

# Application Rate Influences the Soil and Water Conservation Effectiveness of Mulching with Chipped Branches

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Mulching with chipped, pruned branches (MB) is an effective land management practice to reduce surface runoff and to control soil water erosion. The use of MB has extra advantages such as material availability and a low cost compared with other mulching materials, especially in orchards. To evaluate the impacts of application rates on the ecological and economical effectiveness of MB, a plot-scale soil bin experiment was conducted under two representative rainfall regimes. Five treatments were tested: clear cultivation (CC, bare soil without mulching) and four MB application rates of 0.37, 0.74, 1.11, and 1.48 kg m<sup>-2</sup>. The application of MB reduced runoff generation by 15.5 to 78.6% and sediment yield by 40.7 to 98.6% compared to CC. From an ecological view, the soil and water conservation performance of MB generally decreased with increasing rainfall intensity and application rate with an exception of 1.48 kg m<sup>-2</sup> under the heavy rainfall. Different mechanisms, such as soil surface coverage, rainfall interception by mulching, soil permeability, stability of mulching materials, and rill initiation simultaneously affected the effectiveness of MB. From an economical view, this relationship was more complex. The present study confirmed the necessity of determining the proper mulching application rate in the context of site-specific soil, vegetation, and climatic conditions as well as local social status.

**Abbreviations:** CC, clear cultivation; KE, kinetic energy; MB, mulch made of chipped, pruned branches; RSC, ratio of sediment reduction performance to cost; RRC, ratio of runoff reduction performance to cost; RRP, runoff reduction performance; SRP, sediment reduction performance.

Soil erosion is a major threat to land quality and a potential risk for the sustainable development of agriculture of the world (Keesstra et al., 2016). A large proportion of lands in the world are moderately or heavily eroded, increasing the ecological and economical vulnerability (Borrelli et al., 2017). Soil water erosion and the accompanied water runoff are expected to grow in the context of global climate change since intense storms are supposed to be frequent in the future (Borrelli et al., 2017; Marzen et al., 2017; Viola et al., 2016). Mulching has been explored and adopted as an effective type of the best management practice to reduce runoff loss and water erosion for long history (Brevik and Hartemink, 2010). A mulch is a layer of materials other than soil or living vegetation applied to the surface of bare soil or around existing plants (Prosdocimi et al., 2016b). As the threat of soil water erosion is rising worldwide, there is increasing scientific and practical demand to deepen the understanding on the processes and mechanisms of mulching in preventing soil and water loss (Keesstra et al., 2016).

Mulching prevents runoff and soil erosion by different mechanisms such as protecting the soil surface from raindrop-introduced splash erosion, sealing, and crusting (Hu et al., 2016), promoting infiltration during rainfall (Gholami et al., 2014; Rodrigo Comino et al., 2016), reducing the amount, velocity, and connectivity of runoff flow (Cerdà et al., 2016a; Wang et al., 2015) and reducing the available shear-

## Core Ideas

- Soil and water conservation effectiveness of chipped branches mulching was tested.
- Two simulated rainfall events were applied in the experimental condition.
- High application rates may not always be ecologically and economically favorable.

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ing force of runoff for soil detachment (Rahma et al., 2017; Sadeghi et al., 2017). As mulching influences water and soil loss in such a complex way, the efficiency of mulch is simultaneously influenced by some natural factors such as precipitation regime (Marzen et al., 2017; Shi et al., 2013), slope gradient and length (Rodrigo Comino et al., 2016; Sadeghi et al., 2017), soil types (Rahma et al., 2017), and initial soil wetness (Rodrigo Comino et al., 2016), as well as some management factors such as mulch materials (Cerdà et al., 2016b; Copeland et al., 2009), application rate (Foltz and Copeland, 2009; García-Moreno et al., 2013), and pattern (Cai et al., 2015). The optimum application rate is a critical management factor influencing the effectiveness of mulching. Two aspects must be considered to identify the optimized application rate. First is the relationship between application rate and the effectiveness of water and soil conservation. Some previous studies reported that mulching performance is always increasing with application rate (Lin et al., 2018; Donjadee and Tingsanchali, 2016; Gholami et al., 2016; Lattanzi et al., 1974) while others claimed that after a threshold, runoff volume and sediment yield would remain stable or even increase with higher application rate (García-Moreno et al., 2013; Jin et al., 2009; Rahma et al., 2017). Second, as a kind of land management practice, the tradeoff between the efficiency and the cost of mulching should be adequately considered to choose proper application rate (Jabbar et al., 1992; Prosdocimi et al., 2016a). After the designed standards of water and soil conservation are satisfied, further increase in application rate may be economically unfavorable (Meyer et al., 1970). Thus, application rate is vital in mulching practice and should be chosen based on site-specific soil and climatic conditions as well as local social status (Calatrava and Franco, 2011; Prosdocimi et al., 2016b).

Branches chips (also known as wood chips) are a byproduct of the pruning of trees. Mulching with chipped branches (MB) is a common type of mulching; the branches and large stems from pruning are simply cut into segments usually by fodder choppers and then applied to the soil surface. The use of MB is globally and intensively adopted in many cases such as urban road systems, parks, gardens and orchards, for different purposes such as conserving soil moisture, moderating soil temperature and suppressing weed growth (Kargar et al., 2015; Cattan et al., 2006; Wang et al., 2015; Gholami et al., 2016). In these cases, MB usually have unique advantages compared with other mulching types including availability of raw materials, simple and inexpensive application procedures, weaken competition for soil moisture with trees et al. (Calatrava and Franco, 2011; Wang et al., 2015; Jabbar et al., 1992). For the eroded areas, the primary consideration of MB is soil and water conservation (Cerdà et al., 2018; Breton et al., 2016; Gholami et al., 2016; Copeland et al., 2009; Cerdà et al., 2016b). Although the effectiveness of MB in reducing runoff generation and soil water erosion have been widely confirmed (Gholami et al., 2016; Cerdà et al., 2016b; García-Orenes et al., 2009), the studies focused on the proper application rate of MB are still limited. The relationship between soil and water conservation benefits of MB and its application rate has not yet been fully investigated, especially under different precipitation regimes. Further, the information

about the balance between cost and effectiveness of MB is also required. Thus, there is a need to investigate the proper application rate of MB from both ecological and economical aspect.

In this paper, the Chinese loess plateau region, which is well known for serious soil water erosion and soil water shortage (Gao et al., 2016; Pan et al., 2017a) was selected as the case to investigate these relationships. Since 1999, about 0.8 million hectares of orchards (mainly jujube and apple) were established and orchards had become the major land use type. In these orchards, bare soil and vegetation covers are main types of land management practice. Bare soil management leads to great soil erosion and surface runoff (Huang et al., 2014; Li et al., 2016a; Zhou and Wang, 1992). While vegetation covers strongly compete for the limited soil water with orchard trees (Huang et al., 2014; Feng et al., 2016). Every year, large number of branches chips are produced from pruning, making MB a promising and inexpensive alternative of traditional land management practice (Wang et al., 2015). In the present study, an experiment using simulated rainfalls was conducted to (i) evaluate the efficiency of MB in reducing water and soil loss in plot scale, and (ii) identify the ecologically and economically proper application rate of MB in the Chinese loess plateau. The authors believe that the results would provide useful information to optimize the application of mulching with chipped branches in the world, especially in the moderately or heavily eroded areas.

## METHODS AND MATERIALS

### Establishment of Experimental Plots

The laboratory experiments were conducted in an experiment station of Institute of Water Saving Agriculture in Arid Regions of China, Northwest A&F University, Yangling (4°14' N, 108°04' E), a county in the south Loess Plateau, China (Supplemental Fig. S1). Bins ( $n = 15$ ), 2 m long, 0.8 m wide, and 0.8 m high, were equipped with surface runoff collectors (Fig. 1). The bins were filled with sieved (10-mm square aperture sieve), homogenized, air-dried soil (6–10% volumetric water content) collected from the top layer (0–30 cm) of a local jujube orchard in the late autumn, 2014. The bins were filled by packing soil in eight, 10-cm-deep layers to achieve a bulk density of  $1.35 \text{ g cm}^{-3}$ , in accordance with the typical value in traditional local jujube orchards (Li et al., 2016b). Each layer was lightly raked before packing the next layer to minimize discontinuities between layers. Each plot was mounted on four wheels to facilitate transportation. The soil is silt loam according to the USDA soil taxonomy (USDA, 2010) and contained 10% sand (2–0.05 mm), 72% silt (0.002–0.05 mm) and 18% clay (<0.002 mm).

According to a previous survey, pruning produces MB at a rate about  $0.37$  to  $1.50 \text{ kg m}^{-2} \text{ a}^{-1}$  (air-dried,  $25^\circ\text{C}$ , 50% relative humidity), depending on the planting density, stand age, pruning strategy, and other factors of the local jujube orchards. So, five treatments with different MB application rate levels were selected in the experiment: clear cultivation (CC, bare soil without mulching) and MB at  $0.37$ ,  $0.74$ ,  $1.11$ , and  $1.48 \text{ kg m}^{-2}$ . Each treatment was replicated three times in a completely randomized design. The applied jujube branches were obtained from the

autumn pruning of the jujube orchard in the year 2015 (1 Nov. 2015). At the end spring of 2016, the branches were cut into 5- to 10-cm long pieces on site in the local jujube orchard by fodder choppers and transported to the experiment station, and finally uniformly mulched on soil surface (about 2-cm thick) in the soil plots at the given application rate before the simulated rainfall (Fig. 1). The diameter of chipped branches ranged from 0.2 to 2.0 cm. A photo of the employed chipped jujube branches was shown in Supplemental Fig. S2. Ground coverage (the ratio of soil surface area covered by mulches to the total area of soil surface) of MB treatments were determined by analyzing photos with ImageJ software (US National Institute of Health).

### Rainfall Regimes and Measurements

All the simulated rainfall was generated by a needle-type rainfall simulator. The rainfall simulator consists of three parts: (i) a raindrop producer, (ii) a rainfall intensity adjustment/control apparatus, and (iii) the water supply device. According to previous studies, median raindrop diameter ( $D_{50}$ ), dropping height (H), kinetic energy (KE), and rainfall uniformity (U) can greatly influence the processes of runoff generation and soil erosion (Iserloh et al., 2012; Zhou and Wang, 1992). The  $D_{50}$ , KE, and U values of the current simulated rainfalls were 2.2 mm,  $17.7 \text{ J m}^{-2} \text{ mm}^{-1}$ , and 86%, respectively (measured by a laser precipitation monitor; Thies Clima, Germany). In Yangling, the mean  $D_{50}$  and KE of natural erosive rainfalls are about 2.0 mm and  $24.1 \text{ J m}^{-2} \text{ mm}^{-1}$ , respectively (Wu et al., 2011). According to the field survey in the orchards, during the erosive rainfalls the mean  $D_{50}$  and KE were about 2.6 mm and  $19.2 \text{ J m}^{-2} \text{ mm}^{-1}$ , respectively, under the jujube trees' crown. Thus, the  $D_{50}$  and KE of the simulated rainfalls were 110 and 74% of those of the local natural rainfalls and 85 and 92% of those of the throughfall. More detailed information about the rainfall simulator can be found in Pan et al. (2017b) and Huang et al. (2014). For soil and water conservation purposes, accumulated KE is usually employed as a standard to evaluate the rainfall erosivity (Hu et al., 2016; Neumann et al., 2017; Vaezi et al., 2017). In the Chinese Loess Plateau, rainfalls with accumulated KE higher than  $1200 \text{ J m}^{-2}$  will lead considerable soil erosion and are thus defined as 'common erosive rainfall'. While rainfalls with accumulated KE higher than  $2000 \text{ J m}^{-2}$  are defined as 'extreme erosive rainfall' because serious soil erosion will occur (Wu et al., 2011; Zhou and Wang, 1992). The typical duration of erosive rainfalls is about 30 to 100 min (Zhou and Wang, 1992). Based on these thresholds and the kinetic energy of the simulated rainfall, two representative precipitation regimes were selected in the present study: (1) light rainfall, 60 min with a constant rainfall intensity at  $80 \text{ mm h}^{-1}$ ; (2) and heavy rainfall, 60 min with a constant rainfall intensity at  $120 \text{ mm h}^{-1}$ . The light and heavy rainfall have accumulated KE at 1416 and  $2124 \text{ J m}^{-2}$  respectively and thus represented the typical 'common erosive rainfall' and 'extreme erosive rainfall' on the Chinese Loess Plateau. For each treatment, the light rainfall was applied on 4 May 2016 while the heavy rainfall was applied on 13 May 2016. Before each simulated rainfall, the branches mulches (in all the four MB treatments) and top 5-cm soil layer (in all of the



**Fig. 1. Photograph of an experimental plot with mulching application rate at  $1.48 \text{ kg m}^{-2}$ .**

five treatments) were removed and new branches mulches and soil were then applied and repacked. The top soil layer was replaced because the soil surface conditions would likely change (such as bulk density, porosity, and hydraulic conductivity) after the former natural rainfalls. New packed top soil and MB ensured more comparable soil and mulching conditions between the two rainfall events. Before the rainfalls, a sprinkler was used to spray water on the soil surface to ensure that all treatments had similar soil moisture contents, in the range of 10 to 12%. The slope gradient of the plot was constant at  $15^\circ$  during the rainfalls.

### Data Measurements and Treatments

During the rainfall events, surface water runoff was manually collected from the runoff collector (Fig. 1) into a graduated cylinder approximately every minute. The time to runoff ( $T_r$ ), defined as the time delay from the start of rainfall to runoff formation at the runoff collector, was recorded by a stopwatch. The amount of runoff collected by the graduated cylinder was measured. The collected runoff was then oven dried at  $105^\circ\text{C}$  and then weighed to determine the yield of sediment. All the chipped branches in each plot were immediately and carefully collected and weighed after the rainfall event. Since the chipped branches have been weighted before the rainfall when determining the application rate, interception of mulching was calculated from the mass difference of chipped branches before and after rainfall. Water infiltration was then calculated according to the water balance principle, ignoring evaporation and surface ponding:

$$\text{INF} = \text{P} - \text{R} - \text{INT} \quad [1]$$

where INT, P, R, INF are the interception (mm), precipitation (mm), runoff (mm), and infiltration (mm), respectively. In this paper, these components were expressed as depth, by dividing the volume by the projected area of the soil surface ( $1.55 \text{ m}^2$ ).

**Table 1. Average and standard deviation of ground coverage (the ratio of soil surface area covered by mulches to the total area of soil surface) and time to runoff.**

Treatment†	Light rainfall		Heavy rainfall	
	Coverage	Time to runoff	Coverage	Time to runoff
	%	s	%	s
CC, 0 kg m <sup>-2</sup>	–	34 ± 11	–	25 ± 11
MB1, 0.37 kg m <sup>-2</sup>	33.3 ± 4.2	58 ± 14	31.7 ± 3.4	37 ± 12
MB2, 0.74 kg m <sup>-2</sup>	62.0 ± 3.6	93 ± 20	61.2 ± 5.6	61 ± 17
MB3, 1.11 kg m <sup>-2</sup>	96.3 ± 3.8	257 ± 28	96.7 ± 2.9	89 ± 14
MB4, 1.48 kg m <sup>-2</sup>	>99.9	301 ± 22	>99.9	108 ± 19

† CC, clear cultivation (bare soil without mulching); MB, mulching with chipped branches at four different rates.

Two metrics were used to represent the performance of MB compared with CC. The runoff reduction performance (RRP) and sediment reduction performance (SRP) were as:

$$RRP = \frac{R_{CC} - R_{MB}}{R_{CC}} \times 100\% \quad [2]$$

$$SRP = \frac{S_{CC} - S_{MB}}{S_{CC}} \times 100\% \quad [3]$$

where  $R_{CC}$ ,  $R_{MB}$ ,  $S_{CC}$ , and  $S_{MB}$  are mean runoff depth from CC (mm), mean runoff depth from the MB treatment (mm), mean sediment yield from CC (kg), and mean sediment yield from the MB treatment (kg), respectively.

As the cost is mainly determined by the application rate, two metrics were used here to represent the economic efficiency of applying MB to control runoff generation and soil erosion: ratio of runoff reduction performance to cost (RRC) and ratio of sediment reduction performance to cost (RSC):

$$RRC = \frac{RRP}{AR} \quad [4]$$

$$RSC = \frac{SRP}{AR} \quad [5]$$

where AR is the application rate of MB (kg m<sup>-2</sup>). Since RRP and SRP have no unit, RRC and RSC are in the unit of m<sup>2</sup> kg<sup>-1</sup>. Thus, RRP and SRP indicate the runoff and soil erosion control performance in unit application rate in the MB treatments.

A Fisher's least significant difference (LSD) test was performed to test the significance differences ( $p = 0.05$ ) be-

tween means, using the software package MATLAB (R2014b, MathWorks, Inc.).

## RESULTS

Table 1 summarized the ground coverage and Tr. When the MB application rate was below 1.11 kg m<sup>-2</sup>, the ground coverage increased with application rate while almost all the soil surface was covered by branch mulches when the application rate was at 1.48 kg m<sup>-2</sup>. Table 2 illustrated the water budget during the rainfall events. In the present experiment, interception appeared to be a negligible component in the water budget (less than 0.6% of the precipitation in all the treatments). In each rainfall event, a statistically significant decline in runoff was detected with the increase of application rate in most cases (Table 2). Correspondingly, an opposite trend was detected in infiltration (Table 2). Apart from the condition between 1.11 and 1.48 kg m<sup>-2</sup> in the light rainfall, infiltration showed a rapid rising trend with the increment of application rate (Table 2). For the MB treatments, RRP ranged from 15.5 to 78.6% and generally increased with the application rate (Fig. 2a). Under the same application rate, higher RRP was observed in the light rainfall than that in heavy rainfall (Fig. 2a). In the light rainfall, Tr was 257 ± 28 s and 301 ± 22 s in MB at 1.11 and 1.48 kg m<sup>-2</sup>, respectively. In the remaining treatments, Tr was less than 119 s irrespective of rainfall intensity (Table 1).

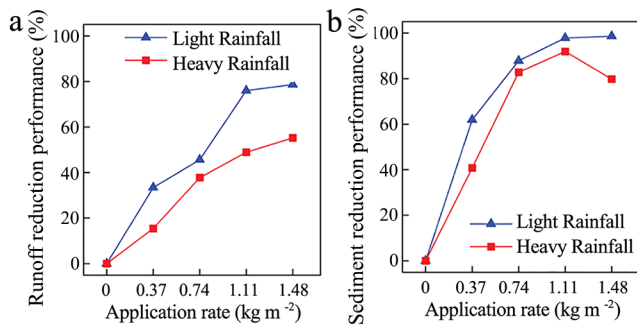
Both sediment yield rate and sediment concentration apparently decreased with the increment of application rate except under the condition of 1.48 kg m<sup>-2</sup> (Table 3). Sediment yield rate generally declined more dramatically than sediment concen-

**Table 2. Average and standard deviation of the components in water budget during the rainfalls ( $n = 3$ ).**

Rainfall	Treatment†	Interception	Runoff		Infiltration
			mm		
Light rainfall	CC, 0 kg m <sup>-2</sup>	–	57.4 ± 1.2 a‡	–	22.6 ± 1.2 a
	MB1, 0.37 kg m <sup>-2</sup>	0.157 ± 0.017 b	38.2 ± 1.2 b	–	41.6 ± 1.2 b
	MB2, 0.74 kg m <sup>-2</sup>	0.273 ± 0.017 b	31.2 ± 1.1 c	–	48.5 ± 1.1 c
	MB3, 1.11 kg m <sup>-2</sup>	0.373 ± 0.039 c	13.8 ± 1.3 d	–	65.8 ± 1.3 d
	MB4, 1.48 kg m <sup>-2</sup>	0.440 ± 0.029 a	12.3 ± 0.4 d	–	67.3 ± 0.4 d
Heavy rainfall	CC, 0 kg m <sup>-2</sup>	–	102.6 ± 1.4 a	–	17.4 ± 1.3 a
	MB1, 0.37 kg m <sup>-2</sup>	0.177 ± 0.021 bc	86.7 ± 3.3 b	–	33.1 ± 3.2 b
	MB2, 0.74 kg m <sup>-2</sup>	0.293 ± 0.019 bc	63.8 ± 2.8 c	–	55.9 ± 2.8 c
	MB3, 1.11 kg m <sup>-2</sup>	0.380 ± 0.030 bc	52.4 ± 1.6 d	–	67.2 ± 1.5 d
	MB4, 1.48 kg m <sup>-2</sup>	0.483 ± 0.029 bc	46.0 ± 3.3 e	–	73.6 ± 3.3 e

† CC, clear cultivation (bare soil without mulching); MB, mulching with chipped branches at four different rates.

‡ Lowercase letters indicate the results of Fisher's least significant difference (LSD) test at a significance level of 0.05. The LSD test was independently conducted between the rainfalls: each treatment was compared only with the other four treatments in the same rainfall regime.



**Fig. 2.** Variations of runoff reduction performance (a) and sediment reduction performance (b) with the application rate of mulching.

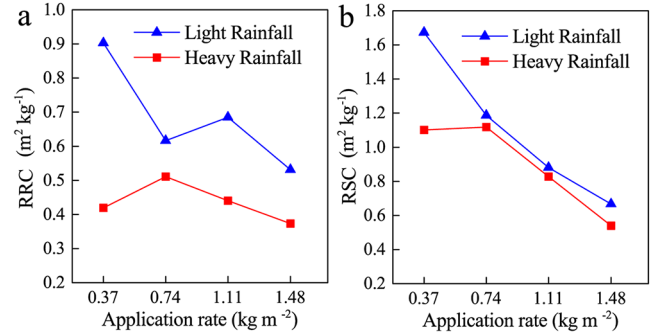
tration (Table 3). In the light rainfall, increasing application rate of MB from 1.11 to 1.48 kg m<sup>-2</sup> only resulted in slightly soil loss while in the heavy rainfall, a raising trend of soil loss was observed (Table 3). Like RRP, SRP decreased with rainfall intensity (Fig. 2b). When increasing application rate from 1.11 to 1.48 kg m<sup>-2</sup>, the raising trend of SRP slowed down in the light rainfall and reversed in the heavy rainfall (Fig. 2b).

RRC and RSC described the efficiency of applying MB to control runoff generation and soil erosion and were summarized in Fig. 3. In light rainfall, the application rate under which highest RRC and RSC were detected was 0.37 kg m<sup>-2</sup> while this value increased to 0.74 kg m<sup>-2</sup> in heavy rainfall (Fig. 3). Two peaks in the RRC curve were observed in the light rainfall (0.37 and 1.11 kg m<sup>-2</sup>, respectively; Fig. 3). Generally, lower application rate of MB led high RRC and RSC despite of its poor performance reducing runoff and sediment.

## DISCUSSION

### Runoff Reduction Performance

The present study showed that mulch with chipped branches had positive effects on water and soil conservation during storms. The application of jujube branches mulching changed the water budget in the storms (Table 2). Interception by the branches was negligible compared to infiltration and runoff. It was also lower than the reported values using other mulching materials (Cook et al., 2006; Peng et al., 2016). A possible reason was the hydrophobic surface of the jujube branches. Unlike other materials, the rain drops on the surface of branches were not absorbed but quickly connected together and then fell to the soil surface.



**Fig. 3.** Variation of ratio of runoff reduction performance to cost (a, RRC) and ratio of runoff reduction performance to cost (b, RSC) with the application rate of mulching.

Infiltration obviously increased with the presence of MB, and showed a positive relationship with the application rate (Table 2; Fig. 2a). Since it was less than three months between MB application and the simulated rainfalls, the short-term effects of MB, such as protecting the soil against sealing, and decreasing the runoff connectivity should be responsible for the decreased runoff amount in MB treatments (Cerdà et al., 2016a; Prosdocimi et al., 2016a). In the experiment, apparent soil sealing was visually observed in bare soil treatment and the uncovered areas in MB treatments while soil sealing happened to much less extent in the covered areas (Fig. 4a). In the absence of MB, aggregates broke down because of the rain drop impact. Some pores at top soil layer were then blocked by smaller soil particles generated from destroyed aggregates. As a result, hydraulic conductivity was likely reduced (Lu et al., 2017). Mulching protected soil surface from rain drop impact and thus likely kept higher original soil hydraulic conductivity and infiltration capability (Lin and Chen, 2015; Mannering and Meyer, 1963; Rahma et al., 2017; Vaezi et al., 2017). Soil surface coverage increased with application rate (Table 1). Thus, with higher application rate, soil sealing happened to less area and more rainfall was converted to infiltration (Table 2; Fig. 2a). Over 90% of soil surface was already covered in 1.11 kg m<sup>-2</sup> and further increases in the application rate made limited changes in ground coverage (Table 1). As a result, from 1.11 to 1.48 kg m<sup>-2</sup>, infiltration increased more gently than that in the treatments with lower application rate (Table 2; Fig. 2a). This indicated that there existed a threshold of application rate after which no significantly further reduction of runoff would be obtained which is in accordance with Jordán et al. (2010), Meyer et al. (1970), and Pearson

**Table 3.** Average and standard deviation of sediment yield rate and sediment concentration ( $n = 3$ ).

Treatment†	Sediment yield rate‡		Sediment concentration§	
	Light rainfall	Heavy rainfall	Light rainfall	Heavy rainfall
	g m <sup>-2</sup> min <sup>-1</sup>		g L <sup>-1</sup>	
CC, 0 kg m <sup>-2</sup>	11.59 ± 0.27	34.67 ± 1.25	12.11 ± 0.08	20.27 ± 0.30
MB1, 0.37 kg m <sup>-2</sup>	4.42 ± 0.15	20.54 ± 0.84	6.93 ± 0.03	14.22 ± 0.10
MB2, 0.74 kg m <sup>-2</sup>	1.41 ± 0.05	5.98 ± 0.40	2.72 ± 0.04	5.62 ± 0.16
MB3, 1.11 kg m <sup>-2</sup>	0.25 ± 0.03	2.80 ± 0.06	1.11 ± 0.07	3.21 ± 0.06
MB4, 1.48 kg m <sup>-2</sup>	0.17 ± 0.01	6.98 ± 1.84	0.81 ± 0.02	9.17 ± 0.82

† CC, clear cultivation (bare soil without mulching); MB, mulching with chipped branches at four different rates.

‡ Sediment yield rate was calculated by divide the total sediment yield in mass by the product of rainfall duration (60 min) and the projected area of the soil surface (1.55 m<sup>2</sup>).

§ Sediment concentration was calculated by divide the total sediment yield in mass by the total runoff in volume.

and Beeson (2015) and contrary to Donjadee and Tingsanchali (2016), Foltz and Copeland (2009), and Gholami et al. (2016). A possible explanation was that the later studies did not involve the situation with almost full ground coverage, like the application of  $1.48 \text{ kg m}^{-2}$  in our experiment.

The tradeoff between mulching application costs and water and soil conservation benefits is an important issue, especially considering the wider adoption of MB practice (Cerdà et al., 2018; Prosdocimi et al., 2016b). A generally decreasing trend was illustrated in RRC curves (Fig. 3a) with two exceptions:  $1.11 \text{ kg m}^{-2}$  in light rainfall and  $0.37 \text{ kg m}^{-2}$  in heavy rainfall. Compared with other treatments, apparently larger  $T_r$  was observed in  $1.11$  and  $1.48 \text{ kg m}^{-2}$  in light rainfall (Table 1). Many mini dams were formed as the branches impeded the flowing of ponded water on the soil surface. These phenomena suggested that the connectivity of surface runoff was delayed and weakened by mulching in these treatments, which further promoted infiltration (Cattan et al., 2006; Cerdà et al., 2016a; Prosdocimi et al., 2016a). For other treatments, surface runoff was rapidly connected because of the lower application rate and/or higher rainfall intensity (Table 1). In other words, runoff inhabitation by the mechanism of hydraulic connectivity reduction did not happen in all rainfall and application rate conditions after mulching practice. This also explained the first exception ( $1.11 \text{ kg m}^{-2}$  in light rainfall) in RRC curves (Fig. 3a). Largest runoff volume was observed in  $0.37 \text{ kg m}^{-2}$  under heavy rainfall among all the treatments with mulching. For  $1.11 \text{ kg m}^{-2}$  of MB in light rainfall, parts of mulching branches were pushed downslope by the surface runoff flow because of the high buoyancy force and shear force leading a damage to the protection on soil infiltration capacity by mulching covers. While in other treatments, mulching materials remained stable. So, the second exception ( $0.37 \text{ kg m}^{-2}$  in heavy rainfall) in RRC curves (Fig. 3a) would be explained by this unique mechanism.

### Soil Conservation Performance

Soil erosion was significantly suppressed by MB from the view of both sediment yield rate and sediment concentration (Table 3). In MB treatments, soil particle detachment happened to less extent since the soil surface under mulching covers was protected from rain drop impact (Gholami et al., 2014; Gholami et al., 2013; Nishigaki et al., 2017). The presence of MB also formed barriers to the runoff flow and increased surface roughness. According to Shi

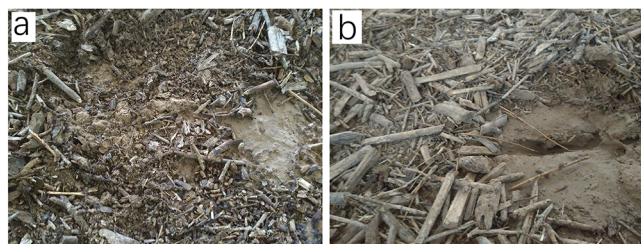


Fig. 4. Photographs of sealed and unsealed soil surface areas in one of the plot with mulching at  $0.74 \text{ kg m}^{-2}$  after heavy rainfall (a) and a discontinuous rill formed in one of the plot with mulching application rate at  $1.48 \text{ kg m}^{-2}$  after the heavy rainfall (b). The branches were manually removed before taking the photograph for clarity.

et al. (2013), with the increase of application rate, less of the energy of runoff water flowing over the soil surface (stream power) was available to remove and transport soil particles from the erosion surface after mulching. Thus, sediment concentration showed a negative relationship with application rate (Table 3), in accordance with Cerdà et al. (2016a) and Mannering and Meyer (1963). The sediment yield rate, which is in proportion to the product of runoff amount and sediment concentration, would thus be explained by both the less runoff amount and lower sediment concentration with the increase of application rate (Table 3).

The present study also showed that the efficiency of reducing soil erosion would not always increase with the application rate of MB, such as  $1.48 \text{ kg m}^{-2}$  in the heavy rainfall (Table 3; Fig. 2b). A possible reason was the occurrence of the early stage of rill-erosion: in  $1.48 \text{ kg m}^{-2}$  under the heavy rainfall discontinuous rills formed at the down slope (Fig. 4b). The mulched branches formed a barrier for the flow of surface runoff. With the highest application rate, the runoff in  $1.48 \text{ kg m}^{-2}$  had more opportunity to flow along individual branches lying on the soil surface which could possibly converge or diverge with flow from other branches depending on the surface pattern of the branches. In the case of convergence, greater turbulence led higher risks of rill formation and development. Similar results were observed by Rahma et al. (2017) under the application rate at  $0.8 \text{ kg m}^{-2}$  of straw mulching. Rill initiation were observed in neither  $1.48 \text{ kg m}^{-2}$  under light rainfall as the runoff amount was less, nor CC,  $0.37$ ,  $0.74$ , and  $1.11 \text{ kg m}^{-2}$  as there was no/less barrier for runoff flow. Once rill-erosion started, runoff flow became more concentrated and the shear forces would be greater than the average runoff amount would suggest (Stehle et al., 2016; Li et al., 2016a). This extrapolation was also supported by Fig. 5, which illustrated the relationship between the cumulative runoff and cumulative runoff collected at the runoff collector. For  $1.11 \text{ kg m}^{-2}$  in heavy rainfall, the linear relationship indicated a transport-limited situation, which is the characteristic of interrill erosion. For  $1.48 \text{ kg m}^{-2}$  in heavy rainfall, similar trend was observed at the early stage. But in the late stage, when the

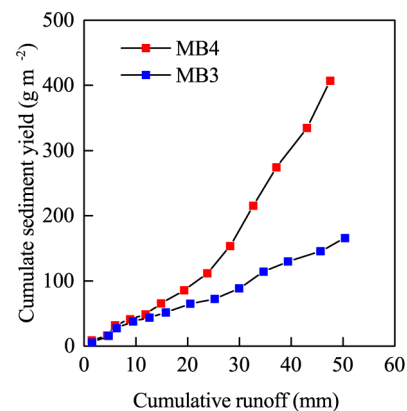


Fig. 5. Relationship between the cumulative runoff and cumulative sediment yield collected at the runoff collector in the heavy rainfall. For each treatment, the data from one of the three replications was shown. MB4 and MB3: mulching with chipped branches at application rate:  $1.48 \text{ kg m}^{-2}$  and  $1.11 \text{ kg m}^{-2}$ , respectively.

runoff rate increased, the relationship seemed to be more exponential rather than linear. This suggested that a detachment limited situation started to be more dominant, which is the characteristic of rill erosion. As a result, higher sediment yield rate and sediment concentration, and lower SRP were observed in 1.148 kg m<sup>-2</sup> than that in 0.74 and 1.11 kg m<sup>-2</sup> under heavy rainfall (Table 3; Fig. 2b). Due to the limited plot length (2 m), only the very early stage of rill development was observed. This unfavorable influence of high application rate on soil erosion was expected to grow when the slope is longer (Rahma et al., 2017). Over the long term, high mulching application rates might lead higher risk of soil erosion by other reasons such as increasing the water repellency (Gao et al., 2017; García-Moreno et al., 2013). But this did not likely happen in the present study. The ratio between soil conservation performance and mulching cost (RSC) decreased with application rate (Fig. 3). The only exception occurred when application rate increased from 0.37 to 0.74 kg m<sup>-2</sup> under the heavy rainfall. This was likely because MB failed to remain stable under the heavy runoff load and thus introduced extra soil erosion (Gholami et al., 2013). The current results suggested that as far as the required soil conservation performance could be achieved, lower application rates might be a better option because higher application rates would be economically unfavorable and might even lead severer soil erosion.

## SUMMARY AND CONCLUSION

Mulching with chipped branches was confirmed as an effective way to prevent soil and water loss during rainfalls in present experiment. It reduced runoff generation by 15.5 to 78.6% and sediment yield by 40.7 to 98.6% compared with the bare soil. The effectiveness of mulching with chipped branches decreased with rainfall intensity and showed complex relationship with its application rate. Different factors, such as soil surface coverage, interception by mulching, soil permeability, stability of mulching materials, and rill initiation, played roles in the effectiveness of MB. The occurrences and/or extent of occurrences of these mechanisms were changed with application rate and precipitation regime. The soil and water conservation effectiveness (RRP and SRP) did not always increase with application rate, especially when the ground coverage of mulching was over 90%. The ratios between ecological benefits and costs (RRC and RSC) generally showed a declining tendency with the application rate. The present results confirmed the necessity of determining the optimum mulching application rate and pattern in the context of site-specific soil, vegetation, and climatic conditions as well as local social status, as pointed out by many former studies (Jin et al., 2009; Mulumba and Lal, 2008; Prosdocimi et al., 2016b).

It should be noted that the current study mainly investigated the immediate effects of mulching on initial soil and water loss processes. When it comes to larger spatial and temporal scales, more factors, such as larger flow rate at downslope, variation of soil properties after application of mulching, and decomposition of mulching materials (Sadeghi et al., 2017), may need to be further considered.

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## SUPPLEMENTAL MATERIAL

Supplemental material is available with the online version of this article. Supplemental Fig. S1 is a map of the experimental site location, and Supplemental Fig. S2 is a photograph of the chipped, pruned branches.

## REFERENCES

- Borrelli, P., D.A. Robinson, L.R. Fleischer, E. Lugato, C. Ballabio, C. Alewell, K. Meusburger, S. Modugno, B. Schütt, V. Ferro, V. Bagarello, K. Van Oost, L. Montanarella, and P. Panagos. 2017. An assessment of the global impact of 21st century land use change on soil erosion. *Nat. Commun.* 8:1–13. doi:10.1038/s41467-017-02142-7
- Breton, V., Y. Crosaz, and F. Rey. 2016. Effects of wood chip amendments on the revegetation performance of plant species on eroded marly terrains in a Mediterranean mountainous climate (Southern Alps, France). *Solid Earth* 7:1–21. doi:10.5194/se-2016-11
- Brevik, E.C., and A.E. Hartemink. 2010. Early soil knowledge and the birth and development of soil science. *Catena* 83:23–33. doi:10.1016/j.catena.2010.06.011
- Cai, T., C. Zhang, Y. Huang, H. Huang, B. Yang, Z. Zhao, J. Zhang, Z. Jia. 2015. Effects of different straw mulch modes on soil water storage and water use efficiency of spring maize (*Zea mays* L.) in the Loess Plateau of China. *Plant Soil Environ.* 61:253–259. doi:10.17221/76/2015-PSE
- Calatrava, J., and J.A. Franco. 2011. Using pruning residues as mulch: Analysis of its adoption and process of diffusion in Southern Spain olive orchards. *J. Environ. Manage.* 92:620–629. doi:10.1016/j.jenvman.2010.09.023
- Cattan, P., Y.M. Cabidoche, J.G. Lacas, and M. Voltz. 2006. Effects of tillage and mulching on runoff under banana (*Musa* spp.) on a tropical Andosol. *Soil Tillage Res.* 86:38–51. doi:10.1016/j.still.2005.02.002
- Cerdà, A., O. González-Pelayo, A. Giménez-Morera, A. Jordán, P. Pereira, A. Novara, E.C. Brevik, M. Prosdocimi, M. Mahmoodabadi, S. Keesstra, F. García Orenes, and C.J. Ritsema. 2016a. Use of barley straw residues to avoid high erosion and runoff rates on persimmon plantations in Eastern Spain under low frequency-high magnitude simulated rainfall events. *Soil Research* 54:154–165. doi:10.1071/SR15092
- Cerdà, A., S. Keesstra, A. Jordán, P. Pereira, M. Prosdocimi, C.J. Ritsema, and M. Burguet. 2016b. The use of chipped pruned branches to control the soil and water losses in citrus plantations in Eastern Spain. *EGU General Assembly*. 17–22 April 2016. Vienna Austria. *Geophysical Research Abstracts* 18:EGU2016-4705.
- Cerdà, A., J. Rodrigo-Comino, A. Giménez-Morera, and A. Novara. 2018. Policies can help to apply successful strategies to control soil and water losses: The case of chipped pruned branches (CPB) in Mediterranean citrus plantations. *Land Use Policy*. doi:10.1016/j.landusepol.2017.12
- Cook, H.F., G.S.B. Valdes, and H.C. Lee. 2006. Mulch effects on rainfall interception, soil physical characteristics and temperature under *Zea mays* L. *Soil Tillage Res.* 91:227–235. doi:10.1016/j.still.2005.12.007
- Copeland, N.S., B.S. Sharratt, J.Q. Wu, R.B. Foltz, and J.H. Dooley. 2009. A wood-strand material for wind erosion control: Effects on total sediment loss, PM10 vertical flux, and PM10 loss. *J. Environ. Qual.* 38:139–148. doi:10.2134/jeq2008.0115
- Donjatee, S., and T. Tingsanchali. 2016. Soil and water conservation on steep slopes by mulching using rice straw and vetiver grass clippings. *Agric. Nat. Resour.* 50:75–79. doi:10.1016/j.anres.2015.03.001
- Feng, X., B. Fu, S. Piao, S. Wang, P. Ciais, Z. Zeng, Y. Lü, Y. Zeng, Y. Li, X. Jiang, and B. Wu. 2016. Revegetation in China's Loess Plateau is approaching sustainable water resource limits. *Nat. Clim. Chang.* 6:1019–1022. doi:10.1038/nclimate3092
- Foltz, R.B., and N.S. Copeland. 2009. Evaluating the efficacy of wood shreds for mitigating erosion. *J. Environ. Manage.* 90:779–785. doi:10.1016/j.jenvman.2008.01.006
- Gao, X., T. Meng, and X. Zhao. 2017. Variations of soil organic carbon following land use change on deep-loess hillslopes in China. *Land Degrad. Dev.* 28:1902–1912. doi:10.1002/ldr.2693
- Gao, X., X. Zhao, P. Wu, L. Brocca, and B. Zhang. 2016. Effects of large

- gullies on catchment-scale soil moisture spatial behaviors: A case study on the Loess Plateau of China. *Geoderma* 261:1–10. doi:10.1016/j.geoderma.2015.07.001
- García-Moreno, J., Á.J. Gordillo-Rivero, L.M. Zavala, A. Jordán, and P. Pereira. 2013. Mulch application in fruit orchards increases the persistence of soil water repellency during a 15-years period. *Soil Tillage Res.* 130:62–68. doi:10.1016/j.still.2013.02.004
- García-Orenes, F., A. Cerdà, J. Mataix-Solera, C. Guerrero, M.B. Bodí, V. Arcenegui, R. Zornoza, and J.G. Sempere. 2009. Effects of agricultural management on surface soil properties and soil–water losses in eastern Spain. *Soil Tillage Res.* 106:117–123. doi:10.1016/j.still.2009.06.002
- Gholami, L., K. Banasik, S.H. Sadeghi, A. Khaledi, Darvishan, and L. Hejduk. 2014. Effectiveness of straw mulch on infiltration, splash erosion, runoff and sediment in laboratory conditions. *J. Water Land Develop.* 22:51–60. doi:10.2478/jwld-2014-0022
- Gholami, L., A. Khaledi Darvishan, and A. Kaviani. 2016. Wood chips as soil conservation in field conditions. *Arab. J. Geosci.* 9:729. doi:10.1007/s12517-016-2731-0
- Gholami, L., S.H. Sadeghi, and M. Homae. 2013. Straw mulching effect on splash erosion, runoff, and sediment yield from eroded plots. *Soil Sci. Soc. Am. J.* 77:268–278. doi:10.2136/sssaj2012.0271
- Huang, J., J. Wang, X. Zhao, P. Wu, X. Qi, and H. Li. 2014. Effects of permanent ground cover on soil moisture in jujube orchards under sloping ground: A simulation study. *Agric. Water Manage.* 138:68–77. doi:10.1016/j.agwat.2014.03.002
- Hu, W., F. Zheng, and F. Bian. 2016. The directional components of splash erosion at different raindrop kinetic energy in the Chinese Mollisol region. *Soil Sci. Soc. Am. J.* 80:1329–1340. doi:10.2136/sssaj2016.03.0066
- Iserloh, T., W. Fister, M. Seeger, H. Willger, and J. Ries. 2012. A small portable rainfall simulator for reproducible experiments on soil erosion. *Soil Tillage Res.* 124:131–137. doi:10.1016/j.still.2012.05.016
- Jabbar, M.A., J. Cobbina, and L. Reynolds. 1992. Optimum fodder-mulch allocation of tree foliage under alley farming in southwest Nigeria. *Agrofor. Syst.* 20:187–198. doi:10.1007/BF00053138
- Jin, K., et al. 2009. Residue cover and rainfall intensity effects on runoff soil organic carbon losses. *Catena* 78:81–86. doi:10.1016/j.catena.2009.03.001
- Jordán, A., L.M. Zavala, and J. Gil. 2010. Effects of mulching on soil physical properties and runoff under semi-arid conditions in southern Spain. *Catena* 81:77–85. doi:10.1016/j.catena.2010.01.007
- Kargar, M., P. Jutras, O.G. Clark, W.H. Hendershot, and S.O. Prasher. 2015. Macro-nutrient availability in surface soil of urban tree pits influenced by land use, soil age, and soil organic matter content. *Urban Ecosyst.* 18:921–936. doi:10.1007/s11252-015-0439-7
- Keesstra, S.D., J.N. Quinton, W.H. van der Putten, R.D. Bardgett, and L.O. Fresco. 2016. The significance of soils and soil science towards realization of the United Nations Sustainable Development Goals. *Soil* 2:111–128. doi:10.5194/soil-2-111-2016
- Lattanzi, A.R., L.D. Meyer, and M.F. Baumgardner. 1974. Influences of mulch rate and slope steepness on interrill erosion. *Soil Sci. Soc. Am. J.* 38:946–950. doi:10.2136/sssaj1974.03615995003800060030x
- Li, H.C., X.D. Gao, X.N. Zhao, P.T. Wu, L.S. Li, Q. Ling, and W.H. Sun. 2016a. Integrating a mini catchment with mulching for soil water management in a sloping jujube orchard on the semiarid Loess Plateau of China. *Solid Earth* 7:167–175. doi:10.5194/se-7-167-2016
- Li, G., F. Zheng, J. Lu, X. Xu, W. Hu, and Y. Han. 2016b. Inflow rate impact on hillslope erosion processes and flow hydrodynamics. *Soil Sci. Soc. Am. J.* 80:711–719. doi:10.2136/sssaj2016.02.0025
- Lin, L., and J. Chen. 2015. The effect of conservation practices in sloped croplands on soil hydraulic properties and root-zone moisture dynamics. *Hydrol. Processes* 29:2079–2088. doi:10.1002/hyp.10348
- Lin, J.S., G. Zhu, J. Wei, F. Jiang, M. Wang, and Y. Huang. 2018. Mulching effects on erosion from steep slopes and sediment particle size distributions of gully colluvial deposits. *Catena* 160:57–67. doi:10.1016/j.catena.2017.09.003
- Lu, P., X. Xie, L. Wang, and F. Wu. 2017. Effects of different spatial distributions of physical soil crusts on runoff and erosion on the Loess Plateau in China. *Earth Surf. Process. Landf.* 42:2082–2089. doi:10.1002/esp.4175
- Mannerling, J.V., and L.D. Meyer. 1963. The effects of various rates of surface mulch on infiltration and erosion. *Soil Sci. Soc. Am. J.* 27:84–86. doi:10.2136/sssaj1963.03615995002700010029x
- Marzen, M., T. Iserloh, J.L.M.P. de Lima, W. Fister, and J.B. Ries. 2017. Impact of severe rain storms on soil erosion: Experimental evaluation of wind-driven rain and its implications for natural hazard management. *Sci. Total Environ.* 590:502–513. doi:10.1016/j.scitotenv.2017.02.190
- Meyer, L.D., W.H. Wischmeier, and G.R. Foster. 1970. Mulch rates required for erosion control on steep slopes. *Soil Sci. Soc. Am. J.* 34:928–931. doi:10.2136/sssaj1970.03615995003400060031x
- Mulumba, L.N., and R. Lal. 2008. Mulching effects on selected soil physical properties. *Soil Tillage Res.* 98:106–111. doi:10.1016/j.still.2007.10.011
- Neumann, M., T. Iserloh, J. Rodrigo Comino, P. Kavka, M. Seeger, and J.B. Ries. 2017. How is initial soil erosion affected by rainfall intensity and kinetic energy? EGU General Assembly. 17–22 April 2016. Vienna Austria. Geophysical Research Abstracts 18:EGU2016-4705.
- Nishigaki, T., S. Sugihara, M. Kilasara, and S. Funakawa. 2017. Effect of mulching with vegetative residues on soil water erosion and water balance in an oxisol cropped by cassava in east Cameroon. *Land Degrad. Dev.* 28:682–690. doi:10.1002/ldr.2499
- Pan, D., X. Gao, M. Dyck, Y. Song, P. Wu, and X. Zhao. 2017a. Dynamics of runoff and sediment trapping performance of vegetative filter strips: Run-on experiments and modeling. *Sci. Total Environ.* 593-594:54–64. doi:10.1016/j.scitotenv.2017.03.158
- Pan, D., Y. Song, M. Dyck, X. Gao, P. Wu, X. Zhao. 2017b. Effect of plant cover type on soil water budget and tree photosynthesis in jujube orchards. *Agric. Water Manage.* 184:135–144. doi:10.1016/j.agwat.2017.01.009
- Pearson, B.J., and R.C. Beeson, Jr. 2015. Influence of mulch type and depth on stormwater runoff and leachate from runoff boxes containing simulated urban landscape soils. *Fla. Sci.* 78:37–46.
- Peng, H., T. Lei, Z. Jiang, and R. Horton. 2016. A method for estimating maximum static rainfall retention in pebble mulches used for soil moisture conservation. *J. Hydrol.* 537:346–355. doi:10.1016/j.jhydrol.2016.03.064
- Prosdocimi, M., A. Jordan, P. Tarolli, S. Keestra, A. Novara, and A. Cerdà. 2016a. The immediate effectiveness of barley straw mulch in reducing soil erodibility and surface runoff generation in Mediterranean vineyards. *Sci. Total Environ.* 547:323–330. doi:10.1016/j.scitotenv.2015.12.076
- Prosdocimi, M., P. Tarolli, and A. Cerdà. 2016b. Mulching practices for reducing soil water erosion: A review. *Earth Sci. Rev.* 161:191–203. doi:10.1016/j.earscirev.2016.08.006
- Rahma, A.E., W. Wang, Z. Tang, T. Lei, D.N. Warrington, and J. Zhao. 2017. Straw mulch can induce greater soil losses from loess slopes than no mulch under extreme rainfall conditions. *Agric. For. Meteorol.* 232:141–151. doi:10.1016/j.agrformet.2016.07.015
- Rodrigo Comino, J., T. Iserloh, T. Lassu, A. Cerdà, S.D. Keestra, M. Prosdocimi, C. Brings, M. Marzen, M.C. Ramos, J.M. Senciales, J.D. Ruiz Sinoga, M. Seeger, and J.B. Ries. 2016. Quantitative comparison of initial soil erosion processes and runoff generation in Spanish and German vineyards. *Sci. Total Environ.* 565:1165–1174. doi:10.1016/j.scitotenv.2016.05.163
- Sadeghi, S.H., M. Kiani Harchegani, and H. Asadi. 2017. Variability of particle size distributions of upward/downward splashed materials in different rainfall intensities and slopes. *Geoderma* 290:100–106. doi:10.1016/j.geoderma.2016.12.007
- Shi, Z.H., B.J. Yue, L. Wang, N.F. Fang, D. Wang, and F.Z. Wu. 2013. Effects of mulch cover rate on interrill erosion processes and the size selectivity of eroded sediment on steep slopes. *Soil Sci. Soc. Am. J.* 77:257–267. doi:10.2136/sssaj2012.0273
- Stehle, S., J.M. Dabrowski, U. Bangert, and R. Schulz. 2016. Erosion rills offset the efficacy of vegetated buffer strips to mitigate pesticide exposure in surface waters. *Sci. Total Environ.* 545-546:171–183. doi:10.1016/j.scitotenv.2015.12.077
- USDA. 2010. Keys to soil taxonomy. US Gov. Print. Office, Washington, DC.
- Vaezi, A.R., M. Ahmadi, and A. Cerdà. 2017. Contribution of raindrop impact to the change of soil physical properties and water erosion under semi-arid rainfalls. *Sci. Total Environ.* 583:382–392. doi:10.1016/j.scitotenv.2017.01.078
- Viola, F., A. Francipane, D. Caracciolo, D. Pumo, G. La Loggia, and L.V. Noto. 2016. Co-evolution of hydrological components under climate change scenarios in the Mediterranean area. *Sci. Total Environ.* 544:515–524. doi:10.1016/j.scitotenv.2015.12.004
- Wang, J., J. Huang, P. Wu, X. Zhao, X. Gao, M. Dumlaio, and B.C. Si. 2015. Effects of soil managements on surface runoff and soil water content in jujube orchard under simulated rainfalls. *Catena* 135:193–201. doi:10.1016/j.catena.2015.07.025
- Wu, G., J. Cheng, F. Wu, and J. Wang. 2011. A study of the erosion force of natural rainfall in Yangling. (In Chinese with English abstract). *Zhongguo Nongcun Shuili Shuidian* 4:6–13.
- Zhou, P., and Z. Wang. 1992. A study on rainstorm causing soil erosion in the Loess Plateau. (In Chinese with English abstract). *J. Soil Water Conserv.* 6:1–5.