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Effects of Shrub on Runoff and Soil Loss at Loess Slopes Under Simulated Rainfall

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Abstract: Improved understanding of the effect of shrub cover on soil erosion process will provide valuable information for soil and water conservation programs. Laboratory rainfall simulations were conducted to determine the effects of shrubs on runoff and soil erosion and to ascertain the relationship between the rate of soil loss and the runoff hydrodynamic characteristics. In these simulations a 20° slope was subjected to rainfall intensities of 45, 87, and 127 mm/h. The average runoff rates ranged from 0.51 to 1.26 mm/min for bare soil plots and 0.15 to 0.96 mm/min for shrub plots. Average soil loss rates varied from 44.19 to 114.61 g/(min·m^2) for bare soil plots and from 5.61 to 84.58 g/(min·m^2) for shrub plots. There was a positive correlation between runoff and soil loss for the bare soil plots, and soil loss increased with increased runoff for shrub plots only when rainfall intensity is 127 mm/h. Runoff and soil erosion processes were strongly influenced by soil surface conditions because of the formation of erosion pits and rills. The unit stream power was the optimal hydrodynamic parameter to characterize the soil erosion mechanisms. The soil loss rate increased linearly with the unit stream power on both shrub and bare soil plots. Critical unit stream power values were 0.004 m/s for bare soil plots and 0.017 m/s for shrub plots.

Keywords: runoff; soil loss; shrub; bare soil; rainfall intensity; loess slope

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1 Introduction

Soil erosion is a serious problem on the Loess Plateau in China. To improve the environmental condition of the Loess plateau, the Chinese Government implemented the Grain for Green Project in 1999, which aimed to transform cultivated land on the steep hill slopes in this region to forest, grass and shrub land use. However, the annual precipitation on the Loess Plateau is about 400 mm, which is not optimal for the growth of wood species. Therefore, the planting of grasses and shrubs was chosen as the main biological soil erosion control practices in this project.

Many researches have been conducted into the benefits of vegetation in reducing runoff and soil loss (Wainwright, 2000; Li *et al.*, 2009; Pan *et al.*, 2010). Zhang *et al.* (2015) indicated that vegetation can increase soil organic matter, improve soil physical properties and soil anti-erodibility, and reduce runoff and erosion to a safe level. Chatterjea (1998) studied runoff and soil loss from both bare and grass-covered plots during natural rainstorms, and concluded that the responses of the bare surfaces to incoming rainfall were more rapid than those of grass-covered plots. Pan *et al.* (2006) showed that a grass-covered surface significantly reduced runoff and soil loss relative to a bare soil during

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the final stages of simulated rainfall events. Wang *et al.* (2008) developed a vegetation–erosion model based on field measurements to determine the relationship between soil loss and vegetation. However, differences in vegetation, soil properties, and surface conditions complicated the interpretation of the experimental results. Based on rainfall simulation studies in the Chihuahuan desert in the USA, Neave and Abrahams (2002) indicated that a shrub-covered plot produced 150% more runoff for a given storm event than a grass-covered plot. Shen *et al.* (2006) showed that runoff and soil loss from bare field plots in the Yanhe Watershed on the Loess Plateau of China were 82 and 150 times, respectively, of those for shrub-covered plots. Most of these studies involved the comparisons of runoff and soil loss from grass-covered and bare plots. Little is known about the effectiveness of shrub cover in reducing runoff and soil loss and the contrast in runoff and soil loss from bare plots and shrub-covered plots. Furthermore, it is essential to have a better understanding of soil erosion processes under shrub cover to identify the most effective surface cover for erosion control.

Soil erosion is a complex process that is primarily governed by the effects of raindrop impact and surface runoff processes (An *et al.*, 2012). Ground cover not only intercepts precipitation, thereby reducing runoff volume, but it also protects the soil surface from the destructive effect of rain drop impact and the scouring action of runoff (Bryan, 2000). Based on field experiments in which grass stems and leaves were cut close to the soil surface, Prosser *et al.* (1995) concluded that flow resistance and critical shear stress of concentrated overland flow in sediment translocation decreased relative to areas with complete grass cover. The hydraulic characteristics of surface runoff on vegetation-covered plots (such as flow velocity, flow depth, and Reynolds number) and their interrelationships have been widely studied in recent years (Pan *et al.*, 2006; Giménez and Govers, 2008; Xiao *et al.*, 2011). Giménez and Govers (2008) studied effects of freshly incorporated straw residue on rill erosion and hydraulics and concluded that effective unit length shear force is closely related to soil detachment. However, relatively little is known about the critical hydraulic parameters of runoff associated with the occurrence of soil erosion on shrub-covered plots.

Numerous studies have been undertaken to document the effects of grass cover on reducing runoff and soil loss, but little research has been conducted to study soil erosion processes on shrub-covered plots. Few studies have been conducted on the applicability of the concepts such as flow shear stress, unit stream power, and unit flow energy, in predicting soil loss from vegetation-covered plots. More information is needed concerning the relationship between erosion processes and the critical hydraulic parameters for shrub-covered plots.

The objective of this study is to determine the effects of shrub cover on runoff and soil erosion under simulated rainfall conditions, to analyze the hydraulic mechanisms of soil erosion and to propose the most sensitive parameters for characterizing hillslope erosion. This study also provides basic data for use in developing a physically-based erosion model that can be applied to vegetation-covered slopes on the Loess Plateau, China.

2 Materials and Methods

2.1 Experimental model design

The experiments were conducted at the Key Laboratory of the Loess Plateau Soil Erosion and Water Loss Process and Control of Ministry of Water Resources, Yellow River Institute of Hydraulic Research in Zhengzhou, Henan Province, China. The hilly-gully region in the Loess Plateau is covered with thick, highly erodible loess material and is one of the most severely eroded areas in the world. By investigation and statistics, the 20° slope steepness was based on the dominance of slopes in the range of 10° to 25°, which constitute 22% to 45% of the total land area within the gullied region of the Loess Plateau (Tang *et al.*, 1984). In addition, a 20° slope is the critical steepness for the occurrence of rill and ephemeral gully erosion (Zheng, 1989). So, the slope of the experimental plots was adjusted to 20°. Two boxes with length of 5 m, width of 3 m and depth of 0.6 m were constructed. Each box was divided into three equal sections of 5-m length and 1-m width using a polyvinyl chloride (PVC) border that was inserted into the soil.

2.2 Experimental setup

The rainfall simulator used was based on the design by Chen *et al.* (1984) and consisted of four side-spray nozzles that produced rain with a drop size distribution ranging from 0.10 to 4.00 mm and a kinetic energy impact rate of 80% that of a natural rainstorm at a corresponding intensity. The rainfall simulator could be set to produce any rainstorm intensity between 10 and 180 mm/h.

Rainfall intensities of 45, 87, and 127 mm/h were used in this study. The 87 mm/h intensity was chosen to simulate intensities of frequently occurring, high-intensity local storms. The higher intensity of 127 mm/h was specifically chosen to determine the effect of shrubs on erosion rates at higher runoff volumes, while the lower intensity regime (45 mm/h) was chosen to represent the effect of runoff on soil loss of shrub plots at lower rainfall intensities.

2.3 Soil box preparation

The soil for this study was taken from the slopes of the Mangshan Mountain near Zhengzhou City. The textural properties are given in Table 1. The air dried soil was crushed to pass a 10-mm sieve. First a 5-cm layer of sand was placed at the bottom of each box to facilitate free drainage. The remaining 50-cm was packed in 10-cm increments with the sieved soil, thereby ensuring a uniform bulk density of 1.35 g/cm^3 for the 10–30 cm zone representing the subsoil. The top 10 cm surface layer simulated a cultivated field and was packed to a bulk density of 1.05 g/cm^3.

2.4 Shrub coverage degree

One box consisting of three contiguous experimental plots was classified as the bare soil box while the other box was planted to shrub cover. The shrub species chosen was Indigobush Amorpha (*Amorphan fruticosa L.*), which has proven to be a very effective shrub in soil and water conservation programs. The shrub stems were planted during the spring with a plant × row spacing of 25 cm × 20 cm. The shrub reached a height of about 105 cm and covered about 63% of the plot area after four months of growth. The percentage coverage was calculated to represent the proportion of the soil surface within the plot covered by the vegetation canopy. The shrub cover protected the soil from raindrop impact and produced conditions similar to those of natural field conditions.

2.5 Experimental procedures

Before each experiment, a specially designed 1-cm diameter auger was used to determine the water content of the soil. In order to have uniform soil conditions and based on the measured water content value, a 10-min rainfall of 30 mm/h intensity was applied on all plots 24 h before a run. No surface runoff occurred during this wetting phase. This rain produced an approximate initial water content of about 15% on all plots and thus reduced initial differences in the antecedent water content among treatments subjected to different rainfall intensity regimes.

Rainfall simulations on the three shrub plots were performed as follows. First, one shrub plot uncovered and the other two shrub plots were covered with two layers of plastic. The uncovered plot was subjected to 45 mm/h rainfall intensity. Once runoff was initiated, samples were continuously collected during the entire storm using 10 L buckets, each with a 2-min sampling time, to assure accurate runoff and soil loss measurements for the analytical phase of this study. Surface flow velocities on the upper, middle, and lower slopes of the plots were recorded at 2-min intervals based on a dye tracer. Flow widths and depths were determined with a steel ruler during the same time interval. At the end of this run, this plot was immediately covered with two layers of plastic. Then, one of the initially covered shrub plot was uncovered and subjected to rain using the same procedure but with an intensity of 87 mm/h. Finally, the third shrub plot was subjected to 127 mm/h rainfall intensity. After the simulated rainfall events ended, runoff volumes were determined with a graduated cylinder to determine runoff rates. The sediment was deposited, separated from the water, dried in a forced air oven at 105℃ to a constant weight. Runoff and soil loss were calculated from the individual samples.

The bare soil plots were subjected to the same sequence of rainstorms in which one plot was used for the run with 45 mm/h rainfall intensity and the other two plots for the runs with 87 and 127 mm/h rainfall intensities, respectively. For both the bare soil and shrub plots, each experimental condition was replicated once. Furthermore, the errors were checked (< 10%) between the

Table 1 Particle size composition of experimental soil

Particle size class (mm)	> 1.000	1.000–0.250	0.250–0.050	0.050–0.010	0.010–0.005	0.005–0.001	< 0.001
Proportion (%)	0	1.1	35.4	43.4	3.2	6.4	10.5

experimental results. If the runoff, soil loss rate, and hydraulic parameters exhibited little variation, thus, they were acceptable. Then, the mean values of the two treatments were used to study effects of shrub on runoff and soil erosion processes.

3 Results

3.1 Runoff processes

The average runoff rates ranged from 0.51 to 1.26 mm/min for bare soil plots and 0.15 to 0.96 mm/min for shrub plots (Table 2). The higher rainfall intensities increased runoff volumes and amount of soil loss. The difference in runoff between bare soil and shrub plots varied from 70.5% for a rainfall intensity of 45 mm/h to 27.7% for a rainfall intensity of 127 mm/h. Rainfall intensity had an appreciable influence on the mean runoff rate for each plot. As expected, the runoff rate increased with an increase in rainfall intensity.

Fig. 1 shows the runoff response during a storm event for both bare soil and shrub plots under different rainfall intensity regimes. With a rainfall intensity of 45 mm/h, the runoff rate on the bare soil plot slowly increased to a maximum level of 0.69 mm/min at 36 min of rainfall duration s (Fig. 1a). The runoff rates for the bare soil plot remained relatively steady after 20 min for storms with intensities of 45 mm/h. This may be because the soil surface morphology changed little under rainfall intensities of 45 mm/h. However, the runoff rates for the shrub plots did not reach steady values at rainfall intensities of 45 and 87 mm/h. The runoff process from bare soil plot showed significant fluctuations and behaved similarly under rainfall intensities of 87 and 127 mm/h. This was due to rill formation and development at about 20 min duration after rainfall started. With rainfall, surface flow gradually converted into concentrated flow, and runoff erosivity increased enough to scour soil clods. Then, small waterfalls evolved into rill headcuts, and rills correspondingly occurred. As rill erosion occurred and evolved into the dominant erosion pattern, runoff rates rapidly increased until they reached a relatively stable stage. These behaviors indicate that the surface conditions and rainfall intensity had clear impacts on runoff. The runoff response for the 127 mm/h rainfall on the shrub plot showed an overall increasing trend (Fig. 1b). When the rainfall intensity increased to 127 mm/h on the shrub plot, the effect of raindrop interception and the increase in hydraulic roughness by shrub stems and foliage became less apparent. Hence, the less reduction in runoff for the shrub plots.

Table 2 Average runoff and soil loss from bare soil and shrub plots for different rainfall intensities

Rainfall intensity (mm/h)	Runoff rate (mm/min)			Soil loss rate (g/(min·m^2))		
	Bare soil	Shrub	Shrub reductions cf. bare soil (%)	Bare soil	Shrub	Shrub reductions cf. bare soil (%)
45	0.51	0.15	70.5	44.19	5.61	87.3
87	1.10	0.42	61.8	81.32	12.04	85.2
127	1.26	0.96	27.7	114.61	84.58	26.2

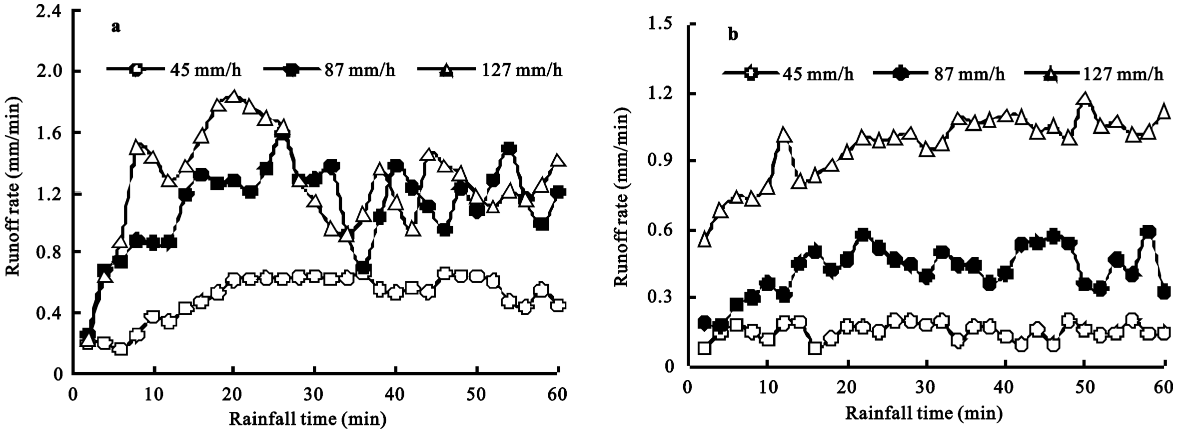


Fig. 1 Runoff rate for bare soil plots (a) and shrub plots (b) under different rainfall intensities

3.2 Soil loss processes

Under the experimental conditions, the average soil loss rates varied from 44.19 to 114.61 g/(min·m^2) for bare soil plots and from 5.61 to 84.58 g/(min·m^2) for shrub plots. The percentage reduction in soil loss rate for the shrub plots relative to that of the bare soil plots ranged from26.2% to 87.3% (Table 2).

The rate of soil loss for both bare soil and shrub plots increased with the increase of rainfall intensity (Fig. 2). For rainfall intensity of 45 mm/h, there was no indication of rill development on either the bare soil or shrub covered plots. Sheet erosion was the dominant mode of erosion and the rate of soil loss was relatively low for the bare soil plot, and the rate of soil loss was relatively constant on the shrub covered plot. For the rainfall intensity of 87 mm/h, the soil surface of the bare soil plot showed evidence of the development of crescent-shaped scouring pits and rill formation after 26 min of rain (Fig. 2a). So, the soil loss for bare soil plot increased sharply and kept a fluctuant trend affected by the advance of rill development. Whereas for the shrub covered plot with rainfall intensity of 87 mm/h, the rate of soil loss remained constant over time. Furthermore, the rate of soil loss for the shrub-covered plot was lower than that of the bare plots over time. For a rainfall intensity of 127 mm/h, the relatively greater availability of soil material due to increased soil splash detachment caused a greater rate of soil loss on the bare soil plot at the beginning of the rainfall. Rill development was initiated after about 18 min of rain, at which point a very substantial increase in soil loss was observed. In the shrub-covered plots, erosion pits developed after about 12 min of rain causing a sharp but fluctuating increase in the rate of soil loss (Fig. 2b). The net effect was that soil loss for the bare soil plot was greater than that from the shrub- covered plot under each rainfall intensity regime.

3.3 Relationships between runoff and soil loss

Vegetation helps reduce soil loss not only by reducing runoff volume, but also by changing the relationship between runoff and sediment yield (Zheng *et al.*, 2007). The relationship between soil loss and runoff as an indicator of soil erosion has commonly been regarded as a linear function under net detachment conditions or a quadratic regression under depositional conditions (Huang and Bradford, 1993). Fig. 3a shows that the soil loss rate (S_{L}) was positively correlated with runoff rate (Q_{R}) in the bare soil plots for different rainfall intensities. The results are similar to those observed in field bare plots in which runoff was significantly positively correlated with soil loss (Huang and Bradford, 1993; Flanagan *et al.*, 2002). The equation coefficient, namely erodibility-related indicator, increased as rainfall intensities increased and ranged from 83.99 g/(min·m^2) for rainfall intensity of 45 mm/h to105.51 g/(min·m^2) for rainfall intensity of 127 mm/h (Table 3).

For the shrub plots, the relationships between S_{L} and Q_{R} were divided into two linear trends: a lower region with a lower runoff rate where S_{L} had only slight correlation with Q_{R} with a constant erodibility under rainfall intensities of 45 and 87 mm/h; and an upper region where S_{L} increased with Q_{R}, which resulted in a strong positive relationship at the rainfall intensity of 127 mm/h (Fig. 3b). For a rainfall intensity of 127mm/h, once rill erosion occurred under the higher rainfall treatment, more runoff was produced and soil loss was correspondingly enhanced. In this case, the relationship of $\mathrm{S_L}$ and Q_{R} presented a trend line similar to that of the

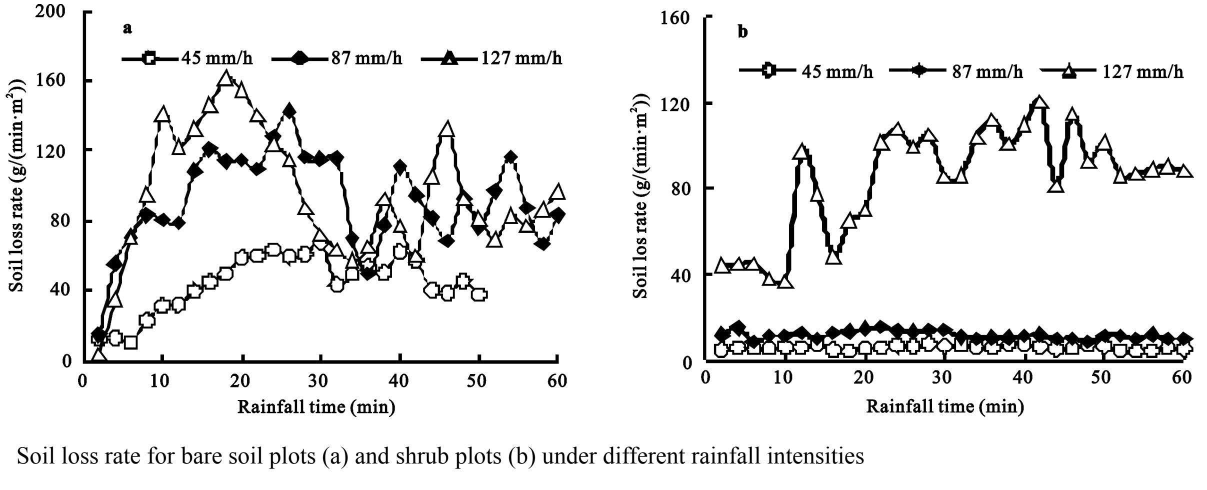


Fig. 2 Soil loss rate for bare soil plots (a) and shrub plots (b) under different rainfall intensities

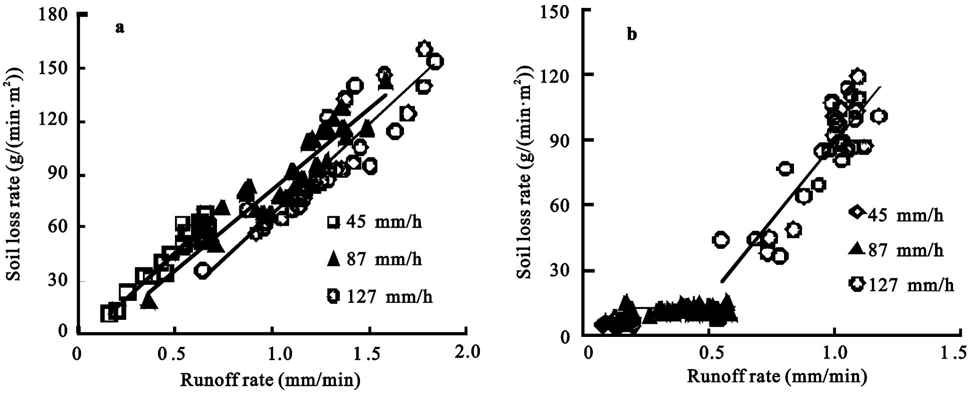


Fig. 3 Relationships between runoff and soil loss for bare soil plots (a) and shrub plots (b)

Table 3 Linear regression of soil loss rate (S_L) and runoff rate (Q_R) for the bare soil and shrub plots

Rainfall intensity (mm/h)	Bare soil plots			Shrub plots		
	Regression equation	R^2	*n*	Regression equation	R^2	*n*
45	$S_L = 83.99\ Q_R - 5.81$	0.931	30	$S_L = 10.64\ Q_R - 4.43$	0.351	28
87	$S_L = 92.52\ Q_R - 10.97$	0.868	29	$S_L = 23.27\ Q_R - 12.81$	0.412	30
127	$S_L = 105.51\ Q_R - 33.77$	0.805	29	$S_L = 145.04\ Q_R - 55.92$	0.746	29

bare soil plot. This may be due to the change of surface morphology with the development of erosion pits, even for the 63% coverage of shrub. This also indicates that rainfall intensity plays a major role in soil erosion and has an important effect on the change of surface morphology.

3.4 Surface morphology

The difference in runoff and soil loss between bare soil and shrub plots must be attributed to surface conditions. The slope hydrology is determined by its morphology and, as a consequence, erosion and sedimentation processes variation, leading to the development of a change in the erosion pattern.

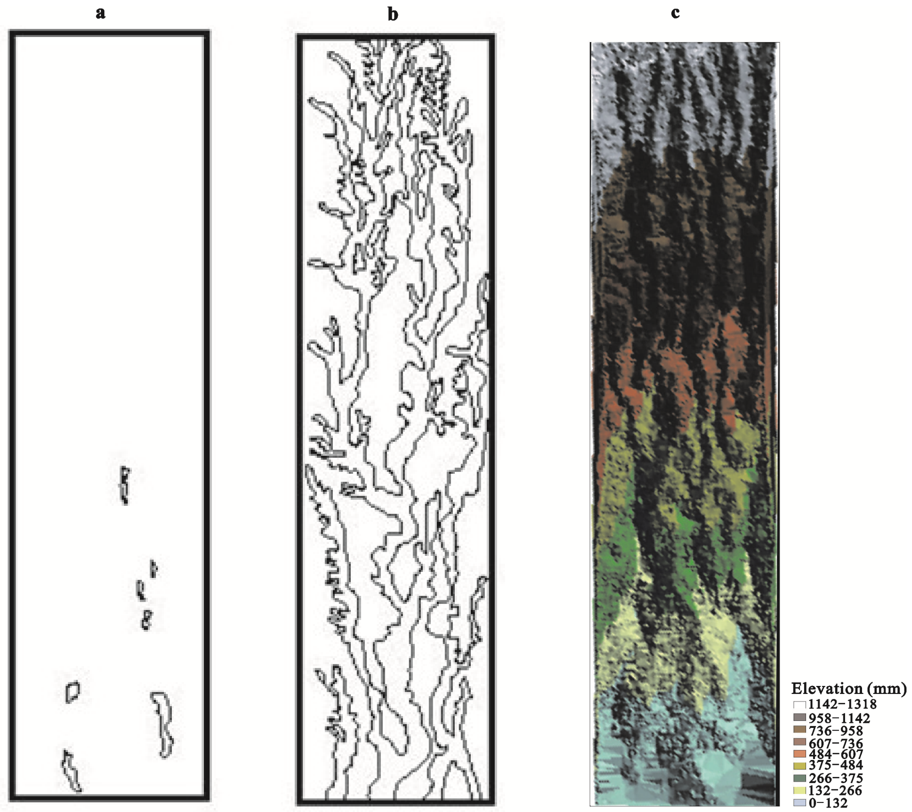
The higher intensity of 127 mm/h at more runoff and soil loss was typically chosen to study the effect of surface morphology on erosion processes. Fig. 4 shows the different surface morphology for the bare soil and shrub plots under the rainfall intensity of 127 mm/h. The soil surface on the bare soil plot showed evidence of the development of crescent-shaped scouring pits and non-uniform distribution of rill spacing. However, there was no indication of rill development on the shrub-covered plots. Sheet erosion was the dominant mode of erosion on the shrub-covered plot and only small pits erosion and waterfalls occurred as a result of this process. In the bare soil plot, most rill lengths were > 450 cm, most rill widths were > 20 cm, and most rill depths were > 15 cm. The mean rill length for the bare plot was 15 times longer than that of the shrub plot. The mean rill width and depth were also larger than those formed on the shrubplot. The mean rill width and depth at rainfall density of 127 mm/h were 10 and 12 times larger on the bare plots than those on shrub plots, respectively. These results indicate that there were important effects of shrubs for resisting soil erosion, but this was also affected by the increase of rainfall because development of erosion pits gradually advanced toward rill morphology.

3.5 Critical hydrodynamic parameter

Several studies have indicated that the stream power concept is a simple and effective predictor of soil detachment and transport and can be used in soil conservation practices to predict soil erosion (Elliott, 1993; Nearing *et al.* 1997; Xiao *et al.* 2011). Unit stream power per unit weight of water was expressed by the following equation, which can be found in Zhang *et al.* (2010).

$$P = VS \tag{1}$$

where P is unit stream power (m/s), V is flow velocity (m/s), S is energy slope (m/m) representing the vertical throw between two points along the hillslope ($S \approx \tan 20°$).



Erosion pits on shrub plot Rill networks on bare soil plot DEM on bare soil plot

Fig. 4 Surface morphology on bare soil and shrub plots at the 127mm/h rainfall intensity. a. Erosion pits on shrub plot; b. Rill networks on bare soil plot; c. DEM on bare soil plot

The average flow velocity ranged from 0.165 to 0.381 m/s for bare soil plots and from 0.042 to 0.156 m/s for shrub plots (Table 4). According to Equation (1), the average unit stream power ranged from 0.060 to 0.139 m/s for bare soil plots and 0.015 to 0.057 m/s for shrub plots. Rainfall intensity had an appreciable influence on the mean flow velocity for each plot. The higher intensity increased runoff volumes and soil loss amount.

Table 4 Average flow velocity (*V*) and unit stream power (*P*) from bare soil and shrub plots

Rainfall intensity (mm/h)	*V* (m/s)		*P* (m/s)	
	Bare soil	Shrub	Bare soil	Shrub
45	0.165	0.042	0.060	0.015
87	0.324	0.095	0.118	0.035
127	0.381	0.156	0.139	0.057

Based on the experimental data of this study, soil loss rate (S_L) was shown to be positively correlated to the unit stream power (P) for both the bare soil and shrub-covered plots. The S_L value increased linearly with P, giving the relationship for the bare soil plots and the shrub-covered plots shown in the regression equation in Fig. 5. Based on the relationship between S_L and P, when no soil erosion occurred, $S_L = 0$, then the critical hydraulics were determined. In this experiment the critical values of P for the bare soil and shrub-covered plots were 0.004 m/s and 0.017 m/s, respectively. The larger critical P values that were obtained for the bare soil and shrub-covered plots indicated the degree of effectiveness of the shrub conservation practices relative to the bare soil condition.

4 Discussion

4.1 Effects of shrub on soil erosion

The lower runoff and soil loss for the shrub plots in comparison to those of the bare soil plots for all the rainfall treatments suggests that shrub cover under certain conditions can be very effective in reducing runoff and sediment. The effect of raindrop interception and the increase in hydraulic roughness by shrub stems and foliage became more apparent relative to the bare soil

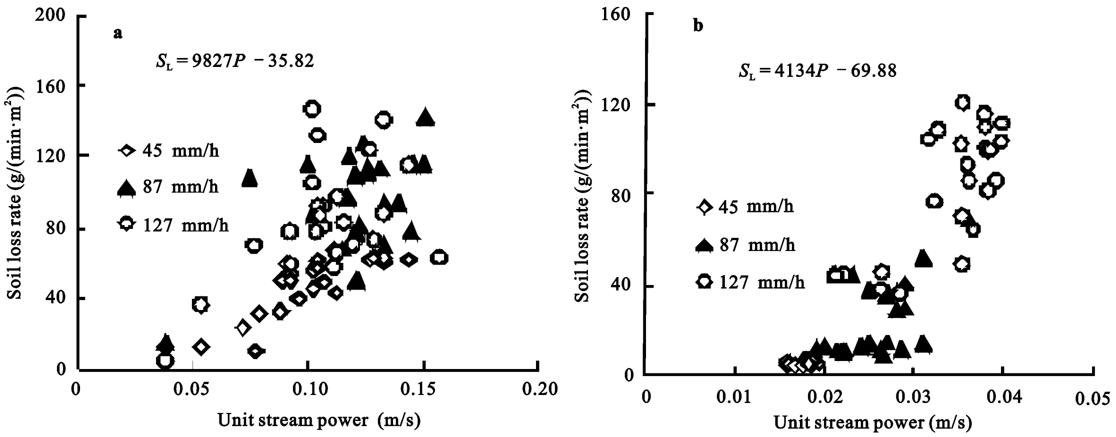


Fig. 5 Relationships between the soil loss rate and the unit stream power for bare soil plots (a) and shrub plots (b)

plot. This behavior had also been found in some studies of vegetation cover controlling the erosion rate (Abrahams *et al.*, 1988; Edeso *et al.*, 1999; Casermeiro *et al.*, 2004). A comparison of the soil loss rate between the bare soil and shrub-covered plots indicated that the shrubs were able to resist soil erosion.

The relationship between runoff and soil loss rate on the shrub-covered plot has commonly been regarded as a linear function. Abrahams *et al.* (1988) showed that sediment concentrations had a negative correlation with flow discharge on shrub land. Cerdà (1998) found that the runoff coefficient was negatively related to sediment concentration on a Mediterranean hillslope with vegetation cover. Our results show a strong positive relationship between runoff and soil loss for rainfall intensity of 127 mm/h, which is different from those observed on vegetated slopes (Abrahams *et al.*, 1988; Cerdà, 1998). The differences in the relationship between runoff and soil loss on shrub plots may be attributed to the development of surface morphology as a result of the rill occurrences for higher rainfall intensity. The results are similar to those observed on the Loess Plateau in China which exhibited a perfect linear relationship between runoff volume and sediment yield for the events with the runoff depth of greater than 1 mm (Zheng *et al.*, 2007). The runoff and soil loss response for the rainfall density of 127 mm/h on the shrub plot showed fluctuations in an overall increasing trend. Therefore, the effect of increased rainfall intensity leading to more runoff and soil loss for the shrub-covered plots must be taken into account when considering cultivated surface soils on the Loess Plateau. For effective soil erosion control, the practitioner need adopt a comprehensive program comprising both agronomic measures, such as vegetative cover, and mechanical soil erosion control measures.

Through this study, we have obtained empirical evidence of the effects of shrubs on reducing runoff and soil loss. In fact, shrubs protect the soil in different ways including the interception of raindrops by the vegetation canopy and the reinforcement of soil by vegetation roots. The role of different factors in soil erosion such as the efficiency of leaf area index, root length density or root area density, aboveground biomass, root biomass in controlling soil erosion should be considered for further study.

4.2 Soil erosion and morphology

Although the same rainfall intensity was designed for the bare soil and shrub plots under the experimental conditions, runoff, and soil loss and rill erosion changed not only for impacts of erosion patterns, but also for different initial surface morphology. For the bare soil plots, the experiment was conducted on a hillslope with a plane surface. For the shrub plots, shrub layers occurred and increased runoff resistance; therefore, few erosion pits occurred. The vegetative canopy cover intercepts raindrops, reducing their impact energy on the soil surface. The surface litter shields the soil surface from direct raindrop impact and significantly enhances infiltration (Lane *et al.*, 1997). The observed difference in runoff and soil loss response between these two plots may also be attributed to the presence of a moss skin, which developed over a relatively short time span on the surface of the shrub plot and had the effect of preventing scouring of soil by runoff and enhanced surface retention.

The linkages between vegetation and hillslope geomorphology have been a major research topic and recent perspectives focus on the two-way interplay between vegetation and hillslope geomorphology (Marston, 2010). The effects of vegetation on soil erosion and morphology were investigated in the current study and we found that rill morphology plays a significant role in determining surface runoff and soil loss in the bare soil plot. The difference in surface morphology between the bare soil and shrub-covered plots also reflects the ability of the shrub cover to resist the destructive impact of raindrops and runoff scouring. Eroding rills evolve morphologically in time and space (Lei and Nearing, 1998), and it is necessary to consider their temporal and spatial variations (Boardman, 2006). Therefore, future research should present temporal and spatial variations of surface networks based on morphological indicators and also analyze the correlations between soil erosion and morphological indicators to propose the optimal indicator for different types of vegetation-covered plots.

4.3 Hydrodynamic mechanisms of soil erosion

Shrubs are very effective in reducing runoff and soil loss. However, studies of soil erosion characteristics and the intrinsic mechanisms behind soil loss remain unclear. Soil erosion by water is a complex problem and both empirical and physical process-based approaches have been used to predict soil erosion rates. When sufficient energy is available to detach and transport soil particles, erosion may occur. Assuming the validity of many sediment transport equations, the flow velocity, stream power, or shear stress is considered dominant variable in soil erosion processes. Additionally, flow velocity has been shown to be the most sensitive hydraulic parameter to estimate flow hydraulic characteristics (An *et al*., 2012).

Because of the large number of variables that affect soil erosion, Shih and Yang (2009) used correlation analysis to identify the most important factors that affect sheet erosion. They concluded that the unit stream power was the most significant parameter for predicting sheet erosion rates. Furthermore, stream power was the optimal hydrodynamic parameter (Nearing *et al*., 1997; Reichert and Norton, 2013) to characterize the dynamic mechanisms of rill erosion. The unit stream power, as defined by Yang (1972), was initially used to describe sediment transport in channel flow, but Moore and Burch (1986) showed that it can also predict the sediment transport rate in shallow surface flow when the unit stream power value of 0.002 m/s is exceeded and when the sediment is in a dispersed state. Based on the simulated rainfall experiments, we found that the rate of soil loss increased linearly with the unit stream power of runoff on both bare and shrub-covered plots.

Soil erosion is a consequence of all simultaneously operating erosion processes involving processes such as rainfall, overland flow, and subsurface flow. Mechanistically, they are often divided into detachment and transport categories, although each process consists of both components. Erodibility is the inherent susceptibility of soil particles or aggregates to become detached and subsequently to be transported by the splash of impacting raindrops or picked up by overland flow. Correlations between soil erosion and hydrodynamic parameters indicated that the unit stream power used in this study were suitable for characterizing the soil erosion mechanisms. The critical unit stream power is a measure of the minimum energy required for the flow to detach soil particles. Based on the findings in this experiment, a shrub-covered plot appears to be more effective in controlling soil erosion.

5 Conclusions

Simulated rainfall intensities of 45, 87, and 127 mm/h were conducted to compare the runoff and soil loss on the bare soil and shrub plots and to determine how the unit stream power controls sediment detachment and transport. The results showed that runoff and soil loss rates increased with the increase of rainfall intensity, and runoff and soil loss rates for shrub plots were generally lower than those for bare soil plots. The runoff and soil loss reducing benefits of shrub cover is more effective for lower rainfall intensity. Soil loss was strongly positively correlated with runoff in the bare soil plots for different rainfall intensities. However, for the shrub plots, the soil loss and runoff showed a strong positive relationship only at the rainfall intensity of 127 mm/h. The runoff and soil loss rates for both treatments were closely related to the change in surface morphology because of the development of erosion pits and rills. Under the experimental conditions of this study, the critical unit stream power value for the shrub-covered plots was approximately four times greater than that for the bare soil plots. Therefore, shrub cover can be very effective in reducing runoff and soil loss under certain conditions.

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