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Impacts of biochar application rates and particle sizes on runoff and soil loss in small cultivated loess plots under simulated rainfall

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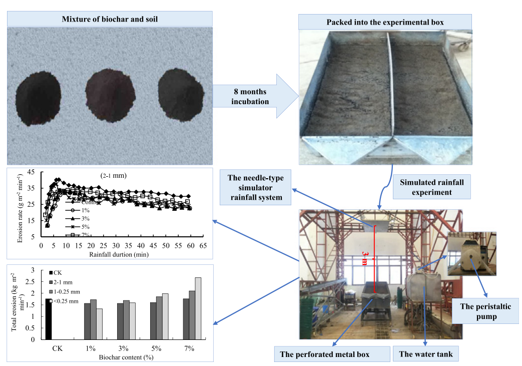
HIGHLIGHTS

- Biochar application reduced runoff production relative to soil without biochar.
- >3% biochar addition accelerated soil loss relative to soil without biochar.
- The effect of the biochar addition rate on runoff and sediment stronger than particle size
- Reasonable addition of the biochar rate and particle size could control soil erosion.

GRAPHICAL ABSTRACT



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ABSTRACT

Increasing literature suggests that biochar can be used to improve soil fertility and subsequently benefit crop yield. However, the effects of biochar application rates and particle sizes on soil erosion processes have yet to be fully identified. The objective of the present study was to evaluate the influence of biochar with different application rates and particle sizes on soil erosion. Addition of biochar to loess generally increased the mean time to runoff by 19.47% relative to the control. The time to runoff decreased with an increase in the biochar application rates and fluctuated with a decrease in biochar particle sizes. The combined 1% and <0.25 mm biochar treatment yielded the longest time to runoff (2.97 min) and the lowest runoff (36.23 kg m^{-2} h^{-1}) and soil loss (1.33 kg m^{-2} min^{-1}). Biochar addition decreased the total runoff volume by 12.21% and generally inhibited soil loss under lower application rates (1% and 3%) while promoting soil loss under higher application rates (5% and 7%). With a decrease in biochar particle size, total runoff volume increased under the 5% and 7% biochar, but no uniform trend was observed under the 1% and 3% biochar treatments. The total soil loss increased with increasing biochar application rates, whereas a negative trend was observed with decreasing biochar particle sizes. The contribution of biochar application rates to runoff and soil loss rates was distinctly greater than the biochar particle sizes. Additionally, biochar addition could increase >2 mm water-stable soil aggregates and saturated hydraulic conductivity (K_{sat}) in this study. We inferred that the positive effects on soil and water loss were potentially due to the improvement in >2 mm water-stable soil aggregates and K_{sat}. The results implied that soil-biochar additions could be a potential measure for conserving soil and water in the Loess Plateau.

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1. Introduction

The magnitude of surface soil erosion is significantly higher than soil formation, especially in agricultural land (Verheijen et al., 2009), and 90% of the world's agricultural land has been subjected to slight to severe soil erosion (Speth, 1994). Severe soil erosion exacerbates the loss of available water and soil components rich in nutrients, while polluting surface waterways, deteriorating soil quality, contributing to soil degradation, and conclusively reducing agricultural and environmental productivity (Pimentel et al., 1995; Quinton et al., 2010). For these reasons, the implementation of all types of measures and soil amendments are very important for conserving soil and water and maintaining the development of agricultural land.

Biochar is produced using organic material under thermal decomposition of plant-derived biomass in the partial or total absence of oxygen (Sohi et al., 2010). It has been increasingly gaining interest in both public and private sectors because of its potential in improving land degradation, being rich in carbon (C) while also being environmentally friendly (Glaser et al., 2002; Beesley et al., 2011; Zhang et al., 2016). Many studies have shown that the use of biochar as a soil supplement can improve soil physical characteristics, such as porosity, bulk density, hydraulic conductivity, and water holding capacity (Uzoma et al., 2011; Abel et al., 2013; Herath et al., 2013; Tammeorg et al., 2014; Ulyett et al., 2014), while altering soil chemical properties, such as increases in pH, the cation exchange capacity (CEC), and nutrient availability (Glaser et al., 2002; Deal et al., 2012; Jien and Wang, 2013; Han et al., 2016; Pandian et al., 2016). These effects on soil properties not only contribute to the improvement of soil productivity (Herath et al., 2013; Jien and Wang, 2013; Ouyang et al., 2013), but they also change the resistance of soil to exogenic forces that could cause erosion (Jien and Wang, 2013). In addition, biochar is highly recalcitrant to decomposition and has been used to extrapolate the mean residence time over centuries and even thousands of years (Hale et al., 2011; Ameloot et al., 2013), consequently guaranteeing long-term benefits associated with soil quality improvements.

However, previous studies have indicated that for the given biochar and soil type, the beneficial effects of biochar on soil physicochemical properties are dependent on biochar application rates and particle sizes. Biochar applied at application rates of 0%, 2.5%, and 5% in highly weathered soil readily improved soil physicochemical properties, including a reduction in bulk density and an increase in soil pH, CEC, porosity, K_{sat}, and the mean weight diameter of soil aggregates; moreover, the effects of these improvements increased with an increase in the biochar application rate (Jien and Wang, 2013). Similarly, Peake et al. (2014) found a positive correlation between the biochar application rate and an improvement in sandy loam soil properties. In contrast, some reports have found that the addition of biochar decreased K_{sat}, and the rate of this decease rose with an increase in the biochar application rate (Brockhoff et al., 2010; Laghari et al., 2015; Liu et al., 2016). Dugan et al. (2010) determined that the optimum biochar application rate by which to increase the water holding capacity was its lowest percentage. In addition, a recent survey reported that the effect of biochar on soil properties was dependent on the biochar particle sizes (Liu et al., 2016). Based on a soil column incubation experiment coupled with an enclosed simulated rainfall experiment, Obia et al. (2016) indicated that the addition of larger (1–5 mm) and smaller (<0.5 mm) biochar particle sizes could both result in equally stronger positive effects on soil physical properties compared with a medium-sized biochar particle size (0.5–1 mm). Reddy et al. (2015) also found that the hydraulic conductivity and shear strength of soil increased while the compressibility of soil decreased with a decrease in biochar particle sizes. These results implied that there may be an optimal biochar application rate and particle size from which to maximize biochar effects on soil physicochemical properties and subsequent soil erosion.

Loess is one of the most common agricultural soil types in the Loess Plateau, covering an area of approximately 6.4×10^5 km^2. Under conditions of extreme rainstorm events, intensive cultivation, and sparse vegetation cover, highly eroded loess is characterized by very low soil organic matter (SOM), CEC, and base saturation percentages. Fu et al. (2011) determined that the mean annual erosion rates in the Loess Plateau ranged from 5000 to 10,000 Mg km^{-2} yr^{-1}. Such severe soil erosion could lead to the transport of a massive amount of soil nutrients into the Yellow River and ultimately into marine ecosystems (Zheng et al., 2005; Zhang et al., 2017), which would result in soil degradation, water pollution, and eutrophication (Wan et al., 1996; Withers et al., 2010).

Large amounts of clipped apple branches are produced in the Loess Plateau in Yichuan County, Yan'an City, and Ansai District, Shaanxi Province, China, because apple trees are a leading local industry and thus widely planted. In the past, clipped apple branches were burned for heating and cooking; however, with economic improvements in combination with an improvement in living standards, this practice has declined. Consequently, local farmers are now faced with the urgent problem of what to do with these clipped branches each year. In view of the poor, drought-stricken, and degraded soil caused by severe soil erosion in the Loess Plateau, some researchers have proposed that biochar could be used to improve soil degradation as well as prevent the continued degradation of loess in the Loess Plateau due to its unique physicochemical properties (Lehmann, 2007). Numerous studies in the laboratory have shown that biochar has both a positive effect and the potential to improve loess quality (Gao et al., 2012; Chen et al., 2013; Yan et al., 2013). Thus, converting clipped apple branches into biochar by the slow thermochemical pyrolysis method and applying it to loess as a soil supplement is not only a simple, sustainable method by which to manage agricultural waste but can also improve the overall physicochemical properties of loess, helping it to retain nutrients and consequently increasing crop yields in the Loess Plateau. However, the main difference between the slope croplands in Loess Plateau and the flat croplands for biochar application is the soil erosion. Thus, we hypothesize that biochar also plays a role in soil erosion control as well as improving loess fertility conditions in the Loess Plateau. Accordingly, it is critically important to clarify the effects of biochar on soil erosion processes prior to applying biochar to improve loess slopes in the Loess Plateau.

Previous studies that supplemented soil with biochar typically focused on restoring soil fertility, crop production, and biochar effects on the physical properties of soil. Few studies have dealt with the influence of biochar on soil erosion, especially the effect of different biochar application rates and particle sizes on soil erosion. Recently, several studies determined that supplementing soil with biochar could significantly reduce soil loss and runoff (Jien and Wang, 2013; Smetanová et al., 2013; Abrol et al., 2016; Sadeghi et al., 2016). However, such studies are limited in that they focused mainly on analyzing improvements in soil physicochemical properties, offering only limited data on total erosion, and they did not incorporate biochar into the soil itself (i.e., a 3 cm biochar layer was spread over the soil surface). Concurrently, Peng et al. (2016) found that the effects of biochar on runoff and sediment yield in ultisol on hillslopes were negligible under natural rainfall conditions over a one-year study period. As noted above, the role of biochar supplementation on influencing runoff and soil loss is complex and therefore requires further study.

In this study, we hypothesize that biochar could affect soil erosion, depending on the rates and particle sizes of the applied biochar. We speculate that a change in soil physical properties was the potential mechanism responsible for their effects, namely, >2 mm water-stable soil aggregate content and K_{sat}. Therefore, the objectives of present study were to (1) examine the effects of the biochar application rates and particle sizes on loess erosion processes, and identify the contribution of biochar particle sizes and application rates to the variations in runoff and soil loss; (2) reveal the mechanisms responsible for effects of biochar particle sizes and application rate on soil erosion by analyzing >2 mm water-stable soil aggregate and K_{sat}. The results from this study should enhance our understanding of the role of biochar addition on soil erosion processes and are expected to provide fundamental support for local farmers as well as policymakers to determine whether biochar addition is a potential measure for improving degraded loess on loess slope croplands.

2. Materials and methods

2.1. Soil and biochar

This study used cultivated loess soil from Ansai District, Shaanxi Province, China, located in the northern section of the Loess Plateau. Ansai (36°51′N, 109°19′E) has a mean annual temperature of 8.8 °C and an annual precipitation of 500 mm (Liu et al., 2014). The soil was collected from the top 0–20 cm layer in cultivated land, after which it was air-dried and crushed for passage through a 5-mm sieve and thoroughly mixed. The United States Department of Agriculture (USDA) classifies this soil as silt loam (30.2% sand, 60.87% silt and 8.93% clay).

The biochar (supplied by the Shaanxi Yixing Technology Co., Ltd., Xi'an, China) was produced from clipped apple branches subjected to pyrolysis at a temperature of approximately 550 °C. After the pyrolytic procedure, the resultant biochar was crushed and passed through 2, 1, and 0.25 mm sieves to obtain biochar of different particle sizes (2–1, 1–0.25, and <0.25 mm). The basic physicochemical properties of both soil and biochar are presented in Table 1, and the scanning electron micrograph (SEM) of biochar is shown in Fig. 1.

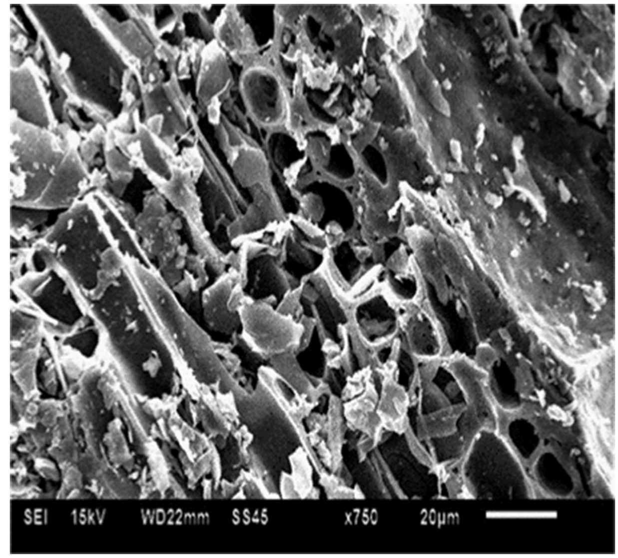

Fig. 1. Scanning electron micrographs of biochar.

2.2. Experimental design

During this study, biochar with each size range was thoroughly mixed into soil based on the farmer use and application procedure, and then the mixture was packed uniformly into the experimental box to a total depth of 25 cm with a similar bulk density to the natural plow layer. This procedure to a certain extent ensured that the artificial treatment of soil and biochar was meant to resemble natural soil conditions and land management, and the obtained results could provide the basic supports for practical application of biochar in the field.

We used three different biochar particle sizes (2–1, 1–0.25, and <0.25 mm) mixed into one soil type (described above) under four application rates of 1%, 3%, 5%, and 7%. These particle sizes and application rates were based on previous studies that applied biochar to cropland soil, and these previous studies displayed beneficial effects on the physicochemical properties and crop growth after biochar addition (Abel et al., 2013; Carter et al., 2013; Qi et al., 2014; Feng et al., 2014; Butnan et al., 2015; Zhang et al., 2015; Liu et al., 2016; Usman et al., 2016). Soil without biochar supplement was used as the control.

Dried and sieved soil was mixed thoroughly with biochar at the designated application rates and particle sizes. Soil-biochar mixtures were incubated in plastic buckets with a field water capacity of approximately 20%. The plastic buckets were covered with lids to avoid evaporation and were placed in the simulated soil erosion experiment hall of the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau for 8 months. The incubation period was designed to be longer than in previously reported studies (Jien and Wang, 2013; Hseu et al., 2014; Sadeghi et al., 2016) to ensure the time effects of biochar on soil properties. In addition, the length of the incubation period was determined by taking into account that severe soil erosion in the Loess Plateau occurs during the summer and autumn and that it was easier to conduct simulated rainfall experiments during these periods because they are the only periods during which the simulated soil erosion experiment hall was in operation. After incubation, soil supplemented with biochar was adjusted to approximately 10% water content (including the control) before packing the control and soil-biochar mixtures into the experimental plots.

A perforated metal plot (1 m length, 0.8 m width, 0.4 m depth) with an adjustable slope gradient from 0% to 70% was used in this study. The plot was evenly divided into two parts (1 m length, 0.4 m width, 0.4 m depth) by a metal board, which also served as replicates for each simulated rainfall experiment. A collection of funnel outlets was fitted to the lower edge of each part to collect runoff and sediment samples. The rainfall intensity (90 mm h^{-1}) and slope gradient (27%) were chosen because a rainfall intensity of 90 mm h^{-1} is representative of the intense rainstorms that occur in the Loess Plateau (Tang, 1990), and a 27% slope gradient is the typical mean of the slopes in the region (between 18% and 37%). A total of 13 simulated rainfall experiments and 26 tests were conducted in the laboratory.

Table 1
Essential physicochemical properties of experimental materials.

Items	Soil Samples	<2 mm Biochar
Sand (%)	30.20	/
Slit (%)	60.87	/
Clay (%)	8.93	/
Texture	silt loam	/
Organic carbon (g·kg^{-1})	1.94	467.47
pH	8.56	9.52
specific surface area (m^2 g^{-1})	/	1.05
Porosity (μm)	/	20
Total nitrogen (g kg^{-1})	0.22	4.55
Total phosphorus (g kg^{-1})	0.55	0.95
Total potassium (g kg^{-1})	19.56	7.35

2.3. Soil plot preparation

The prepared soil-biochar mixture and the soil without biochar addition were packed uniformly into the experimental plots in 5-cm-thick layers to a total depth of 25 cm above a 5-cm-thick layer of coarse sand. To reduce discontinuities between the layers, the surface of each soil layer was gently scored before packing the next layer on top. The top surface layer was smoothed to minimize microtopographic effects. The bulk density was approximately 1.15 g cm^{-3}, which is roughly equivalent to the soil plow layer under natural conditions on sloped cropland in the study region. The prepared plots were positioned under a rainfall simulator for the rainfall experiment at the designated slope gradient of 27%.

2.4. Rainfall simulation

Rainfall simulations were conducted in the simulated soil erosion experiment hall of the State Key Laboratory of Soil Erosion and Dryland

Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and the Ministry of Water Resources, Yangling District, China. We fabricated a needle-type rainfall simulator system similar to that described by Zhao et al. (2014). The system consisted of a constant water supply rate and a rainfall generator; however, for the water supply, we replaced the Markov bottle used by Zhao et al. (2014) with a peristaltic pump (BT-600C Huxi Co., Shanghai, China) with an output flow rate from 0.01 to 180 L h^{-1}. The rainfall generator was located at a height of 3 m from the ground surface and consisted of a water tank (with an effective rainfall area of 1.0 m × 1.2 m), a drop former (#8 steel syringe needles), and a needle plate vibration generator. The steel syringe needles, which protruded through the bottom of the water tank, were configured in a regular pattern following a square design (2 cm × 2 cm). The needle plate gently oscillated in a horizontal direction by the vibration generator, which consisted of eccentric wheels driven by a motor to release raindrops at different positions. The coefficient of uniformity of simulated raindrops was >85%. The energy of each raindrop was 212.4 J m^{-2} h^{-1}. To remove the influence of water quality on soil physical and chemical properties, deionized (DI) water was used for all simulated experiments.

The rainfall intensity was set at 90 mm h^{-1}, which was calibrated prior to the experiment by adjusting the relative water depth in the water tank using the peristaltic pump. The simulated rainfall was generally applied at 60-min intervals for each rainfall event, and one rainfall event was conducted for each treatment. During the simulated rainfall treatments, the time to runoff was recorded, and sediment and runoff from the soil plots were collected continuously using a series of plastic containers with a volume of approximately 5 L. The initial five runoff and sediment samples were collected at 1-min intervals, the subsequent five samples every 2 min, and thereafter every 3 min. After each rainfall event, samples collected in each plastic container were weighed. The sediment collected in each sample was allowed to settle for 24 h and was then separated from the water by siphoning before being oven-dried at 105 °C until a constant mass was achieved for weighing. The runoff amount and sediment yield were then determined for each sampling interval by dividing the runoff and sediment yield per unit area by time.

Soil aggregation is considered one of the main soil properties affecting soil erodibility (De Ploey and Poesen, 1985; Cammeraat and Imeson, 1998; Cerdá, 1998; Barthès and Roose, 2002), and K_{sat} is closely related to infiltration rates, thus affecting runoff and soil loss (Dexter et al., 2004). In this study, three samples from each treatment were measured for soil aggregates and K_{sat}. The >2 mm water-stable soil aggregate content was measured using the wet sieving procedure and was then oven-dried and weighed. The K_{sat} was measured using the constant head method permeability test, following the method reported by Black (1965). All data were analyzed using SPSS by one-way ANOVA and the least significant difference (LSD) at a 0.05 significance level.

3. Results

3.1. Runoff

In general, the time to runoff increased for all biochar treatments compared with the control (Table 2). The combined 1% and < 0.25 mm biochar treatment yielded the longest time to runoff (2.97 min). The time to runoff decreased with an increase in the biochar application rate under the same biochar particle size, with the exception of the combined 1–0.25 mm and 3% biochar treatment (Table 2). In contrast, we found no uniform trends in the time to runoff with a decrease in biochar particle size. The time to runoff for the different biochar particle size treatments at the higher application rates (5% and 7%) ranked in order of time (longer to shorter) as follows: 1–0.25, <0.25, and 2–1 mm; however, the time to runoff increased with a decrease in biochar particle size under the 3% biochar treatment. These results demonstrated that biochar addition was beneficial for delaying the time to runoff and that this benefit varied depending on the specific biochar particle sizes and application rates applied. Moreover, a smaller biochar particle size (<0.25 mm) and a lower application rate (1%) could significantly enhance the effect of biochar on the time to runoff. One-way ANOVA revealed that the biochar application rate was the main factor delaying the time to runoff relative to the biochar particle size and the interaction between them (Table 3).

Table 2
Changes of time to runoff, runoff volume and erosion after biochar treatments.

BPS (mm)	BAR (%)	TR (min)	RCTTR (%)	TR (kg m^{-2} h^{-1})	RCTR (%)	TE (kg m^{-2} min^{-1})	RCTE (%)
CK	0	2.09	–	52.32	–	1.76	–
2–1	1	2.60	24.4	44.62	14.72	1.56	11.36
	3	2.46	17.7	46.07	11.95	1.56	11.36
	5	2.13	1.91	46.65	10.84	1.6	9.09
	7	1.68	−19.62	44.35	15.23	1.68	4.55
1–0.25	1	2.47	18.18	45.08	13.84	1.72	2.27
	3	2.63	25.84	47.55	9.12	1.69	3.98
	5	2.42	15.79	47.82	8.6	1.85	−5.11
	7	2.22	6.22	45.56	12.92	2.1	−19.32
<0.25	1	2.97	42.11	36.23	30.75	1.33	24.43
	3	2.79	33.49	46.57	10.99	1.59	9.66
	5	2.28	9.09	52.30	0.04	1.98	−12.5
	7	2.19	4.78	48.40	7.49	2.67	−51.70

BPS: Biochar particle size; BAR: Biochar application rate; TR: Time to runoff; RCTTR: Relative change of time to runoff; TR: Total runoff; RCTR: Relative change of total runoff; TE: Total erosion; RCTE: Relative Changes of total erosion.

Following the 60 min of simulated rainfall, the control yielded the highest total runoff for all tests, which was 0.04%–30.75% higher than the mixed biochar treatments. For the mixed biochar treatments, the combined 1% and < 0.25 mm and 5% and < 0.25 mm treatments yielded the minimum and maximum values (36.23 and 52.30 kg m^{-2} h^{-1}) of total runoff volume, respectively. The total runoff volume increased with decreasing biochar particle sizes under the 5% and 7% biochar treatments, but under the 1% and 3% treatments, the trend in total runoff volume first both increased and then decreased with a decrease in biochar particle size. With an increase in the biochar application rate from 1% to 7%, the total runoff volume first increased and then decreased, with the 5% biochar application rate and the three different biochar particle sizes yielding the highest values (46.65, 47.82, and 52.30 kg m^{-2} h^{-1}, respectively).

Fig. 2 and Fig. 3 show the dynamic variation curves of runoff rates for each biochar treatment during the rainfall simulations. Rapidly increased runoff rates in all experiments within 15 min after runoff were first produced before arriving at and maintaining a quasi-steady state. Generally, biochar application decreased the runoff rate during rainfall simulations compared with the control (Figs. 2 and 3). However, the scale of this decrease depended on both the biochar application rates and the particle sizes in the experiment.

Table 3
ANOVA of significance and contribution rate of biochar application rate, particle size and interaction affecting time to runoff, total runoff and erosion.

Variable	Source	*F* value	Sig.	CP (%)
Time to runoff	AR	14.180	0.000	52.69
	PS	5.950	0.016	13.19
	AR * PS	1.433	0.020	3.46
	Error			30.65
Total runoff	AR	8.873	0.002	35.93
	PS	0.413	0.049	−1.78
	AR * PS	4.382	0.014	30.87
	Error			34.99
Total erosion	AR	49.445	0.000	52.27
	PS	16.862	0.000	11.41
	AR * PS	13.996	0.000	28.05
	Error			8.27

AR: Application rate (%); PS: Particle size (mm); CP: Contribution percentage (%).

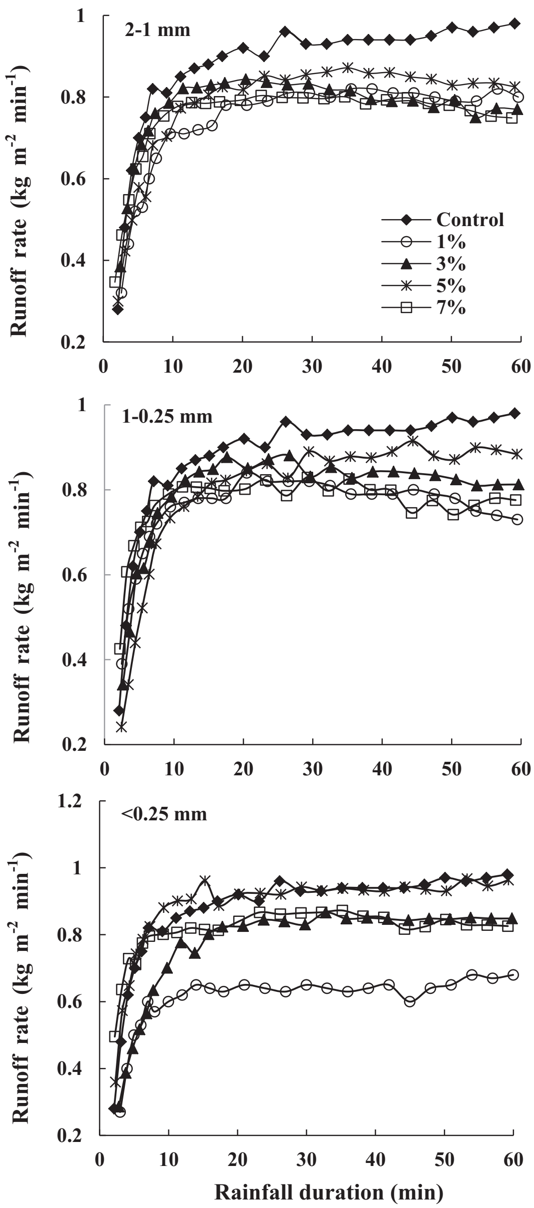

Fig. 2. Effect of the biochar application rate on the runoff rate in each rainfall process.

Fig. 2 indicates that the differences in runoff rates among the experiments were smaller during the 15 min after runoff production, but this difference increased among some treatments during the quasi-steady state. For the biochar treatments with the same biochar particle size, higher runoff rates generally occurred in the 5% biochar application treatment compared with the biochar application rates of 1%, 3%, and 7% throughout the whole rainfall simulation experiment. Although some runoff rates were similar among the 1%, 3%, and 7% biochar application rate treatments in combination with the 2–1 biochar particle size, the order rank of runoff rates (from highest to lowest) of the different biochar application rate treatments was 1%, 3%, and 7% (Fig. 2). In contrast, the order rank of runoff rates (from highest to lowest) of the 1–0.25 mm and < 0.25 mm biochar application rate treatments was 3%, 7%, and 1%, especially for the <0.25 mm biochar treatment, while the 1% biochar application rate yielded the lowest runoff rate throughout the whole rainfall simulation experiment (Fig. 2).

The effect of biochar particle sizes on runoff rates is shown in Fig. 3. In general, we observed an increase in runoff rates with a decrease in biochar particle size under the 3%, 5%, and 7% biochar application rate treatments. In contrast, runoff rates for the 1% biochar application rate treatment increased with an increase in biochar particle size. Clear differences in runoff rates were found between the 2–1 and < 0.25 mm biochar application treatments, but the difference in runoff rates was smaller for the 2–1 and 1–0.25 mm biochar application treatments (Fig. 3). Overall, our results indicated that the addition of biochar could reduce runoff production. However, the effectiveness of reducing the runoff varied in relation to the different biochar particle sizes and application rates. The combinations with smaller biochar particle size (<0.25 mm) and lower biochar application rate (1%) appeared to be more effective in reducing runoff relative to the combinations with a larger biochar particle size and higher application rate. Similar to the time to runoff, the biochar application rate was also the main factor controlling runoff rates relative to the biochar particle size and the interaction between them in this study (Table 3).

3.2. Soil loss

Fig. 4 and Fig. 5 show the dynamic variations in soil erosion rates that occurred under the different biochar application rates (0, 1%, 3%, 5%, and 7%) and particle sizes (2–1, 1–0.25, and <0.25 mm). In general, soil erosion rates exhibited similar trends for all treatments as well as the two distinct stages, namely, a rapid increase during the first 2–6 min of rainfall with an observed peak in the soil erosion rate appearing at 6 min after runoff was first produced, followed by a gradual decrease and arriving at a quasi-steady state or a slight decrease with smaller fluctuations with continued rainfall simulation. Among the four biochar application rates in combination with the 2–1 mm biochar particle size, erosion rates were notably lower compared with the untreated soil (control) (Fig. 4). For the 1–0.25 and > 0.25 mm biochar particle size treatments, the 1% and 3% biochar application rates generally led to a decrease in erosion rates during the rainfall simulation, but a negative effect was observed for the 5% and 7% biochar application rate treatments relative to the control (Fig. 4). In general, the mean erosion rate increased with increasing biochar application rates under the same biochar particle size (Table 2).

The effect of biochar particle sizes on erosion rates is shown in Fig. 5. Both the 1% and 3% biochar application rates clearly decreased the erosion rates, regardless of the biochar particle sizes, relative to the control. Similar to the total runoff volume, the total erosion first increased and then decreased with a decrease in biochar particle sizes for the 1% and 3% biochar treatments, with the <0.25 biochar particle size yielding the lowest total erosion (1.33 kg m^{-2} min^{-1}). However, for the 5% and 7% biochar application rates, only the 2–1 mm particle size had a positive effect on controlling the erosion rate. As the biochar particle size decreased, the total erosion increased (Table 2); in contrast, the <0.25 mm particle size yielded the highest erosion rate (2.67 kg m^{-2} min^{-1}). One-way ANOVA clearly showed that the contribution rate of biochar application rates, particle sizes, interactions, and other sources to the total erosion were 52.27%, 11.41%, 28.05%, and 8.27%, respectively (Table 3).

3.3. Soil aggregate and K_{sat}

Biochar-supplemented soil exhibited a higher average >2 mm water-stable soil aggregate content (>0.57%) than soil without biochar addition (control) (0.32%) (Fig. 6). This result indicated that biochar effectively promoted the aggregation of small particles into larger particles. However, the scale of this effect depended on the biochar particle sizes and its application rates. Of all the biochar application rates investigated, the 2–1 mm biochar application rate yielded the highest >2 mm water-stable soil aggregate content (0.71%), while the 1–0.25 mm biochar application rate yielded the lowest (0.42%). However, the different biochar application rate treatments did not result in statistically significant differences in the >2 mm water-stable soil aggregate content, although the 3% biochar application rate treatment yielded the lowest >2 mm water-stable soil aggregate content (0.53%).

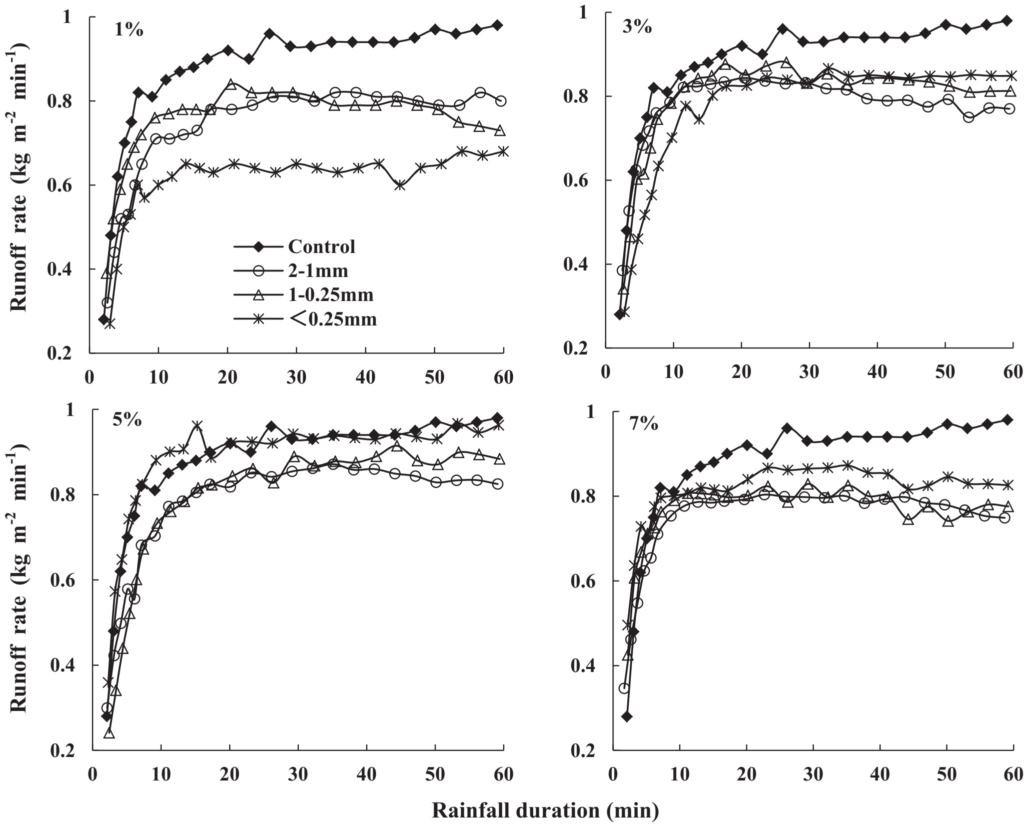

Fig. 3. Effect of the biochar particle size on the runoff rate in each rainfall process.

In addition to the >2 mm water-stable soil aggregate, Fig. 7 shows the changes in the K_{sat} of soil after biochar application. For the control, K_{sat} was only 0.22 m d^{-1}, but K_{sat} increased to 0.27, 0.34, and 0.36 m d^{-1} under the three biochar particle size treatments and to 0.39, 0.36, 0.27, and 0.23 m d^{-1} under the four biochar application rate treatments. This result indicated that the K_{sat} value of the soil decreased with an increase in biochar particle sizes and increased with a decrease in biochar application rates.

4. Discussion

This study investigated the effects of biochar application rates and particle sizes on time to runoff, runoff and soil loss on cultivated loess slopes under simulated rainfall. The results indicated that the addition of supplemental biochar at reasonable application rates and particle sizes to soil generally delayed the time to runoff and decreased runoff and soil loss under certain conditions, consistent with findings from previous studies (Jien and Wang, 2013; Hseu et al., 2014; Lee et al., 2015; Sadeghi et al., 2016). However, the effect depended on the specific biochar application rates and particle sizes used. A comprehensive analysis (Table 2) showed that as application rates increased and particle sizes decreased, the benefits of biochar in controlling erosion gradually decreased before disappearing completely. The 1% biochar application rate and <0.25 mm biochar particle size yielded the optimum effect. However, higher biochar application rates (5% and 7%) had an adverse effect.

Variations in the time to runoff, runoff and soil loss rates between the control plots and amended biochar plots were caused by effective changes in the intrinsic natures of soil and exogenic erosional forces on the surface of loess slopes. Permeability and soil aggregation have been recognized as important factors in the intrinsic properties of soil associated with soil erodibility (Zhu, 1960). Studies have found that biochar can increase the porosity of biochar-supplemented soil as a result of pores inside the biochar particles and between biochar and soil particles (Masiello et al., 2015; Liu et al., 2016). Such an increase enhances the movement of water and helps to maintain a high hydraulic conductivity (Herath et al., 2013; Ouyang et al., 2013), thus increasing rainfall infiltration (Abrol et al., 2016) and weakening exogenic erosional forces by reducing runoff rates (Jien and Wang, 2013; Hseu et al., 2014). Additionally, biochar can interact with SOC, minerals, and microorganisms, and it can increase the content and stability of soil aggregates (Steiner et al., 2010; Liu et al., 2012; Soinne et al., 2014; Obia et al., 2016). The enhancement of soil aggregate stability in topsoil after the application of biochar can increase soil anti-erodibility and anti-scourability by improving the intrinsic properties of the soil (Valmis, 2001; Zhang et al., 2007), consistent with our results.

4.1. Effect of biochar application rates on soil erosion

The biochar application rate significantly alters soil properties (Liu et al., 2016) and thus may affect soil erosion processes. The present study indicated that the effect of controlling runoff and soil erosion significantly decreased with an increase in the biochar application rate. The 1% biochar application rate yielded a greater and more significant reduction of runoff and soil loess (Table 2). We deduced that the effect of biochar on soil erosion varied along with the different biochar application rates due to the effects of biochar application rates on soil aggregates and $K_{sat.}$ Our results showed that biochar could effectively increase K_{sat} and promote the aggregation of small particles into larger particles relative to the control (Fig. 6 and Fig. 7). K_{sat} decreased with an increase in the biochar application rate, but different biochar application rate treatments did not lead to statistically significant differences in >2 mm water-stable soil aggregate content (Fig. 6). Although we found that higher biochar application rates (5% and 7%) could increase the >2 mm water-stable soil aggregate content while lowering K_{sat}, this negative correlation indicated that an increase in the >2 mm

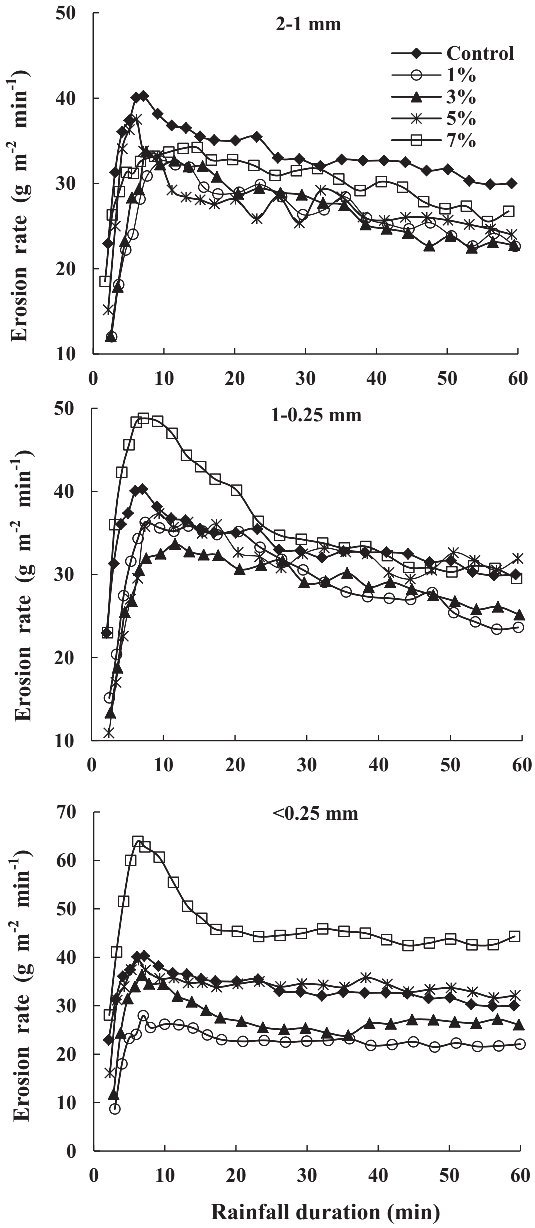

Fig. 4. Effect of the biochar application rate on the erosion rate in each rainfall process.

water-stable soil aggregate content along with an increase in the biochar application rate did not necessarily increase the effective porosity and, thus, did not have a positive effect on K_{sat} in biochar-supplemented soil (Fig. 7), simultaneously producing more runoff. The role of an increase in total runoff on the amount of erosion was much stronger than that of increases in the >2 mm water-stable soil aggregate content. Increasing runoff contributed to a greater increase in exogenic forces on soil erosion under increasing biochar application rates in comparison to an increase in soil stability due to the addition of supplemental biochar, thus resulting in more severe soil erosion relative to the lower biochar application rates. This result suggested that the mechanisms responsible for the effect of biochar application rates on soil erosion must be explained by the simultaneous analysis of the >2 mm water-stable soil aggregate content and K_{sat}. However, the results from previous studies stand in opposition to our findings, reporting that soil loss rates significantly decrease as biochar application rates are increased (Jien and Wang, 2013; Hseu et al., 2014; Abrol et al., 2016). We speculated that these opposing effects could potentially have resulted from soil differences between this study and previous studies. Particles of clay and silt were the main component of the soil in previous studies (Jien and Wang, 2013; Hseu et al., 2014). Higher clay content indicates a larger specific surface area and is more beneficial for soil interactions with biochar than a lower clay content. This feature can cause the soil to bind more tightly and directly biochar or first adsorb soil organic matter and then bind again to adjacent soil particles (Brodowski et al., 2006; Joseph et al., 2010). This behavior causes occlusion of biochar into aggregates and enhances the stability of aggregates (Brodowski et al., 2006). Thus, the soil erosion decreases with increasing biochar application rates. However, particles of sand and silt were the main component of the soil in our study. The adsorption capacity of coarse soil particles (sand) for biochar and other soil particle was weaker than that of small soil particles (clay). Thus, treatments with different biochar application rates did not result in statistically significant differences in the >2 mm water-stable soil aggregate content (Fig. 7), and a negative relationship was observed between the biochar application rate and soil erosion in the present study.

4.2. Effect of biochar particle sizes on soil erosion

Although our study indicated that biochar particle sizes also had an effect on soil erosion under the same application rates, there were no uniform trends in runoff and erosion rates with a variation in biochar particle sizes. In general, the smaller biochar particle sizes used in this study were more effective in delaying time to runoff, reducing runoff and soil erosion rates. To the best of our knowledge, no study has thus far focused on the effect of supplementing different biochar particle sizes into soil to investigate whether biochar has an effect on soil erosion. Therefore, we speculate that the main cause of the reduction in soil erosion was due to changes in K_{sat} and > 2 mm water-stable soil aggregate content in biochar-supplemented soil (Figs. 6 and 7). This study showed that different biochar particle sizes could effectively increase K_{sat} and >2 mm water-stable soil aggregate content relative to the control. K_{sat} increased with a decrease in biochar particle sizes, and the addition of <0.25 mm biochar resulted in both the highest K_{sat} and the medium amount of >2 mm water-stable soil aggregate content. Previous studies have shown that supplementing soil with biochar could increase or decrease K_{sat}, depending on the soil texture. Biochar-supplemented sandy soil could decrease K_{sat}, while biochar-supplemented clay soil could increase K_{sat} (Brockhoff et al., 2010; Herath et al., 2013; Barnes et al., 2014; Githinji, 2014). Qi et al. (2014) indicated that biochar with different particle sizes (2–1, 1–0.25, and <0.25 mm) improved infiltration for anthrosol soil (a typical soil on the Loess Plateau) when the biochar application rate was the same. Obia et al. (2016) found that the effect of biochar particle size (<0.5, 0.5–1, and 1–5 mm) on soil was more significant in loamy sand than sand. The addition of larger biochar particle sizes (1–5 mm) could result in an equally strong positive effect on soil physical properties (soil bulk intensity, aggregate stability, porosity, and available water capacity) in comparison to the form of powdery biochar (≤0.5 mm). In contrast, the addition of 1–0.5 mm biochar particle sizes reduced the effects of supplemental biochar on some soil properties. On the other hand, the addition of biochar could generally increase the content and stability of soil aggregates (Steiner et al., 2010; Liu et al., 2012; Soinne et al., 2014; Obia et al., 2016); however, Grunwald et al. (2016) found that biochar applications did not significantly alter the macroaggregate content compared with the control.

The above-described previous results implied that the effects of biochar particle size on K_{sat} and soil aggregate are complex and are influenced by many factors and that there may in fact be an optimal combination of soil type and biochar characteristics. The distribution of biochar particles used in the present study was generally coarser than that of soil particles (Table 1), and the addition of the <0.25 mm biochar particle size yielded the most significant improvement in K_{sat}. Similarly, the <0.25 mm biochar particle size also yielded optimal soil erosion control under lower biochar application rates. However, a

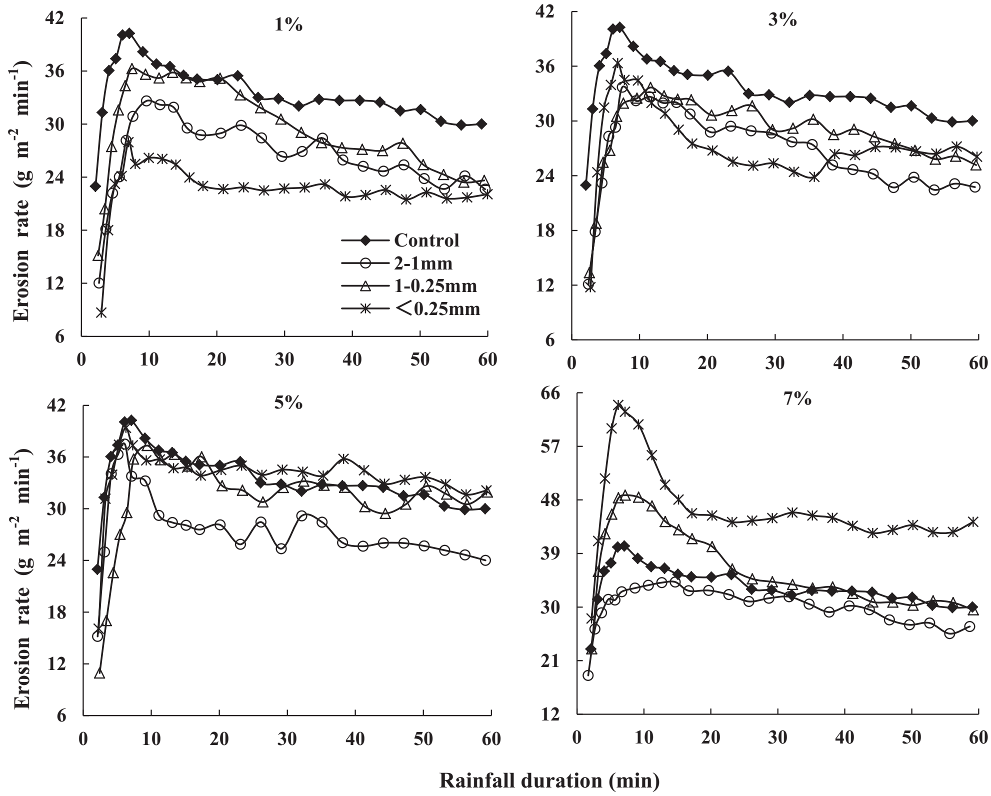

Fig. 5. Effect of the biochar particle size on the erosion rate in each rainfall process.

higher >2 mm water-stable soil aggregate content and more serious soil erosion occurred relative to the other treatments when we applied the 2–1 mm biochar particle sizes. This result could be associated with the soil porosity and the lowest K_{sat} obtained under the 2–1 mm particle sizes, and the main reason for this result was similar to that of the higher biochar application rates, namely, larger biochar application sizes can significantly increase the >2 mm water-stable soil aggregate content but not effectively increase K_{sat}. Additionally, 2–1 mm and <0.25 mm compared with 1–0.25 mm biochar application yielded a higher >2 mm water-stable soil aggregate content. The reasons for the stimulation of soil aggregation could be attributed to variations in the biochar specific surface area for different biochar particle sizes. The specific surface area included the external surface area and inner surface area for porous substances. The larger specific surface area of biochar is mainly due to the surface area of its abundant inner hole. It is known that biochar with a small particle size (1–0.25 mm) has a lower porosity, resulting in a lower specific surface area compared with large biochar particle sizes (2–1 mm). This feature weakens the binding of soil particles, resulting in a lower >2 mm water-stable soil aggregate content. Thus, 2–1 mm biochar application yielded a higher >2 mm water-stable soil aggregate content than 1–0.25 mm. However, the smallest biochar (<0.25 mm) compared with 1–0.25 mm yielded a higher >2 mm water-stable soil aggregate content. This result may be explained by the higher external surface area of the smallest biochar and the much greater level of increase in the higher external surface compared with the decrease in inner surface area due to a decrease in

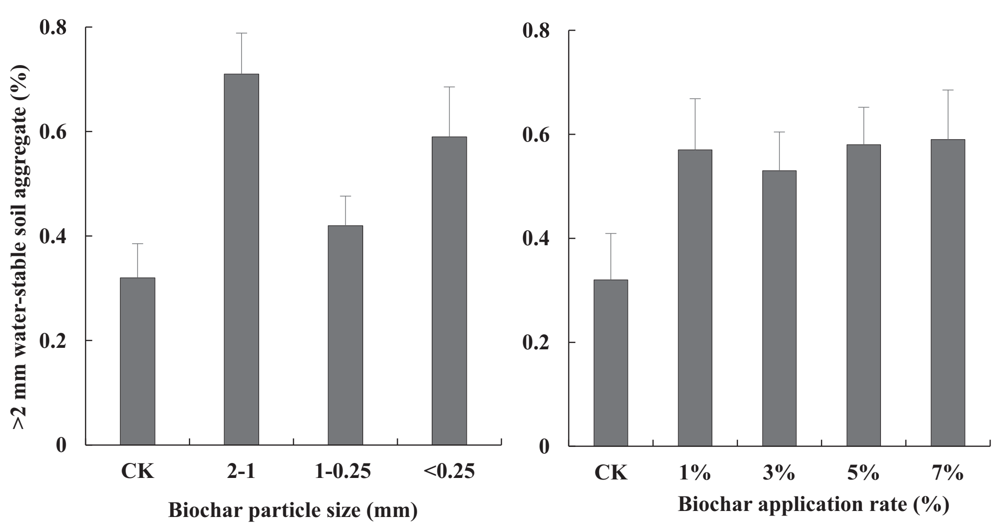

Fig. 6. Effect of the biochar particle size and application rate on >2 mm water-stable soil aggregates.

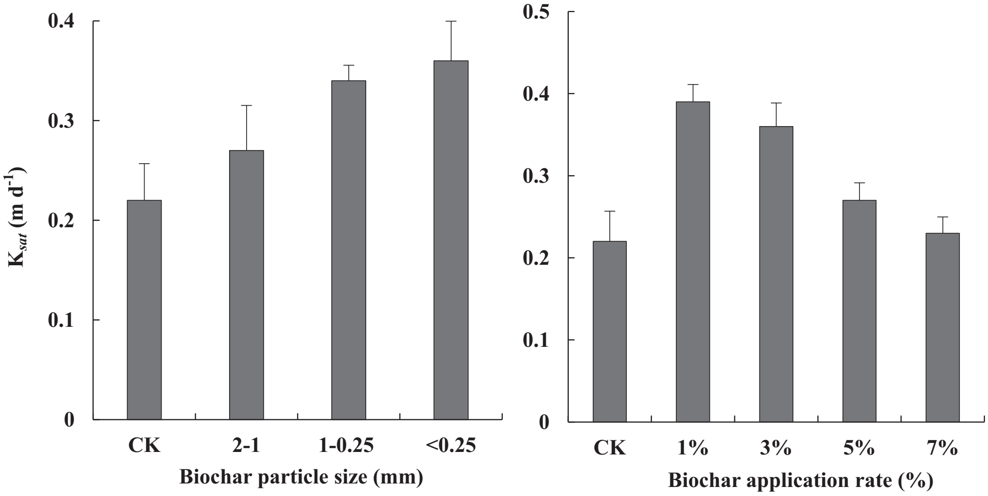

Fig. 7. Effect of the biochar particle size and application rate on K_{sat}.

biochar particle size. This phenomenon contributed to greater content of >2 mm water-stable soil aggregates in <0.25 mm biochar compared with 1–0.25 mm biochar.

The one-way ANOVA results showed that the effect of biochar on soil loss was mainly controlled by the biochar application rates, and the effect of biochar particle sizes on soil loss was negligible (Table 2). The biochar used in this study was considerably coarser than the soil particles themselves (Table 1), which likely resulted in the limited effect of the biochar particle sizes in this study. Therefore, a greater range in biochar particle sizes must be investigated in future studies to explore the effect of biochar particle sizes on soil erosion.

4.3. Implications of the practical application of biochar on cultivated loess slopes

Biochar application methods could change the distribution of biochar in soil and subsequently affect the role of biochar on soil erosion control. In our experiments, we thoroughly mixed biochar with loess, which most closely reflects uniform topsoil mixing conditions and a sufficient interaction between biochar and soil. This corresponds to previous research, such as studies conducted by Jien and Wang (2013), Hseu et al. (2014), and Abrol et al. (2016). Other biochar application methods, such as spreading a given biochar layer over the soil (Sadeghi et al., 2016) and top dressing or deep banding into the soil (O'Laughlin and McElligott, 2009) may result in incomplete interactions between biochar and soil and a large amount of biochar loss washed away with the surface runoff (Rumpel et al., 2006; Nguyen et al., 2008; Major et al., 2010; Wang et al., 2013). In addition, biochar addition by top dressing or deep banding may form a layer of low permeability, causing water to preferentially move horizontally and subsequently producing a lower vertical K_{sat}. Such approaches are less beneficial in studies of the effect of biochar on K_{sat} and soil erosion in comparison to the uniform mixing method applied in this study.

Biochar particle sizes and application rates should be considered together to evaluate the effect of biochar addition on soil erosion for practical applications in cultivated loess slopes. Our study showed that the effect of biochar on soil loss was mainly controlled by the application rate compared with the particle size and the interaction between them. The stability of applying biochar to soil is widely known (Liang et al., 2010; Lehmann et al., 2012), and the mean residence time has been extrapolated over centuries or even thousands of years (Ameloot et al., 2013; Zimmerman and Gao, 2013). Thus, biochar loss from chemical decomposition is extremely low, and the long-term effect of biochar application rates on soil erosion can be maintained. Nevertheless, biochar is subject to structural fracturing at lower strains than the original biomass (Zimmerman and Gao, 2013), and its mechanical strength is reduced through aging (weathering). Consequently, biochar cannot maintain its original physical size after being incorporated into soil (Spokas et al., 2014) and over a long period. These features imply that the effect of biochar particle size on soil erosion is more complex and uncertain in comparison to the biochar application rate, which could have resulted in the more significant contribution rate of the biochar application rate than the biochar particle sizes in the present study (Table 2). Therefore, in comparison to the biochar particle size, it is more important to consider the effect of the biochar application rate on soil erosion in practical applications.

This study has some limitations. Although we found that the combination of a small particle size (<0.25 mm) and low application rate (1%) of biochar could effectively control runoff, reduce the detachment and transport of soil particles, and ultimately reduce soil erosion by effectively changing the structure of the soil surface and maintaining an overall high K_{sat}, many limitations related to the effectiveness of biochar as a soil supplement remain. One such limitation is the way in which biochar is used, namely, the length of time of studies (biochar decomposition and loss rates) and the potential environmental risk, among others, which has not been investigated. Additionally, we did not identify the critical thresholds of effective application rate and particle size. Moreover, an investigation of the effect of supplemental biochar on soil erodibility has yet to be conducted. Simultaneously, given that most experiments related to the effects of biochar on soil erosion have been conducted indoors (in a laboratory) and few comprehensive studies have been carried out in the field to date, immediate steps are required to comprehend and fill existing gaps in the knowledgebase concerning the commercialized production and large-scale application of biochar.

5. Conclusions

In this study, we explored the effects on soil erosion processes of supplementing soil using three different biochar particle sizes (2–1, 1–0.25, and <0.25 mm) and four biochar application rates (1%, 3%, 5%, and 7%). The results demonstrated that the addition of apple branch-produced biochar generally increased the time to runoff, decreased the mean runoff, and increased the >2 mm water-stable soil aggregate content and K_{sat} relative to the control. However, lower (1% and 3%) and higher (5% and 7%) biochar application rates were generally able to inhibit and promote soil loss, respectively, relative to the control. The combined 1% and < 0.25 mm biochar-loess treatment was the optimal combination for delaying the time to runoff and reducing runoff and soil loss. For all biochar treatments, increasing the biochar application rate could prolong the time to runoff, and no uniform trend was observed with decreasing biochar particle sizes. The total runoff volume increased with a decrease in biochar particle size under 5% and 7% biochar application rates, but no uniform trends were observed under 1% and 3% biochar application rates. The total erosion increased with an increase in biochar application rates and decreased with an increase in biochar particle size. The one-way ANOVA results clearly demonstrated that the effect of biochar on soil loss was mainly controlled by the biochar application rates associated with particle size and the interaction between them. We speculated that the effects of biochar on soil and water loss were potentially due to changes in the >2 mm water-stable soil aggregate content and K_{sat}. This study indicated that biochar addition with a reasonable application rate and particle size could improve the degraded loess slope and control soil erosion to some extent. However, some uncertainties remain pertaining to the effectiveness of biochar on soil erosion. Therefore, additional studies utilizing longer incubation times, varied biochar particle sizes and application rates, various rainfall intensities, and different soil types are necessary before recommending the widespread application of biochar as a soil supplement on loess hillslopes.

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