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Effects of vegetation and rainfall types on surface runoff and soil erosion on steep slopes on the Loess Plateau, China

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ABSTRACT

It is widely recognized that vegetation restoration plays a key role in controlling soil erosion in China's Loess Plateau. However, the effects of vegetation types on soil erosion on steep slopes of the Loess Plateau are not yet fully understood. In this study, we carried out our experiments on surface runoff and soil loss monitoring at nine runoff plots with different vegetation types over a nine-year period from 2008 to 2016 to evaluate the effects of vegetation and rainfall on soil erosion. We classified forty-three rainfall events into three rainfall types based on a rainfall concentration index and further analyzed the sensitivities of the runoff and soil loss to these rainfall types. The results indicated that the grassland (*Bothriochloa ischaemum* L.) and shrubland (Sea-buckthorn) with high ground cover had a lower runoff depth and soil loss compared to the forestlands with poor ground cover with an average reduction of 50% in annual runoff depth and 92% in annual soil loss. Comparison of the mean runoff coefficient and soil loss in the three rainfall types demonstrated that rainfall events with high intensity and short duration caused more surface runoff and soil loss under all vegetation types. A power function fitted well in the runoff-soil loss relationship and the result showed that the grassland and shrubland had a smaller magnitude term which reflects less soil susceptibility to erosion. The research implies that the ground cover is an important factor in controlling soil and water loss and vegetation measures with high ground cover should be strongly recommended for soil erosion control on the Loess Plateau. It is helpful for vegetation restoration strategy and conserving soil and water on steep slopes of this area.

1. Introduction

The Loess Plateau of China is the most severely eroded area in the world (Tang et al., 1993; Douglas, 1989). It covers a total area of 624,000 km^2, in which, about 68% of the area suffered from soil erosion (Fu et al., 1994). The average annual erosion rate was 2330 $t\,km^{-2}$, and in some catchments, it reached to over 59,700 $t\,km^{-2}$ (Tang et al., 1993; Shi and Shao, 2000). The severe soil erosion not only causes significant onsite land degradation, but also the offsite riverbed aggradation in the lower reaches of Yellow River threatens the livelihood of the near 0.2 billion population of Henan and Shandong provinces (Tang et al., 1993; Fu, 1989). To control the severe soil erosion, a series of soil conservation measures have been implemented on the Loess Plateau since the 1950s. These measures consist of sediment-trapping dams and reservoirs, terraces, afforestation and pasture establishment (Tang, 2004; Gao et al., 2012). These efforts resulted in a significant reduction in annual streamflow and sediment load in the catchments of the Loess Plateau (Ran et al., 2000; Gao et al., 2012). The annual sediment load of the Yellow River declined from about 1.34 Gt during the period of 1951–1979 to about 0.73 Gt during 1980–1999, and further down to about 0.32 Gt in 2000–2010 (S. Wang et al., 2016). As the sediment trapping dams are filling up and losing their function, using vegetation to control soil erosion is expected to play an important role in the future to maintain the low sediment discharge level of the Yellow River (Zhang et al., 2017; Zhang et al., 2018; S. Wang et al., 2016).

As a fundamental practice of soil conservation measures, vegetation restoration was widely implemented on the Loess Plateau since the 1950s (Wu et al., 2005), but the great improvement of vegetation cover was not achieved until 1999 when the “Grain for Green (GFG)” project was implemented with its aim to convert the sloping farmland to forest and grassland (Tang, 2004; Ran et al., 2000). This project has resulted in great improvement in vegetation cover, which subsequently caused

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significant changes in hydrological and erosion processes (Sun et al., 2006; Zheng, 2006; Zhou et al., 2016). The mechanisms of vegetation to conserve water and soil are well understood (Wu et al., 2005; Zhao et al., 2001; Wu and Zhao, 2001). Native forests are generally superior to shrubs and grasslands in retaining soil and water, but it is very different if they are planted. Huang et al. (2006) investigated the relative efficiency of four representative land-use types in reducing water erosion in runoff plots of a small catchment of Gansu province, and found that planted shrubland (sea buckthorn) and native grassland with high vegetation cover had better soil and water conservation benefits than planted forestland (Chinese pine) plot. Zhou et al. (2000) also found that the grassland with high vegetation cover was more effective than the planted forestland (Yunnan pine) in reducing soil and water loss in the plots of a gorge area of Southwest China. Li et al. (2012) analyzed the benefits of soil and water conservation of different vegetation restoration patterns in the secondary *Pinus massoniana* pure forest plots in Jiangxi province of China, and indicated that the pure forest with a multiply vegetation structure (tree-herb or tree-shrub) had an reduction of 50–60% in runoff and 65–70% in soil loss compared with the pure forest with no understory layer. Wen et al. (2010) and Lei and Wen (2008) quantified the contribution of different vegetation strata to soil and water conservation for the Chinese pine and the aspen communities, and also found that the benefits of soil and water conservation of vegetation with the same canopy cover were actually very different and ranged from16–52%. A large number of researchers pointed out that vegetation actually controls soil erosion through its different stratified structure, especially the near ground layer (Wu et al., 2005; Zhao et al., 2001; Mohammad and Adam, 2010).

On the Loess Plateau, many studies were conducted to investigate the effects of vegetation restoration on runoff and soil erosion in different regions with various topographic conditions and vegetation zonal features. However, these studies mainly focused on several limited vegetation types or inconsistent topographic conditions. Hou and Cao (1990) and Hou et al. (1996) studied the benefits of soil and water conservation of planted vegetation with different ages (e.g., Black locust, sea buckthorn, Chinese pine, and the mixture of them) at runoff plots with various slope aspects in the hilly gully region of Northern Shaanxi province. Three stages were divided according to the benefits of soil conservation from young growth to closed forest. Zheng (2006) quantified the effects of vegetation destruction and vegetation restoration on soil erosion by using the field runoff plots located in different topographic positions of the hillslope in the Ziwuling secondary forest region, and showed that erosion rates in the deforested lands was 797 to 1682 times greater than those in the forested land prior to deforestation. Wei et al. (2007) analyzed the effects of five different land use types on runoff and soil loss at the plots with three different slope degrees (10°, 15° and 20°) in Gansu province and suggested that shrubland was the first choice to control soil erosion whereas grassland and woodland could be used as important supplements to shrubland. Z. Wang et al. (2016) investigated the responses of three different land-use types in controlling soil erosion by using field survey at different slope gradients (11°–40°) in the Northern Shaanxi province and indicated that grassland and woodland were more effective at reducing erosion than orchard. Feng et al. (2016) also investigated the effects five different land-use types on soil erosion at runoff plots with two slope gradients (5° and 15°) in northern Yan'an of the Loess Plateau and found that the composite land-use type (cultivated land and abandoned land) and the artificial grassland were appropriate options. Moreover, Ai et al. (2017) analyzed the impacts of land disturbance and restoration on runoff production and sediment yield by using five runoff plots with different topographic features in Wuqi County of Shaanxi province, and revealed that mixed forest of sea buckthorn and Chinese pine and sea buckthorn shrub were excellent plants for land restoration in this area, especially for relatively gentle slope area. From these studies, we found there is little research comparing surface runoff and soil loss of different vegetation types including trees, shrubs and grasses under the same topographic condition on steep slopes of the Loess Plateau. It is necessary to investigate the effects of vegetation types on the surface runoff and soil loss under an identified condition to fully understand the hydrological processes in vegetation restoration on the Loess Plateau. Our study is focused on the steep slopes as statistics show that the area with steep slopes (> 25°) accounts for 20–60% of the total catchment area on the Loess Plateau. It was estimated that the soil erosion from this part of area occupied 35–90% of the total amount of soil loss (Qi, 1991; Fu, 1989).

Rainfall is another important factor influencing the occurrence and intensity of soil erosion (Kinnell, 2005; van Dijk et al., 2002; Sharma et al., 1993; Ran et al., 2012). On the Loess Plateau, runoff and soil erosion are markedly affected by the characteristics of high intensity rainfalls, which mainly occur between July and September with 60–70% of the total annual precipitation (Fu, 1989; Shi and Shao, 2000). The impacts of rainfall characteristics (generally including rainfall intensity, duration, moving direction and rainfall temporal resolution) on runoff and soil erosion have been extensively studied and are still the subject of many researchers (De Lima et al., 2003; Kinnell, 2005). Among the rainfall characteristics, rainfall intensity and duration are the two primary factors influencing the hydrological and erosion processes (Ran et al., 2012). Due to the formation of surface crusting (De Roo and Riezebos, 1992; Vandervaere et al., 1997), rainfall events with higher intensity and/or longer duration are generally prone to produce earlier runoff generation and higher runoff peak (Wei et al., 2014; Ran et al., 2012), resulting in larger runoff and soil loss (Peng and Wang, 2012; dos Santos et al., 2017; Fortugno et al., 2017). A great number of studies were conducted to investigate the effects of rainfall characteristics on surface runoff and soil erosion under simulated or natural rainfall conditions (Anache et al., 2017; Cao et al., 2015; L. Zhang et al., 2015; Mathys et al., 2005; Kinnell, 2005). Some studies also analyzed the impacts extreme rainfall characteristics on soil erosion (Z. Wang et al., 2016; Wei et al., 2009). However, most of the existing studies focus on the response of the runoff and soil erosion to single rainfall characteristic or typical rainfall events (Kirkby et al., 2005; De Lima et al., 2003; Kinnell, 2005; L. Zhang et al., 2015).

Differently from these previous studies, the aim of this study was to evaluate the effects of vegetation restoration types and rainfall types on surface runoff and soil loss on steep slopes of the Loess Plateau. The specific objectives were: (1) to compare the differences in surface runoff and soil loss under nine different vegetation types; (2) to determine the responses of surface runoff and soil loss to different rainfall types; and (3) to quantify the relationship between surface runoff and soil loss at runoff plots to better understand the effects of vegetation and rainfall on soil erosion.

2. Study area and methods

2.1. Study area

This study was conducted in Wangdonggou watershed (35°13′–35°16′ N, 107°40′–107°42′ E; elevation 946–1226 m; area 8.3 km^2) of the State Key Agro-Ecological Experimental Station, located in Changwu county, Shaanxi Province, China (Fig. 1). The study area is located in the tableland-gully region of the Loess Plateau, and the landforms are characterized mainly with tableland and dissected land, which account for 35 and 65% of the area, respectively (Liu et al., 2010). It has a continental monsoon climate of warm temperate zone with the mean annual precipitation of 560 mm (1984–2014), 60% of which occurs between July and September, the mean open pan evaporation of 1565 mm and the mean temperature of 9.1 °C(Y. Zhang et al., 2015; Chen et al., 2008a). Soil in this region is composed of loessial soil, and the soil is silty clay loam according to the FAO-UNESCO soil classification system (FAO, 1998). The groundwater table is about 50–80 m below the land surface. In the semi-arid loess regions, precipitation is the only natural water source to replenish soil moisture

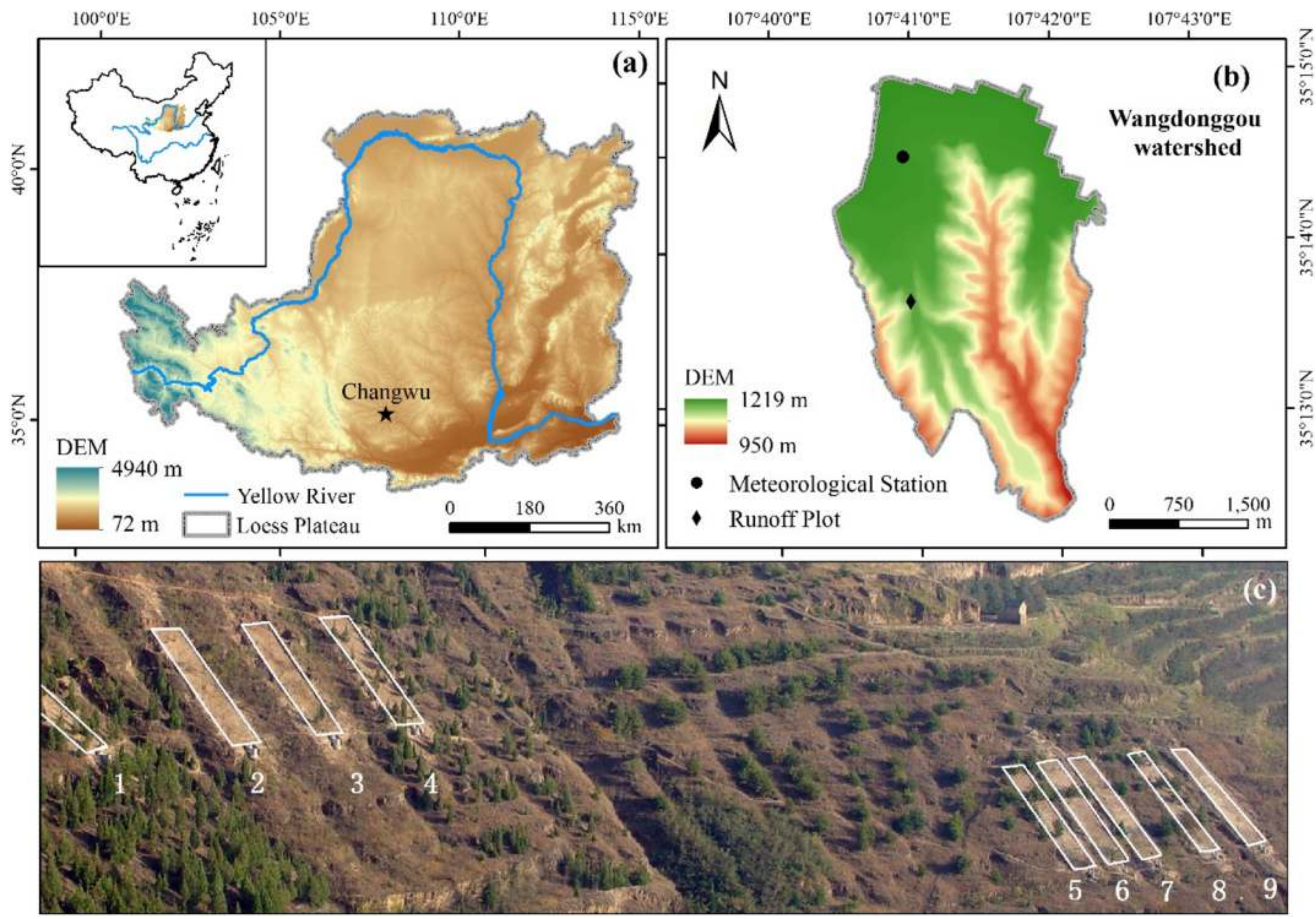

Fig. 1. (a) The location of Changwu Agro-ecological station on the Loess Plateau in China. (b) The location of runoff plots in the study watershed. (c) Layout of the runoff plots on steep slopes.

due to the thick loess depth and very deep groundwater table (Chen et al., 2010). Under these conditions, the growth and survival of vegetation are strongly limited by the availability of water (Jian et al., 2015; Cao et al., 2011). Cultivation takes place mainly in the flat areas of the tableland and gullyland. The main agricultural crops are wheat (*Triticum aestivum* L.), maize (*Zea mays* L.) and broomcorn (*Sorghum bicolor* L.). While dominant plant species in this area include *Robinia pseudoacacia* L., *Populus simonii* Carr L., *Armeniaca sibirica* L., *Agropyron cristatum* L., etc.

2.2. Experimental design

Nine standard runoff plots were established in 2003 (Fig. 1). All the plots were set up on the same slope (35°) with similar soil properties and aspects. Each plot was 100 m^2 in size (5 m in width and 20 m in horizontal length) with the longer side in the downhill direction. The plots were separated by 35-cm-wide cement walls with 20 cm of the walls placed below the soil and 15 cm remaining above the soil surface to isolate the runoff and sediment from the surrounding soils. At the lower end of each plot, a marked H-flume and two conjoined volumetric barrels were installed at the outlet of each plot to collect surface runoff and soil losses.

These plots were bare in the beginning of the experiments in 2003. To evaluate the impact of different vegetation restoration types on soil erosion, five dominant plant species were selected to grow in the nine experimental plots. They are grassland (*Bothriochloa ischaemum* L.) (BOI), shrubland Sea-buckthorn (*Hippophae rhamnoides* L.) (SEB), forestland Black locust (*Robinia pseudoacacia* L.) (LOC), Chinese pine (*Pinus tabulaeformis* L.) (CHP), Chinese arborvitae (*Platycladus orientalis* L.) (CHA). Five of the plots were single species: BOI, SEB, LOC, CHP, and CHA. The remaining four plots were mixture species: SEB + LOC, SEB + CHP, LOC + CHP, LOC + CHA. It was two to three years old when they were planted, and left to grow without any management practices. In 2016, the planted trees were nearly 16 years old. Vegetation properties of these plots were investigated by a quadrat method between 14th and 19th of August 2014 (Huang et al., 2006; Z. Wang et al., 2016). Four quadrats (1 m × 1 m) were used to estimate ground cover of each plot, which included grass and litter cover. Meanwhile, height, diameter at breast height (DBH) of trees, or basal diameter of shrubs, and canopy width of shrub and tree species was measured by four quadrats (5 m × 5 m). The spacing and plant species within each plot were recorded as well. In the grassland plot, *Bothriochloa ischaemum* was a predominant native species and the ground cover was high about 88% (Table 1). Under the shrubland plot, Sea-buckthorn also had a high ground cover of 80%. Unfortunately, the other plots of forestland had different degrees of bare soil and low ground cover characterized by a thin or absent a shrub or herb layer, especially in the plot of Chinese arborvitae. The main herbaceous species in these plots including *Bothriochloa ischaemum*, *Arundinella hirta*, *Patrinia heterophylla*, *Artemisia vestita*, *Leymus secalinus*, *Stipa bungeana*, etc. (Muratjan, 2015). The detailed vegetation properties for the plots are given in Table 1.

Soil properties of these plots were also measured for the top 20 cm soil layer, including soil organic matter (SOM), bulk density (BD), soil porosity (total porosity, capillary porosity and non-capillary porosity), and saturated hydraulic conductivity (K_s) (Table 1). The results showed

Table 1
Vegetation and soil properties of the experimental plots.

Vegetation type	Vegetation properties					Soil properties					
	Spacing (m)	Mean height (m)	Mean DBH/BD (m)	Canopy cover (%)	Ground cover (%)	SOM[a] ($g\,kg^{-1}$)	BD[b] ($g\,cm^{-3}$)	TP[b] (%)	CP[b] (%)	NCP[b] (%)	K_S[b] ($m\,s^{-1}$)
BOI	–	0.4	–	–	88	13.6c	1.17	58.03	45.98	12.05	3.83×10^{-6}
SEB	1 × 2	1.9	2.4	67	80	10.7b	1.18	54.16	47.44	6.73	4.67×10^{-6}
LOC	1 × 2	3.4	2.7	15	77	10.2b	1.23	54.74	46.86	7.87	4.17×10^{-6}
SEB + LOC	1 × 1	2.2	2.6	88	35	10.7b	1.29	50.57	42.18	8.39	2.17×10^{-6}
SEB + CHP	1 × 1	3.2	4.2	81	40	8.6a	1.20	51.72	45.84	5.88	2.17×10^{-6}
LOC + CHP	1 × 1	2.9	3.7	77	55	8.7a	1.31	51.75	44.28	7.47	1.17×10^{-6}
LOC + CHA	1 × 1	2.8	2.5	40	23	11.2b	1.21	52.80	43.20	9.60	3.67×10^{-6}
CHP	1 × 2	2.4	2.4	62	43	10.8b	1.22	54.17	49.04	5.12	2.50×10^{-6}
CHA	1 × 2	4.4	5.4	78	10	8.3a	1.18	50.93	45.34	5.59	2.67×10^{-6}

Notes: the data was compiled from Muratjan (2015). BOI, *Bothriochloa ischaemum*; SEB, Sea-buckthorn; LOC, Black locust; CHP, Chinese pine; CHA, Chinese arborvitae. DBH/BD = diameter at breast height/basal diameter. For Sea-buckthorn, the basal diameter was determined and the diameter at breast height was determined for other tree species. SOM, soil organic matter; BD, bulk density; TP, total porosity; CP, capillary porosity; NCP, non-capillary porosity; K_S, saturated hydraulic conductivity.

[a] Means with the same letter are not significantly different at $P < 0.05$ level.

[b] Indicates that the differences in the BD, TP, CP, NCP, and K_S among the nine plots are not significant ($P < 0.05$).

Table 2
The classification of rainfall types based on rainfall concentration index.
Source: Wang and Jiao (1996).

Rainfall type	Rainfall concentration index (%)
A	≥80
B	20–80
C	≤20

that the content of SOM in the grassland (BOI) and shrubland (SEB) plots was generally higher than that in the other vegetation plots, especially in the grassland plot. Although there were no significant differences in BD, soil porosity (TP, CP, and NCP) and K_s among these plots, compared with the BOI and SEB plots, the other vegetation plots were on average 5.0% higher in BD; 6.5%, 17.4%, and 37.4% lower in TP, NCP and K_s, respectively.

2.3. Data collection

Surface runoff and soil loss from each plot were collected and measured after each rainfall event from 2008 to 2016. The runoff volume in the barrel was determined using a measuring cylinder. A volume of 1000 ml runoff sample was collected from the bottom of the barrel after stirring and mixing of the sediment. Sediment samples collected from each plot were dried in an oven at 105 °C and subsequently weighed to determine the sediment concentration. The soil loss of each plot was calculated by the sediment concentration times the corresponding runoff volume. After the measurement and sampling, the barrels were emptied for the next rainfall event. To avoid the instability in the early stages, we only started to collect the data 5 years after planting in the plots. Thus nine years of data from 2008 to 2016 were used to investigate the influence of vegetation types to the surface runoff and soil loss.

Hourly rainfall data was automatically recorded in the rainy season by a siphon rain gauge installed in Changwu State Key Agro-ecological Experimental Station, which was 1.5 km away from the experimental plots. The depth, duration and intensity of each rainfall event were recorded. In selecting rainfall events, we considered these criteria: (1) the rainfall events were erosive rainfall with a daily rainfall amount > 12 mm; (2) successive rainfall events were separated into two rainfall events when the rainfall intermittent interval exceeded 6 h (Wischmeier, 1959; Renard et al., 1997); and (3) the timing of rainfall events was consistent with that of surface runoff recording.

2.4. Statistical analysis

In this study, the rainfall concentration index (CI) at a 60-min interval was used to classify erosive rainfall events (Wang and Jiao, 1996). It was derived from the statistical analysis of 248 rainstorms with different characteristics on the Loess Plateau. CI is defined as:

$$CI = P_{60}/P \quad (1)$$

where CI represents concentration index of a rainfall event (%), P_{60} is the maximum 60-min rainfall depth of a given rainfall event (mm), and P is the total rainfall depth of the rainfall event (mm). In this study, we classified rainfall type depending on the index of CI (Table 2).

Events data in the nine consecutive years (2008–2016) were used to analyze the surface runoff and soil loss in this study. Two parameters, surface runoff coefficient (C) and soil loss (SL) were calculated as follows:

$$C = (SR/P) \times \% \quad (2)$$

where C, SR and P are surface runoff coefficient (%), the surface runoff depth (mm) and rainfall depth (mm) of a given rainfall event, respectively.

$$SL = (SM/A_P)n^{-1} \quad (3)$$

where SL, SM, A_P and n^{-1} refer to soil loss ($t\,km^{-2}\,year^{-1}$), soil loss amount (t), area of runoff plot (km^2) and number of years (year), respectively.

3. Results

3.1. Rainfall types

During the 9-year study period, 43 erosive rainfall events that generated runoff in the plots were recorded and analyzed. The 43 erosive rainfall events were grouped into three rainfall types (A, B, C) based on the classification of CI (Table 2). The statistics of the three rainfall types are listed in Table 3.

Rainfall type A had the highest values of mean rainfall concentration index and maximum 60-min intensity, followed by rainfall type B and rainfall type C. However, mean rainfall depth and duration decreased in the opposite order (C > B > A). Average rainfall characteristic values represent the general features of rainfall events. Statistics show that type A was the group of rainfall events with high rainfall concentration and intensity (92.3% and 14.4 $mm\,h^{-1}$, respectively), small rainfall depth (15.4 mm) and short duration (2.6 h). Type C consisted of rainfall events with low concentration and intensity

Table 3
Statistics of different rainfall types.

Rainfall type	Variables	Mean	SD	Sum	Frequency
A	P (mm)	15.4	9.0	169.7	11
	I_{60} (mm h^{-1})	14.4	8.6		
	D (h)	2.6	1.9	29.0	
	CI (%)	92.3	8.5		
B	P (mm)	28.0	14.7	587.6	21
	I_{60} (mm h^{-1})	12.3	7.5		
	D (h)	9.0	5.2	189.0	
	CI (%)	44.0	12.6		
C	P (mm)	43.3	37.4	476.8	11
	I_{60} (mm h^{-1})	6.6	4.5		
	D (h)	16.4	6.4	180.0	
	CI (%)	17.9	5.7		

Notes: P, rainfall depth; I_{60}, maximum 60-min intensity; D, rainfall duration; CI, rainfall concentration index; SD, standard deviation.

(17.9% and 6.6 mm h^{-1}, respectively), great rainfall depth (43.3 mm) and long duration (16.4 h). Type B, however, was composed of rainfall events which have moderate rainfall characteristics with a concentration index and intensity of 44% and 12.3 mm h^{-1}, a depth of 28 mm and a duration of 9.0 h. During the experimental period, type A happened 11 times with a total depth of 169.7 mm. Similarly, type C was observed 11 times with a total depth of 476.8 mm. In contrast, type B occurred 21 times with a total depth of 587.6 mm, which was nearly twice as much as that of type A or type C (Table 3).

3.2. Annual surface runoff and soil loss under different vegetation types

Table 4 presents the results of average annual surface runoff and soil loss of the nine vegetation types from 2008 to 2016. It was clear that the runoff and soil loss were strongly affected by vegetation type. The annual surface runoff from the grassland (BOI) plot was the lowest ranging from 1.40 to 4.37 mm with the average of 2.40 mm for the nine years, followed by the shrubland (SEB) plot ranging from 2.06 to 4.47 mm with the average of 3.33 mm (Fig. 2). However, the surface runoff from all the forestland plots was higher, which was averagely 2.4 and 1.7 times higher than that of grassland and shrubland. In CHA plot, the average annual surface runoff reached to 14.67 mm. The annual runoff of the forestlands ranked in the order: CHA > CHP > LOC + CHA > SEB + LOC > LOC + CHP > SEB + CHP > LOC.

Similarly, the BOI plot exhibited the lowest annual soil loss ranging from 0.78 to 13.44 t km^{-2} with the average of 4.98 t km^{-2}. Then followed by the SEB plot ranging from 1.08 to 13.46 t km^{-2} with the average of 6.20 t km^{-2}. The soil loss in all the forestland plots was higher, which was on average 15.1 and 12.1 times higher than that in the grassland and shrubland plots. The highest annual soil loss occurred in the CHA plot with the average of 382.65 t km^{-2}. The annual soil loss of the forestlands descended in the order of CHA > CHP > LOC + CHA > LOC + CHP > SEB + CHP > SEB + LOC > LOC. In our study, the grassland and shrubland had lower runoff and soil loss compared with the forestlands with a reduction of 58% and 42% in annual runoff, 93% and 92% in annual soil loss.

The annual surface runoff and soil loss from these plots in the nine-year period are shown in Fig. 2. It indicates that the annual runoff, especially the annual soil loss was highly variable during the study period in all nine plots. But, in general, the annual runoff and soil loss had the synchronous fluctuation not only under each vegetation type but also among the plots.

3.3. Surface runoff and soil loss of different rainfall types

Rainfall characteristics are the primary factors affecting runoff generation and soil erosion, and different rainfall types can generate varying runoff and soil erosion. Fig. 3 shows that the features of the mean surface runoff coefficient and the mean soil loss of rainfall type events in different vegetation types. The impacts of rainfall types on runoff and soil loss are consistent in general among different vegetation types, they are in the same order: A > B > C. Rainfall type A exhibited the highest runoff coefficient and soil loss with the average of 6.6% and 19.2 t km^{-2}, respectively, followed by type B with the average of 2.6% and 14.3 t km^{-2}, respectively, and then the type C with the average of 1.4% and 3.8 t km^{-2}, respectively. It also demonstrates that the grassland and shrubland had the lower values in runoff coefficient and soil loss compared with the forestlands under all the three rainfall types, while the CHA plot had the highest in both the runoff and soil loss.

3.4. Runoff-soil loss relationship for each vegetation type under different rainfall types

Table 5 shows surface runoff and soil loss relationship for each vegetation type under different rainfall types. They were all fitted well with a power function ($P < 0.05$). The coefficient α of the power function $Y = \alpha X^{\beta}$ can be interpreted as the amount of soil loss per unit runoff (Zhou and Wu, 1993), and be regarded as a parameter to reflect the susceptibility of soil to erode. Comparison of different rainfall types under given vegetation type revealed that the coefficient α of the function showed a decreasing order in rainfall type A > B > C. Furthermore, comparing the coefficient α of the different vegetation types under the three rainfall types showed that grassland and shrubland had smaller coefficient α with the average value of 1.46 and 1.50, respectively, while the other vegetation types exhibited greater coefficient α with the average value ranging from 1.53 in the LOC plot to 6.64 in the CHA plot.

4. Discussion

4.1. Effects of vegetation type and structure on surface runoff and erosion

Vegetation can influence hydrological and associated soil erosion processes through enhancing rainfall reception and evapotranspiration, increasing the infiltration of water into soil and recharging the groundwater (Zhu, 1960; Quinton et al., 1997; Sun et al., 2006). It is evident that the vegetation communities with multiple stratified structure have an advantage in reducing surface runoff and soil loss compared with the mono-species communities (Zhao et al., 2001; Wu et al., 2005; Mohammad and Adam, 2010). From a hydrological aspect, the canopy of forest can protect soil from erosion by intercepting raindrops and absorbing their kinetic energies (Zhao et al., 2001; Bochet et al., 2006; Geißler et al., 2012). However, it was also reported that the canopy could amalgamate small raindrops and increase the

Table 4
Average annual surface runoff and soil loss in different vegetation types from 2008 to 2016.

Indices	BOI	SEB	LOC	SEB + LOC	SEB + CHP	LOC + CHP	LOC + CHA	CHP	CHA
Surface runoff	2.40	3.33	3.66	3.99	3.72	3.74	5.25	5.36	14.67
Soil loss	4.98	6.20	10.29	11.40	14.19	16.69	29.28	60.85	382.65

Notes: Surface runoff (mm); soil loss (t km^{-2} $year^{-1}$); BOI, *Bothriochloa ischaemum*; SEB, Sea-buckthorn; LOC, Black locust; CHP, Chinese pine; CHA, Chinese arborvitae.

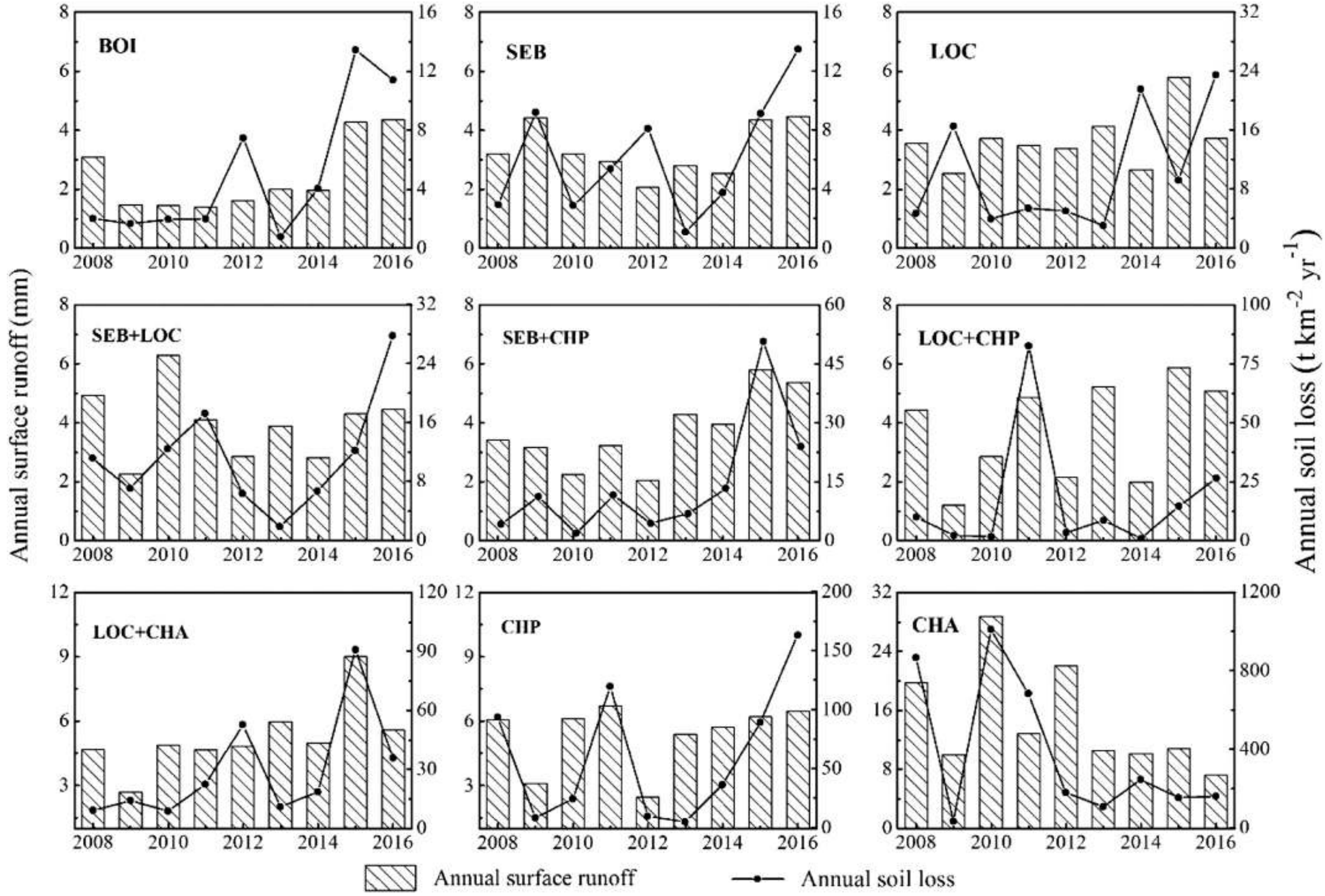

Fig. 2. Annual surface runoff and soil loss under each vegetation type from 2008 to 2016. BOI, *Bothriochloa ischaemum*; SEB, Sea-buckthorn; LOC, Black locust; CHP, Chinese pine; CHA, Chinese arborvitae.

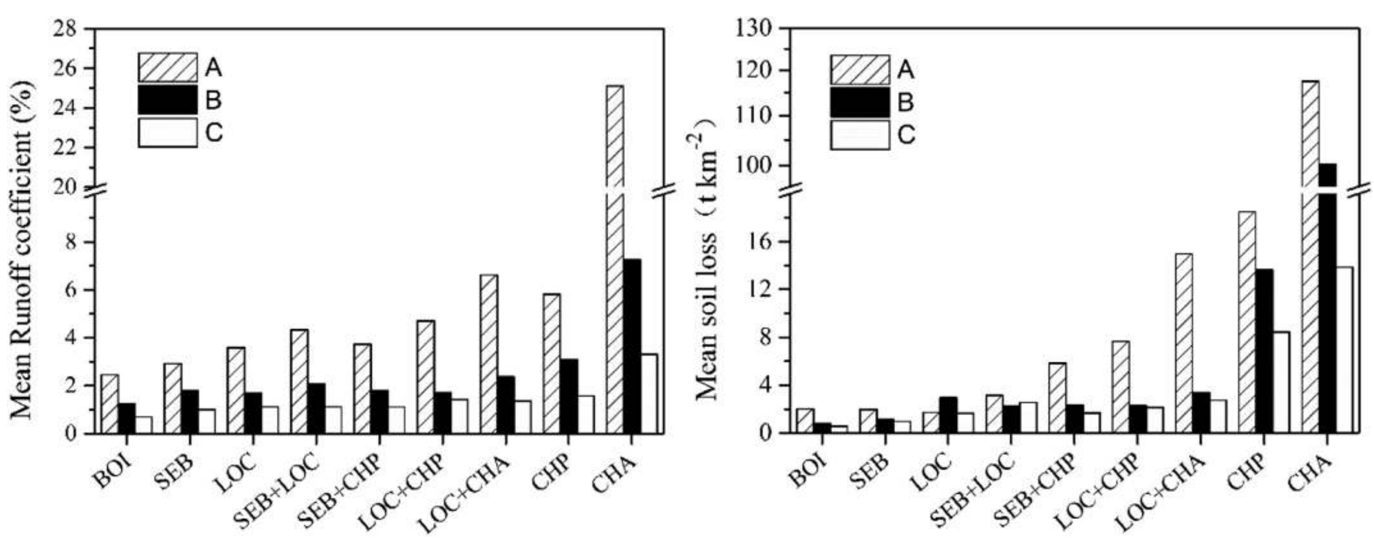

Fig. 3. Mean surface runoff coefficient and soil loss of rainfall type events under different vegetation types. Times of each type of rainfall were shown in Table 3. BOI, *Bothriochloa ischaemum*; SEB, Sea-buckthorn; LOC, Black locust; CHP, Chinese pine; CHA, Chinese arborvitae.

raindrop size leading to larger kinetic energy (Geißler et al., 2012). On the contrary, ground cover such as grass and litter layers which are close to soil surface can provide a more effective protection against raindrop splash (Wang et al., 2001; Wu et al., 1998; Liu et al., 2017). When considering their contribution in controlling soil erosion, the ground cover including grass and litter layers appears to be more important than canopy layer (Wen et al., 2010; Zhang et al., 2005). The removal of the litter layer could result in an averaged 16-fold increase in runoff and soil loss compared to the intact forest floor (Wu et al., 1998). Some areas covered by forest with a thin or absent ground cover still suffered serious runoff and soil loss (Li et al., 2012; Huang et al., 2010; Cao et al., 2015).

Table 5
Relationships between surface runoff and soil loss for nine vegetation types under different rainfall types.

Vegetation type	Rainfall type A			Rainfall type B			Rainfall type C		
	Regression function	R^2	P	Regression function	R^2	P	Regression function	R^2	P
BOI	$Y = 2.72X^{0.99}$	0.47	< 0.05	$Y = 0.93X^{1.06}$	0.32	< 0.01	$Y = 0.73X^{1.06}$	0.45	< 0.05
SEB	$Y = 2.55X^{1.37}$	0.62	< 0.01	$Y = 1.09X^{1.12}$	0.49	< 0.01	$Y = 0.87X^{1.28}$	0.58	< 0.05
LOC	$Y = 2.02X^{1.22}$	0.67	< 0.01	$Y = 1.80X^{1.32}$	0.40	< 0.01	$Y = 0.76X^{1.25}$	0.45	< 0.05
SEB + LOC	$Y = 2.88X^{1.35}$	0.64	< 0.01	$Y = 1.83X^{1.24}$	0.60	< 0.01	$Y = 1.12X^{1.48}$	0.54	< 0.05
SEB + CHP	$Y = 3.82X^{1.42}$	0.74	< 0.01	$Y = 2.01X^{1.49}$	0.84	< 0.01	$Y = 1.05X^{1.37}$	0.59	< 0.01
LOC + CHP	$Y = 3.36X^{1.58}$	0.80	< 0.01	$Y = 1.97X^{1.35}$	0.71	< 0.01	$Y = 0.99X^{1.72}$	0.55	< 0.05
LOC + CHA	$Y = 4.56X^{1.90}$	0.83	< 0.01	$Y = 1.91X^{1.41}$	0.58	< 0.01	$Y = 1.52X^{0.94}$	0.26	> 0.05
CHP	$Y = 10.74X^{1.53}$	0.78	< 0.01	$Y = 4.18X^{1.83}$	0.77	< 0.01	$Y = 2.15X^{2.14}$	0.49	< 0.05
CHA	$Y = 14.16X^{1.24}$	0.68	< 0.01	$Y = 3.72X^{1.70}$	0.61	< 0.01	$Y = 2.04X^{1.29}$	0.43	< 0.05

Notes: X, surface runoff (mm); Y, soil loss (t km^{-2}); BOI, *Bothriochloa ischaemum*; SEB, Sea-buckthorn; LOC, Black locust; CHP, Chinese pine; CHA, Chinese arborvitae.

In this study, the surface runoff and soil loss varied greatly among different vegetation types (Table 4). Plots of grassland (BOI) and shrubland (SEB) had a higher ground cover of 88% and 80%, respectively (Table 1), and the runoff and soil loss were correspondingly lower. In contrast, the plots of forestland with a poor ground cover and lack of a shrub or herb layer had higher amounts of surface runoff and soil loss, particularly in the CHA plot with a ground cover of only 10%. This result was in accordance with the findings of Descroix et al. (2001), Zheng et al. (2008), Wu et al. (1998), Li et al. (2012), and Huang et al. (2010).

For the forestlands with high surface runoff and soil loss in this study, the individual biomass was also poor besides their low ground cover (refer Table 1). For instance, the 14 years Black Locust trees was only 3.4 m of the average height and 2.7 cm of the average DBH in our experiment plot, which were evidently below those of the same age of 10.8 m and 10.6 cm, respectively (Jiao and Liu, 2009). The poor ground cover and a missing of understory layer might be the main reason resulted in a low efficiency in controlling soil erosion. It should be noted that climate (e.g., precipitation and temperature), site conditions (e.g., topographic feature and soil moisture) and human activities all have an impact on tree growth. The trees of this study were two to three years old when they were planted in 2003. During the study period from 2008 to 2016, the trees were from 8 to 16 years old. According to the results of Wu et al. (2005), 8 to 16 years old was the period for trees to show a significant capacity in conserving soil and water in this region. Although the lack of historical tree growth records made it difficult to evaluate the changes in vegetation cover, the comparison with the same age species illustrated that their abilities to conserve soil and water did not show a clearly increasing trend as normal (refer Fig. 2).

The poor growth and incomplete community structures in the forestland plots are closely linked with soil water scarcity within them. Low rainfall and high potential evaporation, deep groundwater table and the location of the sunny and steep slope might be the precondition for the occurrence of soil water scarcity in the experimental plots (Wu and Yang, 1998; Chen et al., 2008a), and the exorbitant planting density in the plots could have accelerated the process of soil water scarcity in range and intensity (Chen et al., 2008b). The planting density of the plots was estimated about 5000 plants hm^{-2} in single species and 10,000 plants hm^{-2} in mixture species, respectively (refer Table 1), which was much higher than the reasonable density of about 2250–5775 plants hm^{-2} in this area (Yang and Shao, 2000). Planted vegetation with high density in the Loess Plateau region can more easily lead to soil desiccation that would heavily influenced the growth and natural succession of vegetation (Chen et al., 2008b; Cao et al., 2011). Duan et al. (2016) investigated the water balance of the vegetation types from 2013 to 2014 in the same experimental plots and showed that soil water deficits commonly occurred under the forestland plots during the growing season. Such deficit was expected to severely hamper plant growth and threaten the sustainability of vegetation restoration in the forestlands, thus affecting the soil and water conservation abilities of them. Additionally, human activities in the forestlands as well as the leaf exudates under the Chinese pine and Chinese arborvitae might also cause the poor growth and absence of a shrub or herb layer (Wu and Yang, 1998; Nanko et al., 2008; Zhao, 2006).

In a word, the grassland and shrubland with the high ground cover are more effective in controlling surface runoff generation and soil erosion. In contrast, whatever monoculture and mixture, the forestlands with poor ground cover generate more surface runoff and associated soil erosion. Therefore, promoting the development of ground cover or paying close attention to changes of it is the key for vegetation to conserve soil and water in this area.

4.2. Response of surface runoff and erosion to different rainfall types

In this study, erosive rainfall events were grouped into three major categories based on rainfall concentration index (Table 3). For rainfall type A, it had a high CI (92.3%), a small depth (15.4 mm) and a short duration (2.6 h). This type of rainfall had been proven to produce more surface runoff and soil loss than type B and C. In contrast, rainfall type C had a low CI (17.9%), a great depth (43.3 mm) and long duration (16.4 h). This type of rainfall produced far less runoff and soil loss. Rainfall type B was a moderate type with a CI of 44%, a depth of 28 mm and a duration of 9.0 h. This type of rainfall caused the moderate surface runoff and soil loss among the three rainfall types (Table 3 and Fig. 3). The three rainfall types are closely related to the weather. Type A is a kind of rainfall event affected by severe convective weather. Type C is influenced by frontal weather, and Type B is a rainfall caused by a combination of frontal and convective weather (Wang and Jiao, 1996).

The effects of rainfall type on surface runoff and soil loss are associated with rainfall intensity, duration and depth (Ran et al., 2012; Mohamadi and Kavian, 2015). Although rainfall depth and duration are two important factors in affecting hydrological processes, the intensity is the dominant factor impacting runoff generation and soil erosion (van Dijk et al., 2002; Kinnell, 2005). In the interaction between rainfall and soil surface, high intensity rainfalls make it much easier to form the surface crusting and sealing, which can reduce infiltration rate and increase surface flow (De Roo and Riezebos, 1992; Vandervaere et al., 1997). And the development of surface sealing promotes soil erosion as it increases sediment transportation by accelerating the surface flow (Assouline, 2004). It was found that the high intensity rainfalls could generally produce an earlier runoff start-time, a larger runoff coefficient, and a higher peak flow velocity compared with low intensity rainfalls (Wei et al., 2014). Simulation experiments showed that peak flow and erosion rate under rainfalls with high rainfall intensity and short duration were usually higher than those with low intensity and long duration (Ran et al., 2012). Moreover, the characteristics of raindrops with high intensity and short duration rainfalls were of difference with those under low intensity and long duration rainfalls (Jiang et al., 1983; Salles et al., 2002). Field studies indicated that raindrop median diameter and kinetic energy under high intensity and short duration rainfalls in the loess area were 1.27 and 1.24 times higher than those under ordinary rainfalls, respectively (Jiang et al., 1983). This probably implies that Type A rainfalls with high intensity and short duration in this area are generally thunderstorm rain and have large rainfall erosivity due to its high intensity and kinetic energy (Chen et al., 1988; Wang and Jiao, 1996; van Dijk et al., 2002). It explains that rainfalls with high intensity and short duration (type A) could produce more runoff, resulting in higher soil erosion. Inversely, rainfalls (type B and C) with low rainfall intensity and long duration comparatively allowed more water infiltration, leading to less soil erosion. Other researchers have reported this as well in different areas (Wei et al., 2007; Peng and Wang, 2012; dos Santos et al., 2017; Fortugno et al., 2017). Therefore, surface runoff and soil loss are more sensitive to the rainfall type A with high intensity and short duration than those of other two types (B, C) regardless of vegetation types, which was evident in our study (Fig. 3).

4.3. Effects of vegetation and rainfall types on runoff-loss relationship

Soil susceptibility to erosion is defined as the amount of soil loss per unit exogenic erosional forces such as rainfall and surface flow (Bryan et al., 1989; Borselli et al., 2012). In our study, coefficient α of the power function between the surface runoff and soil loss can be interpreted as the amount of soil loss per unit runoff, and be regarded as a parameter to reflect soil susceptibility to erosion. The coefficient α showed a decreasing order in rainfall type A > B > C (Table 5). Soil susceptibility to erosion was affected by rainfall intensity (Zhang et al., 2001). It had been proven that high intensity rainfalls made soil easy to be detached by overland flow due to high soil moisture in the topsoil (Wu et al., 2018). With the decrease of rainfall intensity (rainfall types A > B > C), the coefficient α showed a decreasing order, which means the greater soil loss per unit runoff occurred under rainfall type A compared with the other two rainfall types, namely soil susceptibility to erosion increased with rainfall intensity increasing. This conclusion was in agreement with a previous study of Zhou and Wu (1993).

Furthermore, the coefficient α of the grassland and shrubland was smaller compared to the other vegetation types (Table 5). Soil susceptibility to erosion is closely related to the internal properties of soil, which decreased with the improvement of soil properties (Römkens et al., 1977; Bryan et al., 1989; Nzeyimana et al., 2017). In this study, bulk density of the grassland and shrubland plots was lower, and soil organic matter, soil porosity, and saturated hydraulic conductivity of them were generally higher compared with the other vegetation plots (Table 1). The soil properties of these two plots were obviously improved, which consequently reduced the susceptibility of soil to erode. Additionally, the finding of Li et al. (2017) showed that a well-developed fibrous root system of grassland may greatly enhanced soil erosion resistance in the topsoil layer. Therefore, the grassland and shrubland in this study exhibited the lower soil susceptibility to erosion compared with the other vegetation types, namely the smaller coefficient α.

5. Conclusion

This study investigated the effect of nine vegetation types on surface runoff and soil loss on the steep slopes of the Loess Plateau. Surface runoff and soil loss was considerably affected by vegetation types. The grassland and shrubland with high ground cover produced lower runoff and soil loss, while the forestlands with poor ground cover had higher runoff and soil loss. It indicates that the presence of a high ground cover plays an important role in controlling soil and water loss.

Forty-three rainfall events were classified into three types on the basis of rainfall concentration index. The sensitivity of the runoff and soil loss to these rainfall types was obviously different. Rainfall events with high intensity and short duration can induce severe runoff and soil loss under all vegetation types. The runoff and soil loss relationship for each vegetation type under different rainfall type was fitted well with a power function. The coefficient α of the power function can be interpreted as the amount of soil loss per unit runoff to reflect soil susceptibility to erosion. The results indicate that soil susceptibility to erosion increased as rainfall intensity increasing and the grassland and shrubland had the less soil susceptibility to erosion among all vegetation types.

The results emphasize the importance of ground cove in controlling soil erosion. From this point of view, vegetation measures with high ground cover should be given enough attention in controlling soil and water loss on the Loess Plateau, especially on steep slopes of this area.

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