (2017) applied conocarpus biochar in sandy loam soil and found the cumulative evaporation was the lower (32.2–35.5 mm) in the biochar-treated soil than in the non-treated soil (40.9 mm), which suggested that biochar can reduce soil evaporation. But Zhang et al. (2016) found that adding biochar powder to sandy soil did not decrease the water evaporation loss, it may be related to soil texture and biochar particle size. Xu et al. (2016) reported that biochar effectively restricted soil evaporation at a low addition amount (5%) but promoted it at a high addition amount. Therefore, it is not clear whether the increase in water holding capacity after biochar addition can be maintained through the entire evaporation processes (Karhu et al., 2011). Furthermore, the effects of the particle size and addition amount of biochar on soil evaporation are also unclear. Evaporation is a comprehensive function that involves multiple soil properties, such as the soil texture and particle size distribution (Qiu et al., 1998), applying the biochar affects these properties, especially the soil porosity and its distribution via

Table 2
Physicochemical properties and surface characteristics of the biochar.

Physical and chemical properties	Unit	Value	Surface characteristics	Test item	Value	Unit
pH		8.96 ± 0.08	Surface area	BET surface area	17.807	m^{2}·g^{-1}
Electrical conductivity	/μs·cm^{-1}	790.0 ± 4.04		Langmuir surface area	23.734	
Cation exchange capacity	/cmol·kg^{-1}	35.74 ± 1.66		BJH Adsorption cumulative surface area	6.142	
Total carbon	/g·kg^{-1}	196.49 ± 15.02		BJH Desorption cumulative surface area	7.564	
Total nitrogen	/g·kg^{-1}	2.34 ± 0.01	Pore volume	Single point adsorption total pore volume	0.08	cm^{3}·g^{-1}
Nitrate nitrogen	/mg·L^{-1}	5.09 ± 0.56		BJH Adsorption cumulative volume	0.076	
Ammonium nitrogen	/mg·L^{-1}	401.80 ± 29.19		BJH desorption cumulative volume	0.075	
Particle composition	2–0.02 mm/%	92.94	Pore size	Total adsorption average pore width	17.958	nm
	0.02–0.002 mm/%	5.89		BJH Adsorption average pore width	49.66	
	< 0.002 mm/%	1.16		BJH Desorption average pore width	40.322	

Table 3
Soil water content of each treatment.

Biochar size	Biochar addition amount (g/kg)	Water content (%)				
		Eum-Orthic Anthrosols	Isohumisols	Loessal soil	Sandy loessal soil	Aeolian sandy soil
	CK (0)	37.64 ± 0.11e	36.59 ± 0.11bc	37.42 ± 0.11f	36.26 ± 0.10bc	19.34 ± 0.06f
2–1 mm	10	38.00 ± 0.11e	35.65 ± 0.10c	38.38 ± 0.11ef	36.08 ± 0.10c	19.52 ± 0.06f
	50	38.63 ± 0.11e	37.12 ± 0.11bc	38.50 ± 0.11ef	36.29 ± 0.10bc	21.31 ± 0.06e
	100	39.82 ± 0.11d	37.97 ± 0.11ab	39.52 ± 0.11de	36.42 ± 0.11bc	22.02 ± 0.06d
	150	41.17 ± 0.12bc	38.37 ± 0.11ab	39.57 ± 0.11e	34.94 ± 0.10c	23.38 ± 0.07c
1–0.25 mm	10	37.86 ± 0.11e	36.79 ± 0.11bc	38.75 ± 0.11e	35.47 ± 0.10c	19.98 ± 0.06f
	50	39.77 ± 0.11d	38.03 ± 0.11ab	39.30 ± 0.11e	36.25 ± 0.10c	22.14 ± 0.06d
	100	41.36 ± 0.12bc	38.85 ± 0.11ab	40.70 ± 0.12 cd	37.23 ± 0.11b	24.39 ± 0.07b
	150	41.75 ± 0.12b	39.89 ± 0.12a	41.31 ± 0.12bc	39.23 ± 0.11a	24.85 ± 0.07b
< 0.25 mm	10	37.09 ± 0.11e	35.64 ± 0.10c	39.14 ± 0.11e	35.93 ± 0.10c	19.56 ± 0.06f
	50	40.34 ± 0.12 cd	36.95 ± 0.11bc	41.41 ± 0.12bc	37.35 ± 0.11b	23.12 ± 0.07c
	100	43.10 ± 0.12a	36.92 ± 0.11bc	42.14 ± 0.12bc	39.48 ± 0.11a	26.11 ± 0.08a
	150	43.94 ± 0.13a	38.58 ± 0.11ab	43.29 ± 0.12a	39.72 ± 0.11a	26.95 ± 0.08a

Note: The lowercase letters in the table indicate the significant difference between the same indexes, $P < 0.05$.

biochar's particle size, different particle sizes and addition amounts will thus differentially affect the evaporation process. However, there are few reports regarding the effects of biochar particle size and addition amount on soil evaporation in different soil types on the Loess Plateau. Therefore, we investigated evaporative processes in five typical soil types (Eum-Orthic Anthrosol, Isohumisol, Loess, Sandy loess, and Aeolian sand) of the Loess Plateau at five different biochar addition amounts (0, 10, 50, 100, and 150 g-biochar/kg soil) and three particle sizes (2–1 mm, 1–0.25 mm, and < 0.25 mm) via soil column simulation experiments in the laboratory. The objectives of this study were to (1) determine whether biochar addition could reduce or increase soil evaporation, (2) quantify the general effects of biochar on the two soil evaporation stages, and (3) analyse the primary and secondary effects of the particle size and addition amount of biochar on soil evaporation. We hypothesized that biochar would decrease evaporation for all soils proportionally to biochar addition rate and that smaller particles of biochar would reduce soil evaporation more than larger particles. Elucidating the mechanisms of biochar's effects on soil water evaporation can help inform selection of the appropriate biochar and application method. It would play important roles in guiding the use of biochar as a soil amendment to reduce soil water evaporation in arid regions.

2. Materials and methods

2.1. Soil and biochar

A laboratory experiment was conducted in the artificial drought simulation hall of the Institute of Soil and Water Conservation (ISWC), Chinese Academy of Sciences (CAS), located in Yangling, Shaanxi Province, China. Five temperate soils varying in texture were collected from five field sites in the Loess Plateau. The basic physical properties of the five soils are shown in Table 1.

Biochar derived from a mixed source of trees, including poplar, elm, pagoda, and apple, was produced through rapid pyrolysis (550 °C, 4 h) by the YIXIN Bioenergy Technology Co. Ltd. (Yangling, Shaanxi, China). The carbon content of this biochar was 83.24 ± 2.36%, determined by the dry combustion method (800 °C). The biochar was sealed in airtight plastic bags after being sieved into three sizes (2–1 mm, 1–0.25 mm, and < 0.25 mm).

The soil mechanical components were measured using an MS-2000 laser particle size analyser (Malvern Instruments Ltd., Malvern, UK). The images of a biochar particle were obtained at 2000-fold magnification using a JSM-6510LV scanning electron microscope (JEOL Ltd., Tokyo, Japan). The specific surface area and pore size of the biochar were measured on a V-Sorb 2800P (Gold APP Instrument Corporation Ltd., Beijing, China) specific surface area and pore size analyser. The infrared spectra of biochar was obtained using a Vertex70 transform infrared spectrometer (FTIR) (Bruker Ltd., Beijing, China). The basic physicochemical properties and surface characteristics of the biochar are shown in Table 2, and the characterization results are shown Figs. S1–S3.

2.2. Treatments and measurements

Three particle sizes of biochar (2–1 mm, 1–0.25 mm, and < 0.25 mm) at five addition amounts (0, 10, 50, 100, and 150 g/kg, equivalent to a field application of 0, 26, 130, 260, and 390 t biochar/ha, respectively) were mixed with the five soils with three replicates, resulting in 65 treatments and a total of 195 specimens. The samples columns from the same soil treatment were packed according to its field bulk density. Each PVC cylinder (10 cm height × 10 cm) was filled layer by layer to ensure the uniformity of the whole soil column. The level of zero g-biochar/kg soil served as the control treatment (CK).

The experiment was conducted with the soil columns without

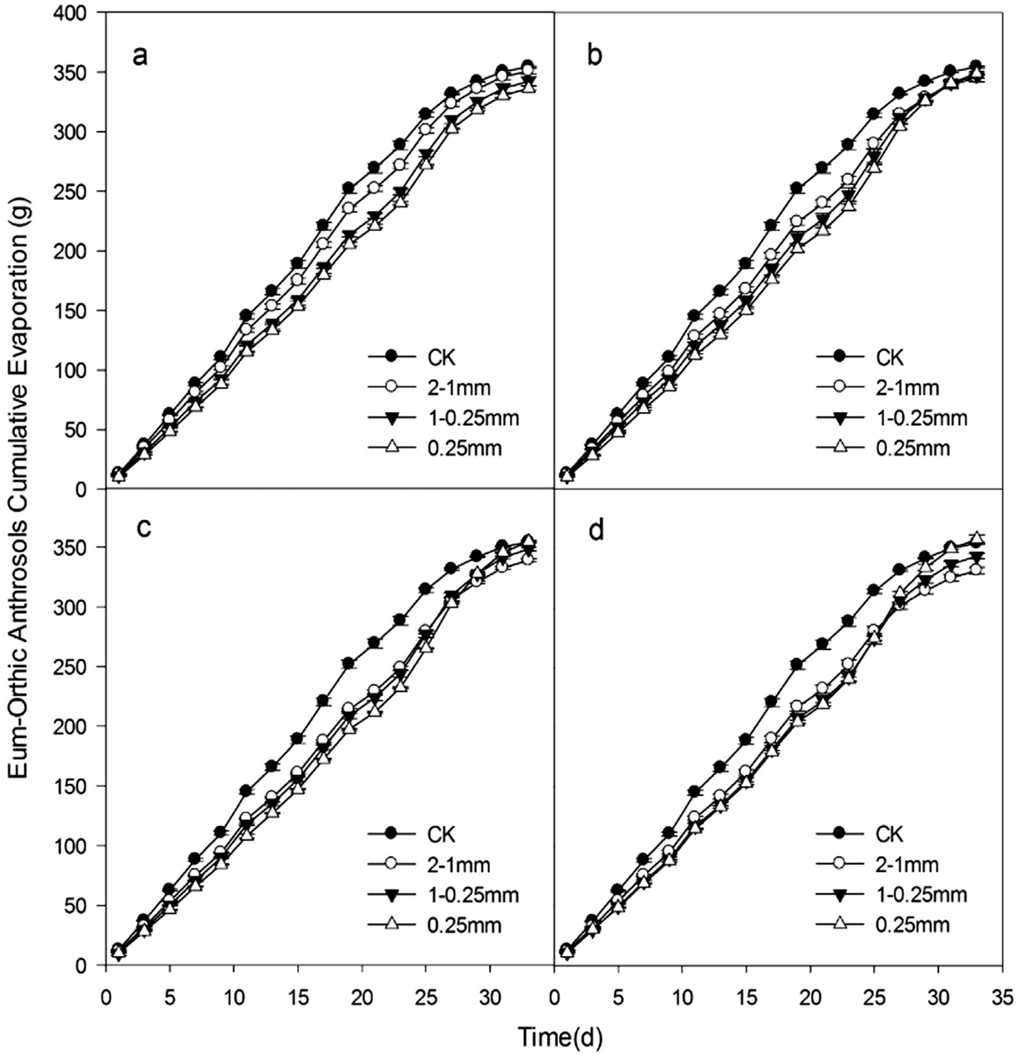

Fig. 1. Cumulative soil evaporation of Eum-Orthic Anthrosols under different treatments. CK is control treatment, 2-1 mm, 1–0.25 mm and 0.25 mm is biochar size respectively. "a" "b" "c" "d" denote biochar addition amounts are 10, 50, 100, and 150 g biochar/kg soil respectively.

human disturbance in an indoor laboratory environment. The bottom of each cylinder was sealed with cotton gauze. Distilled water was used to prevent the ions contained in water from influencing the soil structure and evaporation. Each soil column was wetted from the bottom by capillary action (self-absorption method) until the top surface of the soil column was wetted and then soaked for 24 h to ensure saturation. Meanwhile, the top of the soil column was covered with plastic film to prevent evaporative loss. The saturated soil column was drained for 24 h to ensure field capacity, and the bottom of the soil column was then sealed with plastic film.

The soil water content was determined gravimetrically at 16:00 every two days by the drying method. The measurement accuracy was ± 0.01 g, and the entire experiment spanned 33 days. The laboratory temperature was 20 ± 5 °C as determined by thermometer, and the relative humidity was 40–60%. The soil water content of each treatment is shown in Table 3.

2.3. Data analysis

According to soil water balance method, the cumulative evaporation (CE_i) was calculated as follows:

$$CE_i = W_0 - W_i \quad (i = 1, 3, \ldots 33) \tag{1}$$

where W_0 is the initial weight of the soil column in the beginning of the experiment, and W_i is the weight of the soil column on the ith day.

Since the initial soil water content of each treatment was different and increased with biochar addition, the data were averaged to evaluate what biochar size and addition amount were most useful for inhibiting soil evaporation. We used the ratio of evaporative loss (the proportion of the final CE to the initial water content of the soil, Li and Li, 1991) as a more appropriate index to illustrate evaporative effects. If the ratio is high, the treatment is relatively prone to water evaporation.

The evaporative loss ratio (R) was calculated as follows:

$$R = \frac{M_1}{M_2} \tag{2}$$

where M_1 is the final CE of water (g) and M_2 is the initial water content (g) absorbed by the soil column.

One-way ANOVA using SPSS 17.0 software was conducted to compare the means of the measured values at $P < 0.05$ for each treatment. Multiple comparisons were also performed in SPSS 17.0. Tests of between-subjects effects were conducted using a general linear model. Differences between treatments were considered significant at P-value < 0.05 based on the LSDs (least-significant differences).

3. Results

3.1. Biochar properties

Fig. S1 shows an uneven surface of biochar that is enriched with particles with pores in between and that has a squamous texture and chaotic arrangement. These pores are important, providing a large

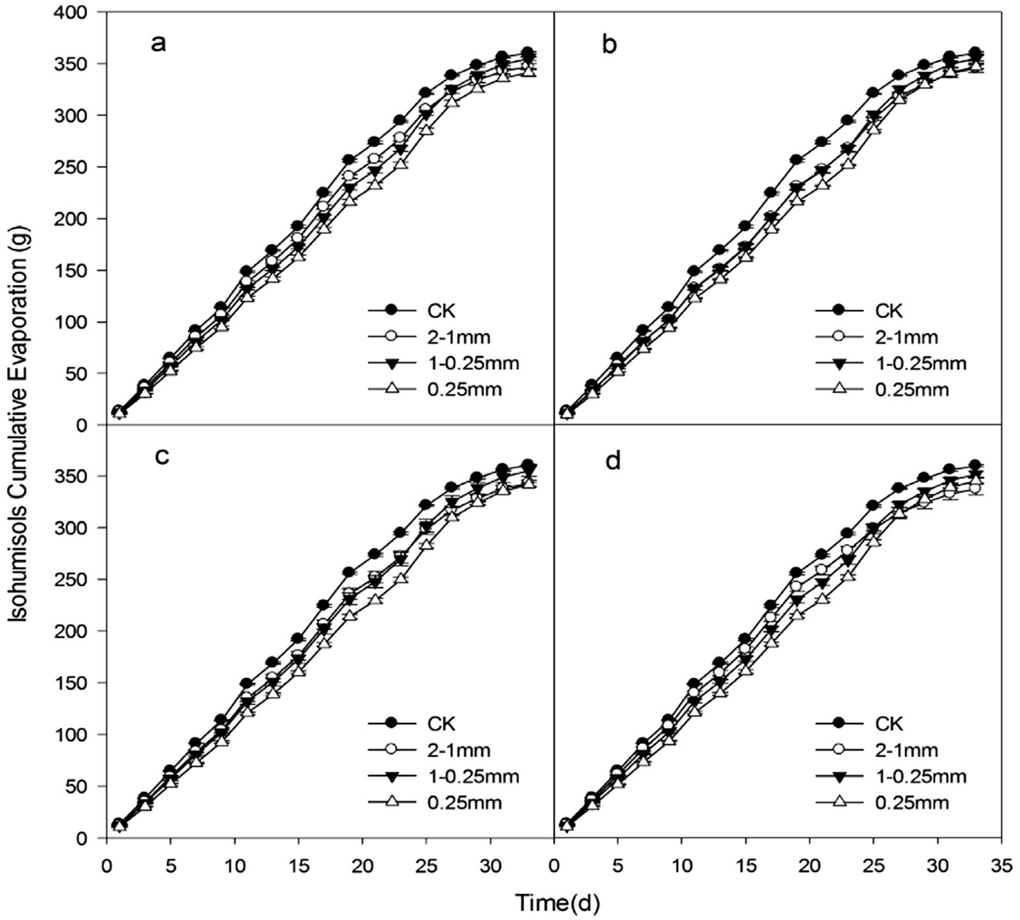

Fig. 2. Cumulative soil evaporation of Isohumisols under different treatments.
CK is control treatment, 2–1 mm, 1–0.25 mm and 0.25 mm is biochar size respectively.
"a" "b" "c" "d" denote biochar addition amounts are 10, 50, 100, and 150 g biochar/kg soil respectively.

surface area and facilitating strong adsorption. Fig. S2 shows the biochar pore size distribution is concentrated near the mesopores. The pores were highly elliptical, suggesting that the original porous structure of the wood feedstock had become distorted during pyrolysis. Most pore sizes were distributed between 1.7 nm and 53.6 nm (due to pore elongation). Fig. S3 shows FTIR spectrograms of biochar. It could found that biochar has −OH ($3418\ \mathrm{cm}^{-1}$), aromatic acids −COOH ($1697\ \mathrm{cm}^{-1}$), the amide stretching vibration of −C=O base ($1650\ \mathrm{cm}^{-1}$), NH_4^+($1396\ \mathrm{cm}^{-1}$), and aromatic compounds such as pyridine and indole ($500–900\ \mathrm{cm}^{-1}$) groups, indicating that the biochar surface has abundant functional groups. These functional groups are representative of hydrophilic groups, such as hydroxy group (−OH), carboxyl group (−COOH) and amino group (NH_4^+). It implies that biochar has the surface hydrophilicity. Table 2 shows that biochar contains abundant chemical elements and had a large specific surface area, with the BET surface area reaching 17.807 m^2/g.

3.2. Effects of biochar addition on the soil water content of different soils

Table 3 presents the soil water content for each experimental treatment, clearly illustrating that biochar addition can increase the soil water content: average water content in the biochar treatments (35.6%) was higher than that in the control treatments (33.5%). Specifically, average water contents of the biochar treatment was 40.2% for Eum-Orthic Anthrosols (CK = 37.6%), 37.6% for Isohumisols (36.6%), 40.2% for Loessal soil (37.4%), 37.0% for Sandy loessal soil (36.3%), 22.8% for Aeolian sandy soil(19.3%). At the same biochar particle size, all soil water contents increased with increasing biochar addition amount. For example, at 2-1 mm biochar particle size treatment in Eum-Orthic Anthrosols, soil water content also increasing from 38.0% to 41.2% as the addition amount increased from 10 g/kg to 150 g/kg. This pattern was observed in all of the treatments, implying that greater biochar addition enhances soil moisture retention within an appropriate range. At the same biochar addition amount, the soil water content generally increased with decreasing biochar particle size in the different soil types, except for Eum-Orthic Anthrosols soil at 10 g/kg and Isohumisol. In the Eum-Orthic Anthrosol, Loess, Sandy loess and Aeolian sandy soils, the highest soil water content was detected the in treatment with < 0.25 mm biochar added at 150 g/kg, but the highest soil water content in Isohumisol was detected in the treatment with 1–0.25 mm biochar added at 150 g/kg. This difference may be related to the soil type and biochar particle size.

3.3. Effects of biochar addition on the two-stage CE processes of different soils

We observed the effects of biochar on evaporation process in all soils (Figs. 1–5). It could be clearly found the effects of biochar on the CE of soils had two distinct evaporation stages, initially decreasing and later increasing soil evaporation. Biochar significantly reduced the CE in the initial stage of evaporation in all soils. Overall, the average final CE in the biochar treatments was 322.64 g and in the control treatments was 326.68 g. The transition point (i.e., time) between the two evaporation stages was earlier in Aeolian sandy soil (day 15, Fig. 5) than in the other four soils (Eum-Orthic Anthrosol, Isohumisol, Loessal, and Sandy loessal soils, day 19, Figs. 1–4). Moreover, final CE of the other four soils, ranging from 330 g to 360 g, was directly proportional to the clay content ($R^2 = 0.778$, $P = 0.118$).

In stage I, which occurred before the 15th day of evaporation in Aeolian sandy soil and before the 19th day in the remaining soils, biochar reduced the initial soil CE by 16.0% in Eum-Orthic Anthrosols ($P < 0.001$), 11.0% in Isohumisols ($P < 0.001$), 14.8% in Loessal soil

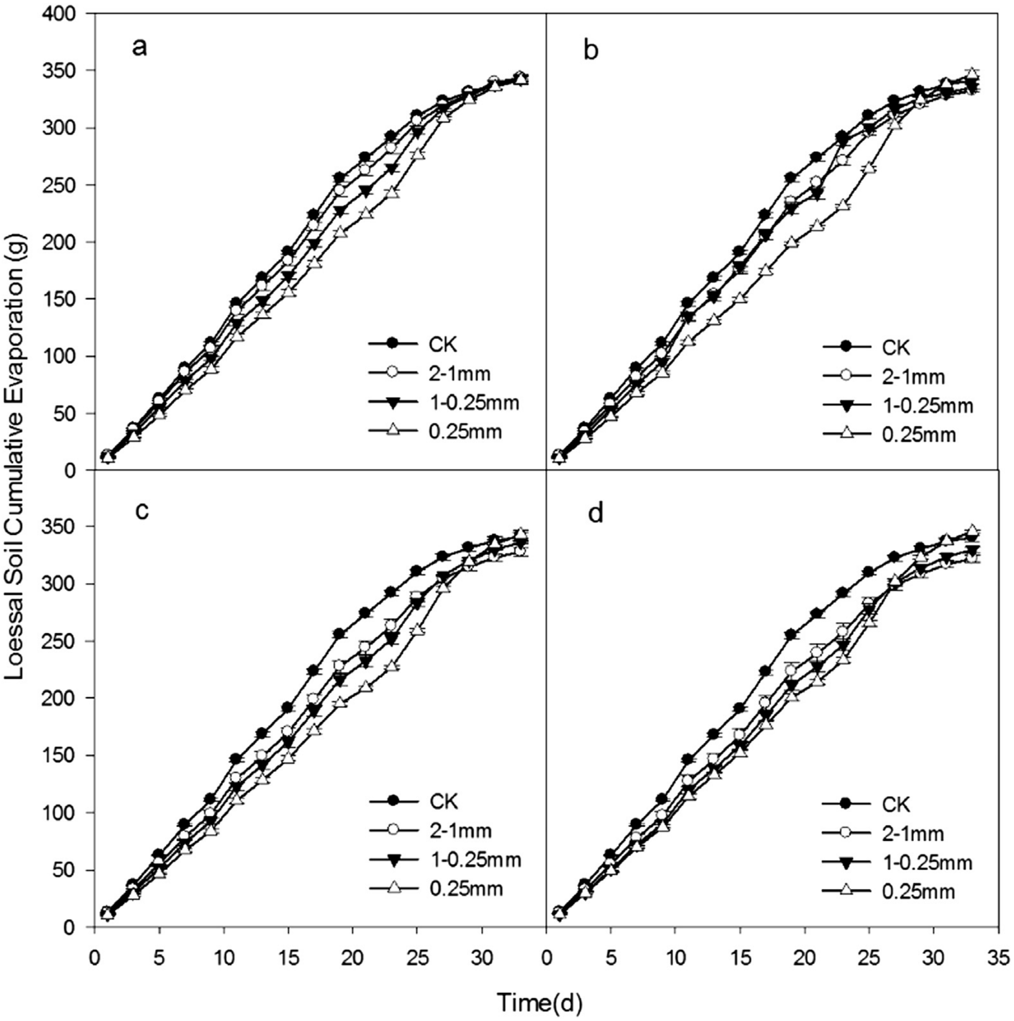

Fig. 3. Cumulative soil evaporation of Loessal soil under different treatments.
CK is control treatment, 2–1 mm, 1–0.25 mm and 0.25 mm is biochar size respectively.
"a" "b" "c" "d" denote biochar addition amounts are 10, 50, 100, and 150 g biochar/kg soil respectively.

(P < 0.001), 13.3% in Sandy loessal soil (P < 0.001), and 13.7% in Aeolian sandy soil (P < 0.001). However, in stage II (after the 15th day in the Aeolian sandy soil and after the 19th day in all other soils), biochar significantly increased the CE significantly by 14.4% in Eum-Orthic Anthrosols (P < 0.001), 38.7% in Isohumisols (P < 0.001), 33.7% in Loessal soil (P < 0.001), 21.7% in Sandy loessal soil (P < 0.001), and 95.0% in Aeolian sandy soil (P < 0.001).These contrasting effects in the two stages resulted in small differences in the final CE. Biochar addition decreased the final CE by 2.5% in Eum-Orthic Anthrosols (P = 0.002), 3.7% in Isohumisols (P < 0.001), 1.2% in Loessal soil (P = 0.110), and 3.6% in Sandy loessal soil (P = 0.001), but it increased the final CE by 7.7% in Aeolian sandy soil (P = 0.01).

3.4. *Effects of biochar particle size on soil CE*

The effects of biochar size on soil CE were also different in the two evaporation stages (Figs. 1–5). In stage I, the biochar in the different size classes significantly reduced the soil CE by an average of 18.5% (< 0.25 mm, P < 0.001), 13.4% (1–0.25 mm, P < 0.001), and 9.3% (2–1 mm, P < 0.001) in the five soils relative to CE of the control treatments. However, in stage II, CE significantly increased across all soil types by an average of 64.1% (P < 0.001) with the < 0.25 mm diameter biochar, 39.7% with the 1–0.25 mm biochar (P < 0.001), and 6.4% with the 2–1 mm biochar (P < 0.001) compared with the control treatments.

Due to the interaction between the two stages of evaporation, the effect of biochar size on the final soil CE was also varied. At the average biochar addition amount, in Eum-Orthic Anthrosols, < 0.25 mm, 1–0.25 mm, and 2–1 mm biochar decreased the final CE by 1.4%, 2.5%, and 3.6%, respectively (Fig. 1). In Isohumisols, < 0.25 mm, 1–0.25 mm, and 2–1 mm biochar decreased the final CE by 4.6%, 1.7%, and 4.7%, respectively (Fig. 2). In Loessal soil, < 0.25 mm biochar increased the final CE by 0.9%, whereas 1–0.25 mm and 2–1 mm biochar decreased the final CE by 1.5% and 2.8%, respectively (Fig. 3). In Sandy loessal soil, < 0.25 mm, 1–0.25 mm, and 2–1 mm biochar decreased the final CE by 1.2%, 4.7%, and 4.8%, respectively (Fig. 4). In Aeolian sandy soil, < 0.25 mm, 1–0.25 mm, and 2–1 mm biochar increased the final CE by 14.5%, 8.2%, and 0.6%, respectively (Fig. 5). The effect of biochar size on the soil CE was affected by the soil type. In Eum-Orthic Anthrosols, Isohumisols, Loessal soil, and Sandy loessal soil, the 2–1 mm biochar decreased evaporation more than the 1–0.25 mm and < 0.25 mm biochar. However, in the Aeolian sandy soil, the fine (< 0.25 mm) biochar increased evaporation more than the other two biochar particle sizes.

3.5. *Effects of biochar addition amount on soil CE*

The effect of the amount of biochar addition on the CE was dependent on the soil type and biochar particle size (Fig. 6). Comparing Fig. 6(a) and (c) reveals that regardless of the soil type and biochar particle size, the initial CE decreased with decreasing amount of biochar addition in stage I of evaporation. Fig. 6(b) shows that the final CE of Eum-Orthic Anthrosols, Isohumisols, Loessal soil, and Sandy loessal soil was decreased by 10.03 g, 15.08 g, 8.28 g, and 15.47 g,

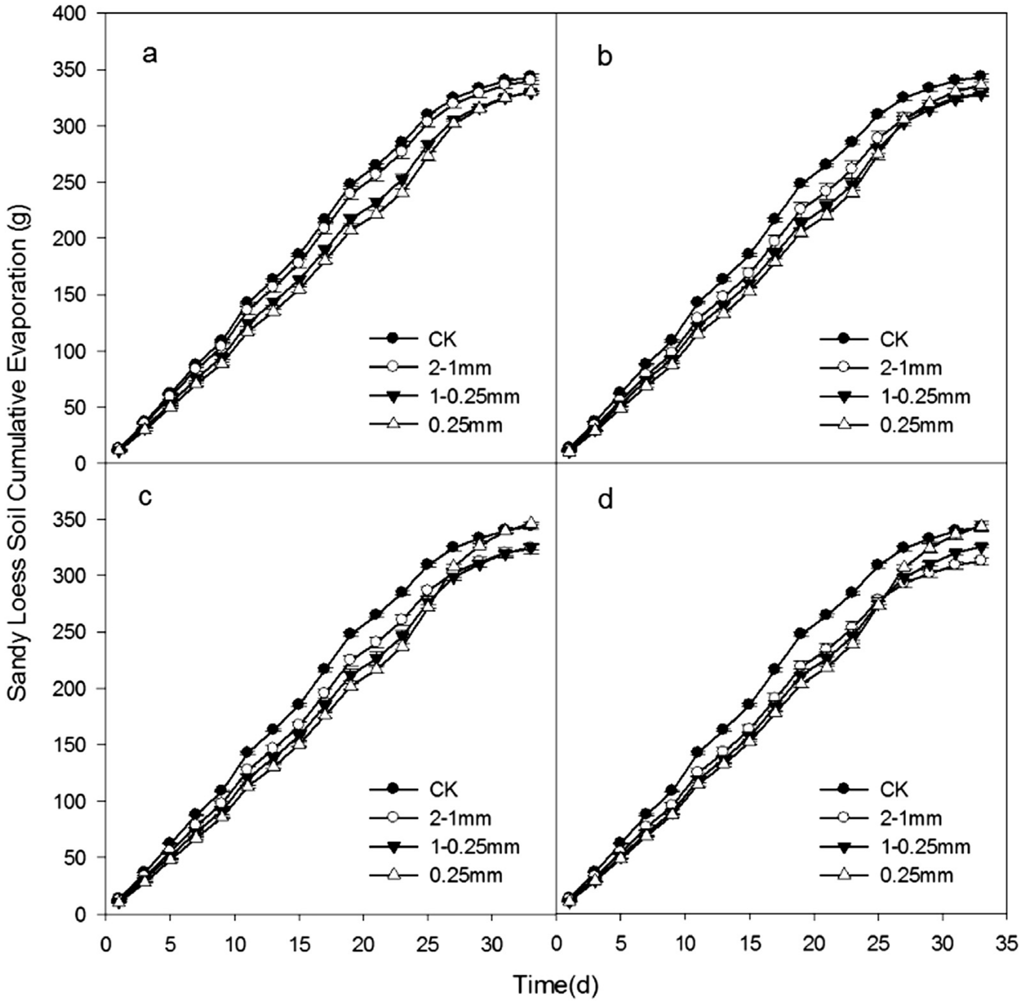

Fig. 4. Cumulative soil evaporation of Sandy loessal soil under different treatments.
CK is control treatment, 2–1 mm, 1–0.25 mm and 0.25 mm is biochar size respectively.
"a" "b" "c" "d" denote biochar addition amounts are 10, 50, 100, and 150 g biochar/kg soil respectively.

respectively. However, in Aeolian sandy soil, the final CE increased from 233.97 g in the 0 g·kg^{-1} treatment to 262.91 g in the 150 g·kg^{-1} treatment, representing an increase of 28 g of water. These results confirmed that increasing the biochar addition amount reduced soil evaporation from all soils except the Aeolian sandy soil. Examining Fig. 6(d) reveals that the final CE in the 2–1 mm biochar treatments decreased with increasing biochar addition, whereas the final CE in the < 0.25 mm biochar treatments increased with increasing biochar addition. The final CE remained relatively unchanged with increasing addition of the 1–0.25 mm biochar.

3.6. Ratio of evaporative loss

Fig. 7(a) clearly shows that biochar reduced soil evaporation in all treatments because the ratios of evaporative loss in the control treatments were the highest among all of the treatments. The evaporative loss ratio decreased with increasing biochar addition amount, suggesting that a higher addition amount could enhance the inhibition of soil evaporation by biochar. The biochar particle size and addition amount had an interacting effects on the soil evaporative loss ratio. As shown in Fig. 7(b), the smallest biochar particles (< 0.25 mm) decreased the ratio of evaporative loss by 55.4% and 17.6% more than the largest biochar particles (2–1 mm) when 10 and 50 g·kg^{-1} were added, respectively. However, as the biochar addition amount increased (such as in the 100 and 150 g·kg^{-1} treatments), the larger biochar particles reduced the ratio of evaporative loss more than the smaller biochar particles.

4. Discussion

4.1. Main and interactive impacts of three factors on soil evaporative loss

In summary, different soil types, biochar sizes and addition amount had different effects on soil evaporative loss. To understand the primary and secondary influences of these three factors on soil evaporative loss, the main and interactive effects of the soil type, biochar size and addition amount on the final CE were assessed; the results are shown in Table 4. Using a general linear model yielded the best fitting results ($R^2 = 0.989$), which had obvious statistical significance. The main and interactive effects were significantly different because the P-values (e.g. sig.) were all < 0.05, indicating that the soil type, biochar size, addition amount, and their interaction significantly impacted the soil evaporative loss. A higher F value indicates a greater influence of the factor on the outcome if the degrees of freedom are relatively small. For the main effects, the F value (2535.547) of the soil type was greater than that of the biochar size (110.654) and addition amount (4.416), which indicates that the main order of influence from large to small is soil type, biochar size and biochar addition amount. The reason for this ordering was similar to that reported by Eibisch et al. (2015), who concluded that biochar plasticity, especially particle size, likely dominated the improvement of soil hydraulic properties.

4.2. Analysis of the effect of biochar particle size on soil evaporation processes

As described in Section 3.2, the soils with greater soil clay contents

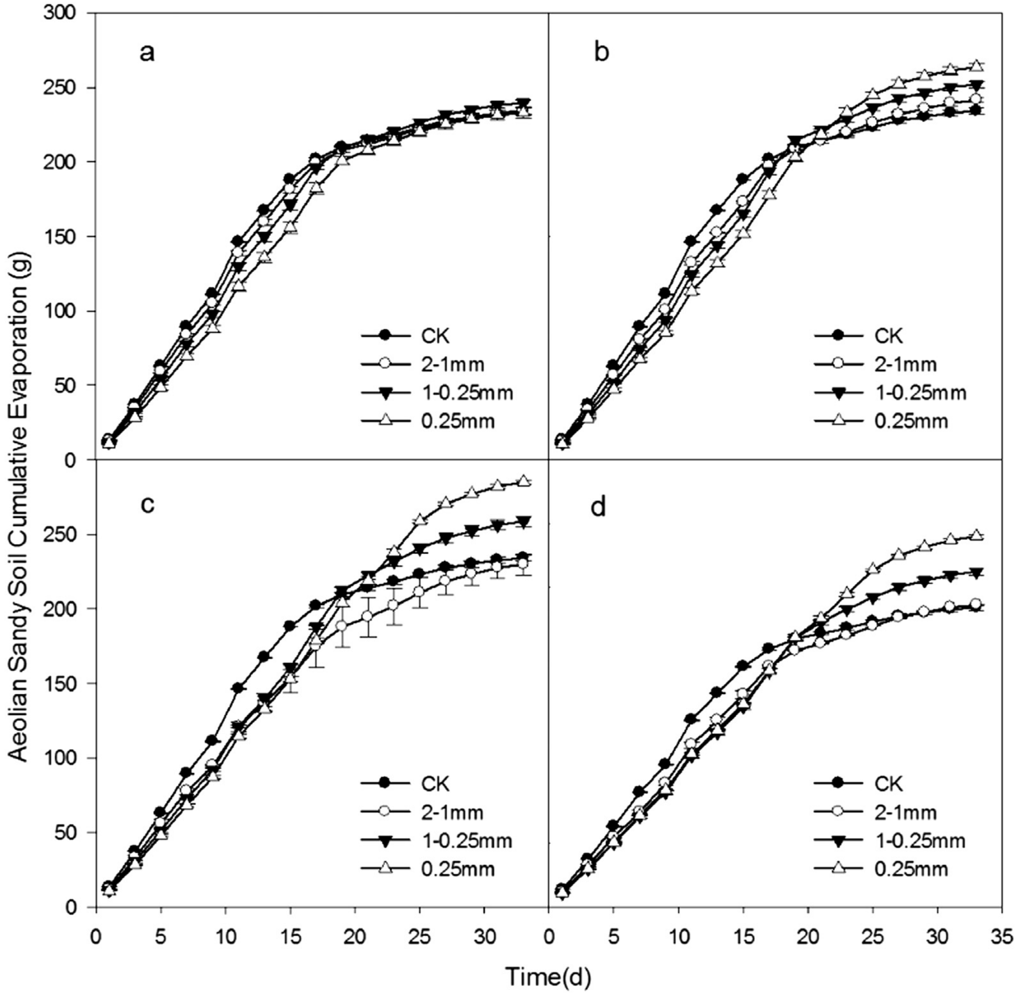

Fig. 5. Cumulative soil evaporation of Aeolian sandy soil under different treatments.
CK is control treatment, 2–1 mm, 1–0.25 mm and 0.25 mm is biochar size respectively.
"a" "b" "c" "d" denote biochar addition amounts are 10, 50, 100, and 150 g biochar/kg soil respectively.

exhibited a later transition point because fine-grained soils hold more water and release it more slowly than coarse-textured soils (Noy-Meir, 1973). In stage I, these results are consistent with initial soil evaporative loss from capillary flow because water is lost first from larger pores during evaporation (Or et al., 2013). Small biochar particles likely reduced soil macropores and subsequently reduced evaporation. In stage II, evaporative loss occurs through vapour diffusion. Biochar with a smaller particle size created more capillary pores and consequently increased the diffusion rate of water vapour (Or et al., 2013). Thus, the final CE increased beyond the control treatment, particularly in the Aeolian sandy soil (Fig. 5). However, the increase in CE in the second stage with smaller biochar particles was not observed in the other four soils (Figs. 1-4), perhaps because the theoretical final CE of these four soils (Eum-Orthic Anthrosols, Isohumisols, Loessal soil and Sandy loessal soil) was not reached during the experimental period. Treatments added with the smaller size biochar should have a higher final CE under the same amount of biochar addition as a result of a higher initial water content and more efficient hydraulic conductivity in the latter period (Abel et al., 2013). In general, the larger biochar was more effective at reducing soil evaporation, which can also be confirmed in Fig. 6(d); at the same biochar addition amount except at 10 g/kg, the final CE decreased with increasing biochar particle size.

4.3. Mechanistic analysis of the effect of biochar on soil evaporation

In general, the addition of biochar can effectively reduce soil evaporation, and the inhibition of evaporation is enhanced with increasing biochar particle size and addition amount. These phenomena result from the fact that biochar has a structure with well-developed interspaces and a large surface area (Table 2); due to its high moisture absorption capacity, biochar can significantly increase the soil water holding capacity (Section 3.2). Initially, soil evaporation is mainly controlled by atmospheric evaporation, and the soil hydraulic conductivity is relatively high, with large quantities of water being transported from within the soil to the surface. When the same addition amount of biochar was applied to the soil, a larger specific surface area corresponded to a stronger water-holding capacity and greater inhibition of soil water evaporation. In addition, the addition of biochar can obviously change the soil structural properties by increasing soil micropores, which have poor water conductivity, and simultaneously destroy the pore continuity of the soil. As a result, the effective soil hydraulic conductivity decreases and the transport of water contained within the soil to the soil surface (or the supply capacity) is reduced. The results of this study were similar to those reported by Zhang et al. (2016). The evaporation rates of the biochar treatments were lower than that of the control treatment at the beginning of evaporation, and the evaporation decreased with the decrease in particle size; however, the duration of this process was very short. The porous structure of biochar is better maintained by a larger biochar particle size, and the structure may change as the particle size decreases. Abel et al. (2013) believed that soil amended with smaller biochar particles should have a higher final CE than soil amended with the same amount of larger biochar particles because of a higher initial water content and more efficient hydraulic conductivity in the later evaporation stage.

Biochar can absorb the maximum amount of soil water before evaporation. During evaporation, the soil loses more water, but the

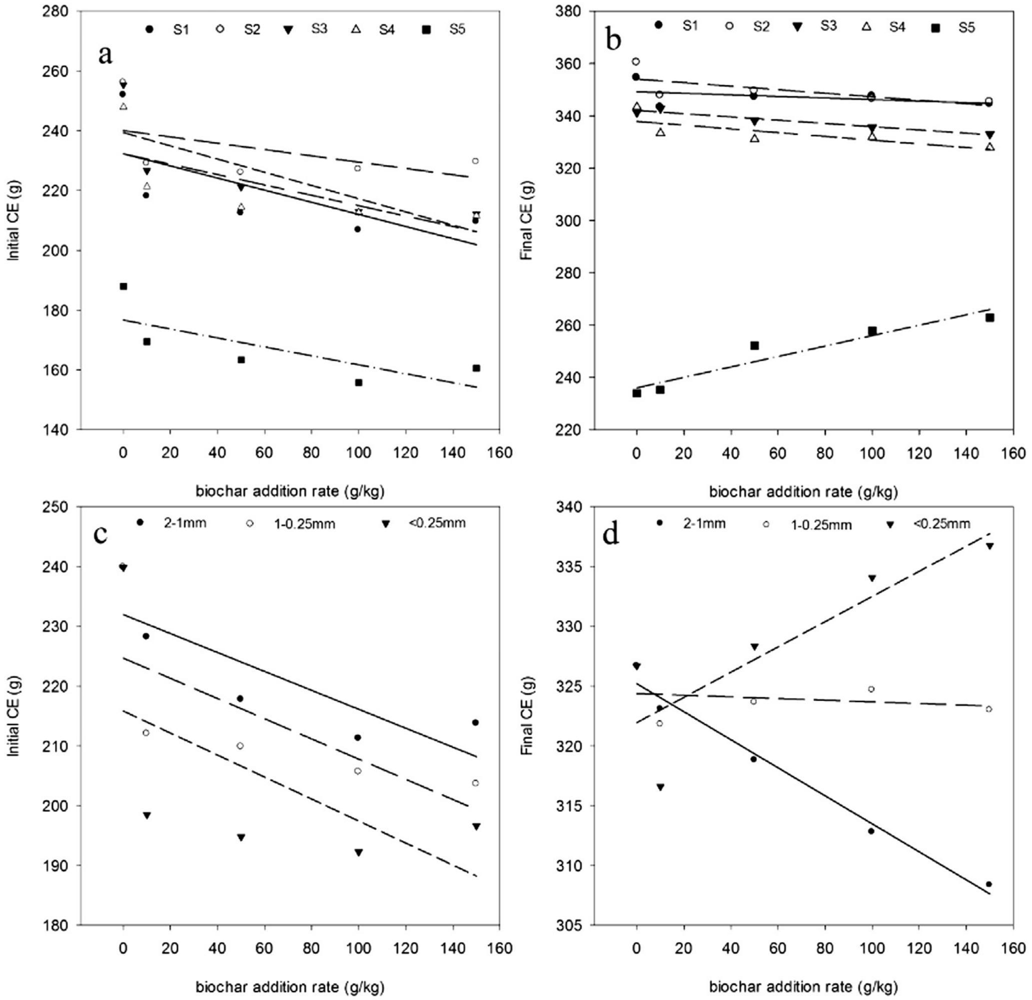

Fig. 6. Initial CE (before 19th day, 15th for Aeolian soil) and Final CE as a function of biochar addition amount (0, 10, 50, 100, 150 g/kg), soil type (S1, Eum-Orthic Anthrosols, S2, Isohumisols, S3, Loessal soil, S4, Sandy loessal soil, S5, Aeolian sandy soil), and biochar size (2–1 mm, 1–0.25 mm, < 0.25 mm).

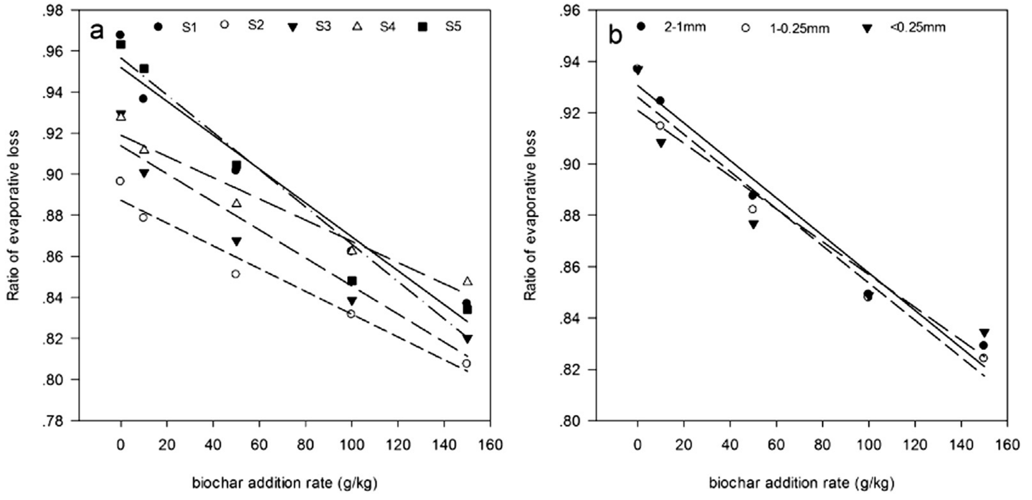

Fig. 7. The evaporative loss ratio as a function of biochar addition amount (0, 10, 50, 100, 150 g/kg), soil type (S1, Eum-Orthic Anthrosols, S2, Isohumisols, S3, Loessal soil, S4, Sandy loessal soil, S5, Aeolian sandy soil), and biochar size (2–1 mm, 1–0.25 mm, < 0.25 mm).

residual water in the soil simultaneously increases, enabling the soil to store more water. The biochar-treated soil had a more persistent water supply and was able to maintain soil moisture for longer periods than was untreated soil under the same evaporation conditions. Furthermore, the coarser texture of the Aeolian sandy soil (Table 1) resulted in a lower water content and greater evaporative loss (Wythers et al., 1999; Yan et al., 2013) than observed in the other four soils (Section 3.6).

Zhang et al. (2016) considered that biochar had a strong ability to adsorb water compared with sandy soil, but the effects of biochar on water evaporation were insignificant ($P > 0.05$) when 100 mL of water was added. When over 200 mL of water was added, this effect was influenced by biochar type, mixing methods, and the particle size of the added biochar significantly influenced the hydraulic properties of the sand-biochar mixture. Grinding the biochar into powder destroys the pore structure, which simultaneously reduces the water absorption ability and hydraulic conductivity of the biochar. However, Hardie et al. (2014) found no evidence to suggest that biochar application

Table 4
Main and interactive effects of soil type, biochar size and addition amount on final CE.

Dependent variable: final CE

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	284,944.701[a]	64	4452.261	187.426	0.000
Intercept	1.77E + 07	1	1.77E + 07	743,255.835	0.000
Soil type	240,925.045	4	60,231.261	2535.547	0.000
Biochar size	5257.104	2	2628.552	110.654	0.000
Addition amount	314.723	3	104.908	4.416	0.005
Soil type * biochar size	4536.589	8	567.074	23.872	0.000
Soil type * addition amount	4396.893	12	366.408	15.425	0.000
Biochar size * addition amount	5260.455	6	876.743	36.908	0.000
Soil type * biochar size * addition amount	1630.45	24	67.935	2.86	0.000
Error	3088.116	130	23.755		
Total	2.06E + 07	195			
Corrected total	288,032.817	194			

[a] R squared = 0.989 (adjusted R squared = 0.984).

influenced soil porosity through a direct pore contribution, the creation of accommodation pores, or an improved aggregate stability. Therefore, the mechanism of biochar effect on soil evaporation is porous structure and large surface area of biochar, especially the choice of appropriate particle size is more important, but the more detailed mechanism remains unclear and further investigation is needed.

5. Conclusion

Biochar addition changed the soil physical properties and subsequent water evaporation dynamics. Our study found that biochar addition can generally increase the soil water content and effectively reduce soil evaporation, and the inhibition of evaporation was enhanced with increasing biochar particle size and addition amount. Biochar addition had contrasting effects during the two evaporation stages which were dependent on the soil type, biochar particle size, and biochar addition amount. The addition of biochar decreased evaporation through capillary flow during the first stage of evaporation but increased evaporation during the second, diffusion-limited vapour transport stage of evaporation, particularly in the Aeolian sandy soil.

Biochar addition reduced the final CE in all soils except the Aeolian soil, where more water was lost because of a greater soil water content. In Eum-Orthic Anthrosols, Isohumisols, Loessal soil, and Sandy loessal soil, the 2–1 mm biochar decreased evaporation more than other two biochar particle sizes. However, in the Aeolian sandy soil, the fine (< 0.25 mm) biochar increased evaporation more than other two biochar particle sizes. It indicates that larger biochar particles are better at reducing soil evaporation than smaller particles. With increasing biochar addition amount, the final CE decreased, except in Aeolian sandy soil whose final CE was increased. However, when the data were expressed as a ratio of evaporative loss, all biochar addition treatments reduced evaporation in this column study.

Our study illustrates the importance of considering not only specific soil types and textures but also biochar particle size when choosing a biochar for soil amendment. Our research reinforces the study direction about the effects of biochar on soil hydraulic properties and demonstrates that the effect of biochar addition on soil evaporation processes for five typical soil types in the Loess Plateau of China.

Acknowledgements

Funding was provided by the Natural Science Foundation of China (41571225), the National Key Research and Development Plan of China (2016YFC0501702 and 2015BAC01B01).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2017.11.013.

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