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Effects of adding biochar of different particle sizes on hydro-erosional processes in small scale laboratory rainfall experiments on cultivated loessial soil

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ABSTRACT

Adding biochar to soil is an efficient method to improve soil physicochemical properties. Understanding the effect of this method on soil and water loss is also important. However, there is insufficient data available to assess this effect. Thus, a simulated rainfall (intensity 90 mm h^{-1}) study was conducted to explore the effect of biochar particle sizes (2–1, 1–0.25, and < 0.25 mm) and incubation times (0 and 8 months) of biochar and soil mixture on soil and water loss. Our experiments consisted of measuring soil loss, surface runoff, > 2 mm water-stable soil aggregate content, and soil saturated hydraulic conductivity (K_{sat}) from a perforated box (1 m long and 0.4 m wide) with a 27% slope gradient that contained soil, with a constant application rate of biochar at 1% (wt/wt). Soil without biochar was used as the control. The results indicated that biochar-treated soil delayed the time to runoff compared to the control by 12.67% to 32.58%, with the smallest particle size (< 0.25 mm) and 8 months incubation being the most effective. In general, all tested biochar particle sizes had some control on soil and water loss. The total runoff volume after biochar additions of 2–1, 1–0.25, and < 0.25 mm particle sizes decreased by 2.04%, 24.21%, and 29.63% and by 14.72%, 13.83%, and 30.76% with no incubation and 8 months of incubation, respectively, while the total erosion decreased by 12.86%, 34.30%, and 34.29% and by 20.41%, 11.85%, and 31.93% with no incubation and 8 months of incubation, respectively, compared to the control. Eight months of incubation could effectively decrease both the total runoff and amount of erosion only for soil amended with 2–1 mm biochar particles compared to those with no incubation. Furthermore, 2–1, 1–0.25, and < 0.25 mm biochar treatments could increase > 2 mm water-stable soil aggregate content and K_{sat} relative to the control. We speculated that the positive effects of biochar on soil and water loss were possibly due to an improvement in soil physical properties, such as an increase in the > 2 mm water-stable soil aggregate and K_{sat}.

1. Introduction

Biochar, also known as agrichar, is a carbon-rich product derived from the thermal decomposition of a wide range of carbon-rich biomass materials, such as livestock manure, sewage sludge, crop residue, wood, and compost (Sohi et al., 2010; Yuan et al., 2011). Biochar, as a soil amendment, has received increased attention because of its many beneficial impacts on soil physical properties. Previous studies have shown that biochar can enhance soil water-holding capacity (Dugan et al., 2010; Obia et al., 2016), improve soil structure by maintaining soil aggregation stability (Busscher et al., 2010; Jien and Wang, 2013; Hseu et al., 2014; Burrell et al., 2016), reduce soil bulk density, shear strength, and penetration resistance (Busscher et al., 2010; Laird et al., 2010; Verheijen et al., 2010), increase apparent porosity, field capacity, and the microaggregate stability of soil (Liu et al., 2012; Liu et al., 2016; Obia et al., 2016; Omondi et al., 2016) and change K_{sat} in response to different soil textures (Jien and Wang, 2013; Bayabil et al., 2015; Lim et al., 2016; Gao et al., 2018). In addition to the impacts on the physical properties of soil, biochar amendment can also increase soil fertility and crop productivity by reducing the leaching of nutrients

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and supplying nutrients to plant growth (Glaser et al., 2002; Lehmann et al., 2003; Major et al., 2010; Han et al., 2016; Pandian et al., 2016). The effects of adding biochar on soil physicochemical properties might vary in relation to the length of time of its incorporation into soil. A longer time was found to be more beneficial for improving soil properties because biological and abiotic processes that are both involved in biochar decomposition take time (Lehmann et al., 2011; Jien and Wang, 2013; Kasin and Ohlson, 2013; Mukome et al., 2014). On the other hand, biochar application has been suggested to mitigate global climate change by reducing emissions of NO_x and CH_4 to the atmosphere, sequestering carbon in the soil, and controlling the mobility of a variety of environmental pollutants such as heavy metals, pesticides and other organic contaminants (Lehmann et al., 2006; Sohi et al., 2009; Verheijen et al., 2010; Qin et al., 2016).

Soil erosion is one of the most serious environmental problems in the world, and approximately 90% of the world's agricultural land suffers slight to severe erosion (Speth, 1994). Soil and water loss can reduce soil productivity and crop yield by reducing available water and removing on-site soil that is rich in nutrients (Pimentel et al., 1995; Quinton et al., 2010). Previous studies regarding the benefits of biochar on soil quality have been carried out on the flat croplands. Most results have shown that adding biochar can improve the quality of flat croplands (Laird et al., 2010; Jien and Wang, 2013; Peake et al., 2014). Considering the significant adverse impacts that are induced by soil erosion on both soil quality and its inhabitants of sloped croplands, some researchers question whether biochar can be used to improve the degraded soil and prevent the degradation of sloped croplands based on previous results that suggest its effect on soil properties on the flat croplands. Its benefits for improving degraded sloped croplands will be more meaningful than its use for improving flat croplands without soil erosion. However, the key difference between the sloped croplands and the flat croplands for biochar application is soil erosion. Understanding how biochar addition affects soil erosion on sloped croplands is of primary importance before biochar is used to improve sloped croplands.

Recently, most studies related to amending soils with biochar have focused on greenhouse gas emissions, soil fertility, crop production, and soil physicochemical properties, as described above, whereas few studies have examined the effects of biochar application on soil erosion. Jien and Wang (2013) and Hseu et al. (2014) found that adding biochar to soil could significantly reduce soil loss and that soil loss decreased with an increasing biochar application rate. However, the studies have mainly focused on analyzing the improvements in physicochemical properties of soil and have provided limited data on total erosion. Lee et al. (2015) studied the synergistic effects of biochar and polyacrylamide on plant growth and soil erosion and found that biochar addition reduced soil loss on gentle slopes regardless of whether rainfall was simulated (10% slope) or natural (2.58% ± 0.33% slope). Similarly, Smetanová et al. (2013) also found that 10% (vol/vol) biochar addition could decrease runoff. Sadeghi et al. (2016) studied the variations in runoff and soil loss from small plots treated with biochar that was produced from vinasse under a rainfall simulation. Although their results showed that the application of vinasse-produced biochar could effectively control runoff and soil loss, they did not incorporate the biochar into the soil (it was spread over the soil surface as a 3 cm layer) and their rainfall duration was short (15 min). Peng et al. (2016) found that the effect of biochar on runoff and sediment yield on the ultisol hillslopes was negligible under natural rainfall conditions over a one-year period, and the main reason for this finding may be related to the different soils used. Ultisols (29.1% sand, 33.9% silt, and 37.0% clay), with a homogeneous distribution of soil particle size, were used by Peng et al. (2016). However, the compositional distribution of soil particles was inhomogeneous in other studies (Jien and Wang, 2013; Hseu et al., 2014; Lee et al., 2015; Abrol et al., 2016; Sadeghi et al., 2016). Additionally, previous studies have also shown that biochar or black carbon can be easily removed from the soil surface together with runoff and sediment (Rumpel et al., 2006; Nguyen et al., 2008; Major et al., 2010; Wang et al., 2013), and thus the erodibility of biochar may limit its potential beneficial effects on controlling soil erosion. As noted above, the role of biochar amendment on controlling runoff and soil loss is complicated and it further study is necessary.

The effect of biochar on soil improvement has also been linked to biochar particle size, which influences soil physicochemical properties as well as soil erosion (Jien and Wang, 2013; Liu et al., 2016). The addition of larger (1–5 mm) and smaller (< 0.5 mm) particle sizes of biochar have both been shown to have stronger positive effects on soil physical properties than mid-sized biochar particles (0.5–1 mm) (Obia et al., 2016). Reddy et al. (2015) also found that the hydraulic conductivity and shear strength of soil increased, and the compressibility of soil decreased with an increase in biochar application rate and a decrease in biochar particle size. However, the potential influence of biochar with different particle sizes and incubation time of the biochar and soil mixture on runoff and soil loss has not yet been investigated. In particular, we considered that biochar has a time effect on soil improvement. Thus, the objective of the present study was to analyze the effects of adding biochar of different particle sizes to soil and varying the incubation time of the biochar and soil mixture on the hydrologic and erosive processes during simulated rainfall, as well as identify the influencing mechanisms by analyzing the variation in properties of soil amended with biochar. Our results are expected to provide a greater understanding of the role of biochar in the soil system and its effect on the environment and agriculture.

2. Materials and methods

2.1. Soil and biochar

The soil used in the tests was a cultivated loessial soil (Calcaric Cambiols, Food and Agriculture Organization) from Ansai County in the Shaanxi Province, which is located in the northern part of the Loess Plateau. Ansai (36°51′N, 109°19′E) has a mean annual temperature of 8.8 °C with 500 mm of annual precipitation (Liu et al., 2014). The soil was classified as a silt loam (30.2% sand, 60.87% silt, 8.93% clay, and 1.94 $g\,kg^{-1}$ organic matter) based on definitions provided by the U.S. Department of Agriculture (Table 1). The soil was collected from the top 0–20 cm layer of cultivated land and its field capacity, wilting point, and bulk density were 20%–28%, 3%–10% and 1.0–1.2 $g\,cm^{-3}$, respectively. The collected soil was air dried, crushed to pass through a 5 mm sieve, and thoroughly mixed.

The biochar (supplied by Shaanxi Yixin Biological Energy Science and Technology Development Company) consisted of clipped apple

Table 1
Essential physicochemical properties of experimental materials.

Experimental materials	Particle size (mm)	Particle content (%)					Organic carbon ($g \cdot kg^{-1}$)
		2–1	1–0.25	0.25–0.05	0.05–0.002	< 0.002	
Soil sample		–	–	30.20	60.87	8.93	1.94
Biochar	< 2	20.22	30.02	22.47	25.68	1.60	467.47
	< 1	–	39.46	33.23	25.97	1.33	
	< 0.25	–	–	78.25	20.50	1.25	

branches that were subjected to a pyrolysis temperature of approximately 550 °C. After pyrolysis, the resulting biochar was pulverized to pass through 2, 1, and 0.25 mm sieves to provide biochar with different particle sizes (2–1, 1–0.25 and < 0.25 mm). The basic properties of both the soil and biochar are presented in Table 1.

2.2. Experimental design

During this study, biochar of each size range was thoroughly mixed into soil's plough horizon (0–20 cm) based on the farmer use and application procedure and was then packed uniformly into the experimental box to a total depth of 25 cm with a bulk density and moisture content that were similar to the plough layer. To a certain extent, this procedure ensured that the artificial treatments of soil and biochar were meant to resemble natural soil conditions and land management and that the obtained results can be used in practical applications.

We used three different particle sizes (2–1, 1–0.25, and < 0.25 mm) of biochar mixed into one soil type (described above) with an application rate of 1% (wt/wt). The particle sizes and application rate were based on previous studies that used biochar in cropland soil (Abel et al., 2013; Qi et al., 2014; Liu et al., 2016). Soil without biochar amendment was used as the control. Dried and sieved soil was mixed thoroughly with each size range of sieved biochar at a designed application rate. All soil-biochar mixtures were divided into two parts. One part together with the control were adjusted to an approximate 10% water content, and were immediately used for simulated rainfall experiments. The second part was incubated in a plastic bucket with a field water capacity of approximately 20% except for the control because we assumed that the properties of soil without biochar were relatively stable under natural conditions over time. 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 time was designed to be longer than reported studies (Jien and Wang, 2013; Hseu et al., 2014; Sadeghi et al., 2016) to explore the time effect of biochar addition on soil erosion and soil properties. In addition, the length of incubation time was determined by assuming that severe soil erosion on the Loess Plateau occurs during the summer and autumn, and rainfall was easy to simulate during this period because the Simulated Soil Erosion Experiment Hall was only running in this period. After incubation, the soils amended with biochar were air-dried again, crushed to pass through a 5 mm sieve and adjusted to an approximate 10% water content together with the control before placing the control soil and mixture into box.

A perforated metal box (1 m length, 0.8 m width, 0.4 m depth) with an adjustable slope gradient from 0% to 70% was used to contain the soil and biochar mixture. The box was evenly divided into two parts (1 m length, 0.4 m width, 0.4 m depth) by a metal board and served as replicates for each simulated rainfall experiment. A collection funnel outlet was located at the lower edge of each part to collect runoff and sediment samples. 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 storms that occur on the Loess Plateau (Tang, 1990) and land with a slope of 27% (between 18% and 37%) is widely distributed in this area. A total of seven simulated rainfall experiments and fourteen tests were conducted in the laboratory.

2.3. Soil box preparation

The prepared mixture of soil and biochar or untreated soil was packed uniformly into the experimental box in 5-cm-thick layers to a total depth of 25 cm over a 5-cm layer of coarse sand. To reduce discontinuities between layers, the surface of each soil layer was gently scored before packing the next layer. The top surface layer was smoothed to minimize microtopographic effects. The bulk density was approximately 1.15 g cm^{-3}, which was almost equal to that of the soil under natural conditions in sloped cropland. The prepared box was placed under the rainfall simulator for the rainfall experiment with a designed slope gradient of 27%.

2.4. Rainfall simulation and measurements

Rainfall simulations were conducted in the Simulated Rainfall 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 Ministry of Water Resources, Yangling. We used a homemade needle-type simulator rainfall system similar to that described by Zhao et al. (2014). This system consisted of a rainfall generator with a constant rate of water supply; however, for the water supply, we replaced the Markov bottle of Zhao et al. (2014) with a peristaltic pump (BT-600C) with an output flow 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 water tank (effective rainfall area of 1.0 m × 1.2 m), drop former (8# syringe steel needles), and a needle plate vibration generator. Steel syringe needles protruded through the bottom of the water tank in a regular pattern following a square design (2 cm × 2 cm). The needle plate was gently oscillated horizontally by the vibration generator, which consisted of eccentric wheels driven by a motor to release raindrops in 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 water was used for all simulated experiments.

Rainfall intensity was set at 90 mm h^{-1}; this was calibrated prior to the experiment by adjusting the relative water depth in the water bank using the peristaltic pump. Simulated rainfall was generally applied for 60 min for each rainfall event, and one rainfall event was performed for each treatment. During the simulated rainfall, the time to runoff was recorded, and sediment and runoff from the box was collected continuously by 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, the samples collected in each of the plastic containers were weighed. The sediment collected in each sample was allowed to settle for 24 h and was then separated from the water by siphoning, oven dried at 105 °C until a constant mass was achieved, and then weighed. The runoff amount and sediment yield were then determined for each sampling interval.

Soil aggregate is considered one of the main soil properties that regulates 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, runoff and soil losses (Dexter et al., 2004). In this study, the > 2 mm water-stable soil aggregate contents were measured by wet sieving and were oven-dried and weighed. K_{sat} was measured using the constant head method, which was followed using the methods documented by Black (1965). The rainfall experiments and measurement of > 2 mm water-stable soil aggregate and K_{sat} consisted of two stages. The first stage was performed in October 2014, and after incubating soil-biochar mixtures for 8 months, the second stage was performed in June 2015. The averaged values of soil aggregate and K_{sat} were eventually determined by measuring three samples for each treatment and the means of time to runoff, runoff and soil loss with the replicate tests were used in all data analysis process.

3. Results

3.1. Effect of biochar on runoff

Fig. 1 presents the time to runoff for each treatment in our study. The control had the shortest time to runoff for all treatments. The time to runoff was delayed by 12.67% to 32.58% for all biochar treatments, regardless of biochar particle size and incubation time, compared to the

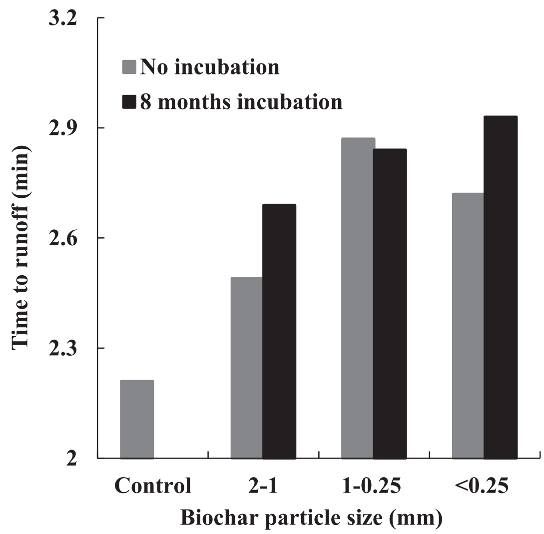

Fig. 1. Effect of biochar with different particle sizes on the averaged time to runoff.

control. The time to runoff for different particle sizes of biochar treatment with no incubation ranked in order of longer to shorter times was 1–0.25, < 0.25, and 2–1 mm, but for the biochar treatments with 8 months incubation, the time to runoff increased with the decreasing particle size of biochar. There was little difference in the time to runoff between no incubation and 8 months incubation for the 1–0.25 mm biochar treatment, whereas the time to runoff for the 2–1 mm and < 0.25 mm biochar treatments with 8 months incubation was delayed 9.1% and 9.5% compared to no incubation. These results demonstrated that our tested biochar particle sizes were beneficial for delaying the time to runoff and that this benefit varied according to biochar particle size and incubation time. A smaller particle size of biochar and a longer incubation time could enhance the effect of biochar on the time to runoff. Overall, the variation in the time to runoff among all tests was small.

Fig. 2 presents the dynamics of the runoff rates for each treatment during the simulated rainfall. In general, the runoff rates showed similar trends for all treatments, and two distinct stages, i.e., a rapid increase in the first 6–10 min of rainfall and then a quasi-steady state or slight increase with smaller fluctuations, were identified. The difference in runoff rates among treatments was smaller in the first stage, but this increased among some treatments during the second stage. With the exception of the 2–1 mm biochar addition with no incubation, the biochar treatments had significantly lower runoff rates than the control during rainfall process. The 2–1 mm biochar treatment with no incubation had a lower runoff rate compared to the control for approximately the first 32 min of rainfall, after which its runoff rate was slightly higher than that of the control.

For the biochar treatments with no incubation, although some runoff rates were similar between the 1–0.25 mm and < 0.25 mm biochar treatments, in general, the runoff rates decreased with decreasing biochar particle size. For the biochar treatments with 8 months incubation, the < 0.25 mm biochar treatment had much lower runoff rates compared to biochar particle sizes of 1–0.25 mm and 2–1 mm. Although smaller differences in runoff rates between the 1–0.25 mm and 2–1 mm biochar treatments were apparent, runoff rates from the 1–0.25 mm particle sizes were slightly higher than those of the 2–1 mm particles in the first 32 min of rainfall, after which the rates were slightly lower than those of the 2–1 mm treatment. In addition, runoff rates from the 2–1 mm and < 0.25 mm biochar treatments decreased, whereas those from the 1–0.25 mm treatment increased, after the 8-month incubation period.

During the rainfall events, the total runoff volume produced from soil without biochar addition was greater than that from the biochar-treated soils (Fig. 3). For the biochar treatments with no incubation, the total runoff volume decreased by 2.03%, 24.21%, and 29.63% for the 2–1, 1–0.25, and < 0.25 mm particle sizes, respectively, compared to the control. We found a negative correlation between the reduction of runoff volume and biochar particle size. Biochar treatments with 8 months incubation showed a significant decrease in the total runoff volume (by 14.72%, 13.83%, and 30.76% for the 2–1, 1–0.25, and < 0.25 mm biochar treatments, respectively) compared to the control. The < 0.25 mm particle size had the greatest decrease in runoff regardless of incubation time. Furthermore, the runoff volume for treatments with 8 months incubation was less than that of samples with no incubation for 2–1 mm and < 0.25 mm biochar addition (by 12.68% and 1.12%, respectively). In contrast, the total runoff volume for the 1–0.25 mm biochar addition increased after the 8-month incubation period compared to no incubation.

Overall, our results indicated that 1% biochar addition could reduce runoff production regardless of the biochar particle size or incubation period. However, the effectiveness of controlling runoff varied according to the biochar particle size and incubation length. Biochar with a smaller particle size appeared to be more effective in reducing runoff production than biochar with a larger particle size, but the effect of incubation on runoff production differed among the different particle sizes.

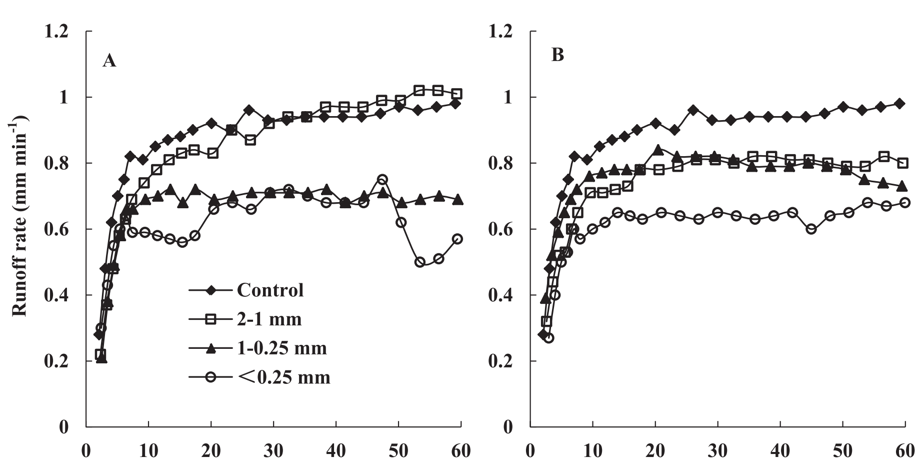

Fig. 2. Effect of biochar with different particle sizes on the averaged runoff rates during each rainfall event under no incubation (A) and 8 months incubation (B).

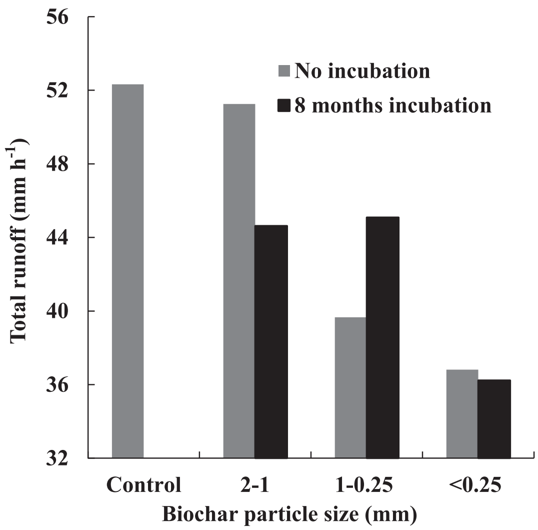

Fig. 3. Effect of biochar with different particle sizes on the averaged total runoff.

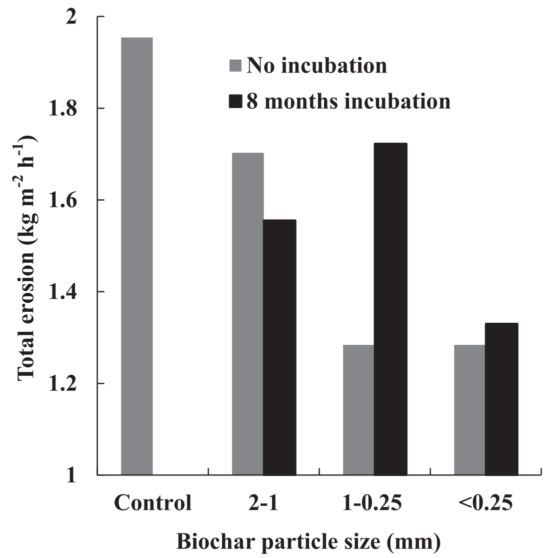

Fig. 5. Effect of biochar with different particle sizes on the averaged total erosion.

3.2. Effect of biochar on soil loss

We found marked differences in erosion rates among the control, 2–1, 1–0.25, and < 0.25 mm biochar treatments during each rainfall event (Fig. 4). In general, the trends of erosion rates were similar for all treatments. Similar to the runoff, two distinct stages, a rapid increase within the first 6–10 min of rainfall and then a slight decrease with greater fluctuations for no incubation treatments and smaller fluctuations for 8 months incubation, were identified. The erosion rates for biochar treatments were notably lower than that of untreated soil.

Among the three biochar treatments with no incubation, the soil erosion rates reached a peak during the initial 7 min of rainfall and then showed a decreasing trend with an increase approximately midway through the rainfall period. Erosion rates for the < 0.25 mm biochar addition fluctuated markedly, reaching rates that were at times greater than those for the 1–0.25 mm biochar. By the end of the rainfall simulation, erosion rates for the < 0.25 mm biochar addition were lower than those for all other treatments. The erosion rates for the 2–1 mm biochar treatment were always higher than those for the 1–0.25 mm particle size and always less than those of the control.

With 8 months incubation, the erosion rates for the different particle sizes of biochar treatment were the highest for the 1–0.25 mm treatment and the lowest for the < 0.25 mm treatment during the simulated rainfall. The differences in erosion rates among the three particle sizes gradually increased in the early and middle stages of rainfall, but this difference gradually decreased during the second half of the rainfall period. In addition, 8 months incubation of the 2–1 mm biochar treatment resulted in soil erosion rates that were less than those of the same treatment with no incubation. In contrast, the 1–0.25 mm and < 0.25 mm biochar addition with 8 months incubation produced higher erosion rates than the same treatments with no incubation (Fig. 4B).

Fig. 5 presents the total erosion (kg m^{-2} h^{-1}) for each treatment. The untreated soil produced higher total erosion than all biochar treatments. Total erosion was reduced by 12.86%, 34.30%, and 34.29% for the 2–1, 1–0.25, and < 0.25 mm particle sizes with no incubation and by 20.41%, 11.85%, and 31.93% for these treatments with 8 months incubation, respectively, compared to the untreated soil. The 1–0.25 mm and < 0.25 mm biochar treatments with no incubation resulted in the lowest total erosion for all treatments. With 8 months incubation, total erosion was lowest for the < 0.25 mm biochar addition, intermediate for the 2–1 mm addition, and highest for the 1–0.25 mm particle size. Furthermore, total erosion after 8 months incubation was greater than that for no incubation, except for the 2–1 mm biochar addition, which is inconsistent with the findings of the total runoff volume (Fig. 3).

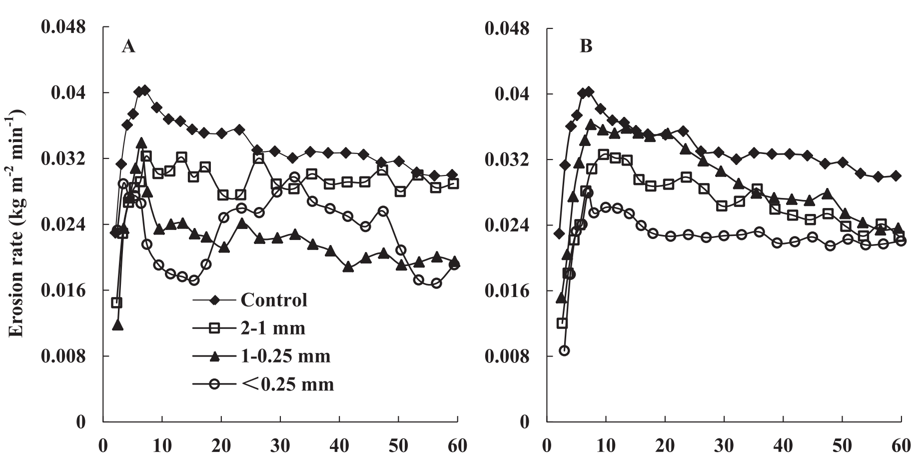

Fig. 4. Effect of biochar with different particle sizes on the averaged erosion rates during each rainfall event under no incubation (A) and 8 months incubation (B).

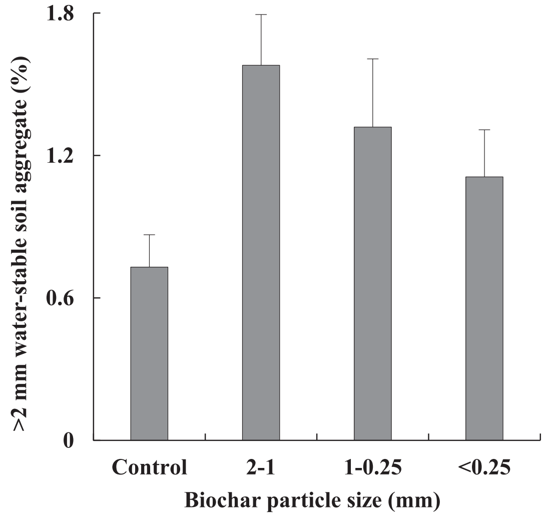

Fig. 6. Effect of biochar with different particle sizes on the averaged > 2 mm water-stable soil aggregate content.

3.3. Effects on aggregates and saturated hydraulic conductivity

In this experiment, the formation of macroaggregates in soils amended with biochar was the critical factor to improve soil erosion potential. Thus, the average aggregate of the soil and biochar mixture was surveyed after 8 months of incubation. In general, the stability of > 0.25 mm water-stable soil aggregate was used to assess the soil resistance to erosion (Barthès and Roose, 2002). However, 2–1 mm and 1–0.25 mm biochar particles were included within > 0.25 mm water-stable soil aggregate, thus the > 2 mm water-stable soil aggregate content was used to illustrate the effect of biochar addition on soil aggregate stability and was analyzed in our study (Fig. 6). After 8 months incubation, the > 2 mm water-stable soil aggregate content of the biochar-amended soils increased significantly from 0.73% to 1.58%, and the rate of increase decreased with the biochar particle sizes (Fig. 6).

In addition, K_{sat} was measured for all tests (Fig. 7). The results indicated that biochar addition caused an increase in K_{sat} relative to the control. Although no significant differences in K_{sat} between the amended biochar soil for no incubation and the control were found, K_{sat} tended to increase slightly with the decreasing biochar particle sizes.

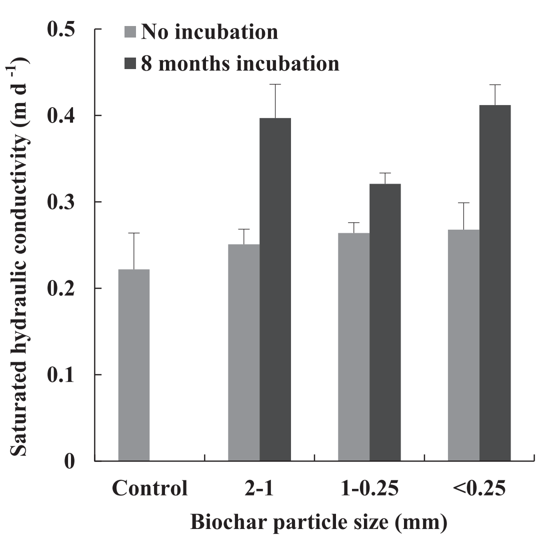

Fig. 7. Effect of biochar with different particle sizes on the averaged soil saturated hydraulic conductivity.

After 8 months of incubation, K_{sat} was higher than that of no incubation for all treatments. The lowest $K_{sat,}$ with a value of 0.32 m d^{-1}, and the highest, with a value of 0.41 m d^{-1}, occurred in the 1–0.25 mm and < 0.25 mm biochar-amended soil, respectively. This indicated that biochar addition after 8 months of incubation could increase the > 2 mm water-stable soil aggregate content and improve K_{sat} relative to the control.

4. Discussion

The addition of biochar has been shown to alter the physicochemical properties of soil (Lehmann et al., 2011; Herath et al., 2013; Mukherjee and Lal, 2013; Laghari et al., 2015; Han et al., 2016). These alterations in soil properties directly impact soil infiltration and soil erodibility, and consequently, runoff and sediment production. The results from our study showed that a 1% biochar addition to soil markedly delayed time to runoff, decreased runoff rates, and reduced erosion rates regardless of biochar particle size and incubation time relative to untreated soil. Our results confirmed that a reasonable percentage of biochar addition to soil could help to control soil loss under certain conditions; these findings are consistent with previous studies (Jien and Wang, 2013; Hseu et al., 2014; Lee et al., 2015; Sadeghi et al., 2016).

Biochar amendment can increase the soil porosity by providing large pores inside the biochar particles and from pores between the biochar and soil particles (Masiello et al., 2015), which permit water migration, change the tortuosity of flow paths, and increase hydraulic conductivity (Herath et al., 2013). In this study, the similar results that biochar treatments could increase K_{sat} relative to the control, especially for < 0.25 mm biochar treatment after 8 months incubation (Fig. 7), were observed. Meanwhile, the longest time to runoff, the lowest total runoff and lower erosion also occurred under < 0.25 mm biochar treatment after 8 months incubation. These suggested that the increase in K_{sat} after biochar addition might be an important factor for the reduction of runoff and soil loss in this experiment. The results were consistent with Jien and Wang (2013) and Hseu et al. (2014), who reported that the application of biochar could increase K_{sat} and reduce soil loss.

Previous studies have also shown that biochar addition significantly increased soil aggregate sizes and soil stability (Liu et al., 2012; Awad et al., 2013; Herath et al., 2013; Ouyang et al., 2013; Soinne et al., 2014; Sun and Lu, 2014). This increase in soil aggregation can be attributed to biochar surface characteristics, which result in the direct binding of soil particles or the sorption of soil organic matter (Brodowski et al., 2006; Joseph et al., 2010). The improvement of aggregation (Fig. 6) in our study might reduce the physical and chemical disintegration of surface soil aggregates, avoid soil seal formation, and subsequently cause an increase in infiltration and a decrease in runoff and soil loss during rainfall (Figs. 3 and 5), as reported by Jien and Wang (2013). Therefore, the increase in the aggregate content of biochar-amended soils might be another important factor for reducing soil and water loss of the biochar addition soil in this study.

Our results indicated that there were no uniform trends in runoff and erosion rates with decreasing biochar particle size. In general, the smaller biochar particle sizes were more efficient in delaying the time to runoff and reducing runoff and erosion rates (Figs. 1, 2 and 4). To the best of our knowledge, no study to date has focused on the effect of adding different biochar particle sizes to soil on soil and water loss. We propose that the effect of biochar particle size on soil and water loss resulted from the changes to K_{sat} and aggregate content of the biochar-amended soil (Figs. 6 and 7). However, the responses of biochar particle size to K_{sat} and aggregate content of the biochar-amended soil were complex. Liu et al. (2016) found that biochars of different particle sizes have different effects on K_{sat} when the biochar particle size is equal to, greater than, or less than the sand particle size. In general, biochar particles that are coarser or smaller than sand particles could decrease

K_{sat}. However, Qi et al. (2014) found that the effects of biochar particle sizes (2–1, 1–0.25, and < 0.25 mm) on infiltration were associated with the biochar addition rate and soil texture. Similar results were also produced by Obia et al. (2016), who found that the effect of biochar particle size (≤0.5, 0.5–1 and 1–5 mm) on water retention and porosity was more important in loamy sand than in sand. In addition, they found that the addition of larger particle size biochar (1–5 mm) might result in equally strong positive effects on water retention and porosity as powdery biochar (≤0.5 mm). In contrast, adding biochar of 1–0.5 mm particle size had weaker effects on water retention and porosity. In this study, the improvement of K_{sat} and the reduction of soil erosion under < 0.25 mm biochar addition was the highest, but the improvement of > 2 mm water-stable soil aggregate was lowest. In contrast, the highest > 2 mm water-stable soil aggregate content and the most serious soil erosion occurred under 2–1 mm biochar addition. These results were attributed to the different effects of biochar particle sizes on K_{sat} and > 2 mm water-stable soil aggregate content. Although 2–1 mm biochar can increase more > 2 mm water-stable soil aggregate content than < 0.25 mm biochar (Fig. 6), the lower K_{sat} of 2–1 mm biochar addition (Fig. 7) led to the production of more runoff. The effect of increasing total runoff on soil erosion was much stronger than that of the increasing > 2 mm water-stable soil aggregate content. These complex responses of soil properties to biochar particle size might result in the inconsistent trends in runoff and erosion rates with decreasing biochar particle size.

Compared to no incubation, an 8-month incubation could delay the initial time to runoff and reduce runoff and erosion rates for treated soil with 2–1 mm and < 0.25 mm particle sizes of biochar, but the opposite results were observed with 1–0.25 mm particle size (Figs. 1, 3 and 5). Previous studies have indicated that the role of biochar on soil properties had a time effect, and a longer time within the soil was beneficial for the improvement of soil properties (Jien and Wang, 2013; Kasin and Ohlson, 2013; Mukome et al., 2014). Due to the scarcity of experimental data on the effect of incubation of biochar-treated soil on hydro-erosional processes, our explanation of this is based on the effect of incubation on soil physicochemical properties. Jien and Wang (2013), for example, found that the bulk density of biochar-amended soils decreased slightly, whereas porosity and aggregation gradually increased in 2.5% and 5% biochar-amended soil after 60 days. However, we found smaller differences in the runoff and erosion rates between 0 and 8 months incubation in most cases, and the opposite results with 1–0.25 mm biochar. These results are similar to those of Peng et al. (2016), who found that incubation had no significant effect on the dry and wet aggregate stability for biochar-amended soils. In addition, the data of K_{sat} and soil aggregate in this study did not also perfectly explain the effect of incubation time on the variation in soil and water loss. This finding led us to conclude that there are still some uncertainties regarding the effect of incubation time on hydro-erosional variables. Such uncertainties could be attributed to the length of the incubation time and other incubation conditions. More studies are therefore warranted to assess the incubation effect of biochar on soil properties and soil erosion.

5. Conclusions

We explored the effects of amending soil with three different particle sizes (2–1, 1–0.25, and < 0.25 mm) of biochar on soil erosion processes under constant rainfall intensity (90 mm h^{-1}) and slope gradient (27%) conditions. The results indicated that the effects of biochar addition on soil and water loss were significant and variable depending on the particle size. When compared to untreated soil, the addition of biochar significantly delayed the time to runoff and decreased the total runoff volume and soil loss. There were no uniform trends in runoff and erosion rates with decreasing biochar particle size. In general, the smaller biochar particle size was more effective in delaying the time to runoff and reducing the runoff and soil erosion rates. An incubation period of 8 months increased the time to runoff and decreased the runoff volume when larger (2–1 mm) and smaller (< 0.25 mm) particles of biochar were applied; however, the effect of 8 months of incubation on soil erosion was different for different particle sizes of biochar relative to those with no incubation. We speculate that the effect of biochar particle size on soil and water loss might result from the changes to K_{sat} and aggregate content of the biochar-amended soil. However, some uncertainties regarding the effectiveness of this method in preventing soil erosion still exist. For example, varied slopes, rainfall intensities and soil types were not studied, and effective particle size thresholds were not clearly identified. Additionally, the obtained results from the indoor simulated experiment were uncertain in practical applications, and comprehensive studies in the field have not yet been performed. Therefore, further studies are warranted to comprehend and fill existing gaps before recommending the widespread application of biochar as a soil amendment process on loessial hillslopes.

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