Earth and Environmental Science Transactions of the Royal Society of Edinburgh, **109**, 397–406, 2019 (for 2018)

Earth Surface Processes and Environmental Sustainability in China

Combined effects of rainfall regime and plot length on runoff and soil loss in the Loess Plateau of China

Jianbo LIU[1,2], Guangyao GAO[1], Shuai WANG[1] and Bojie FU[1]*

[1] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, China.
Email: bfu@rcees.ac.cn
[2] University of Chinese Academy of Sciences, China.
*Corresponding author

ABSTRACT: The purpose of this paper was to study the interaction effects of rainfall regime and slope length on runoff and soil loss under different land uses. Event runoff and soil loss in forest, shrub and grass were measured in plots with lengths of 5, 9 and 13 m in the Loess Plateau from 2008 to 2016. A total of 59 erosive rainfall events were recorded and classified into three rainfall regimes. Firstly, the results showed that the runoff coefficient was grass > shrub > forest, and soil loss was grass > forest > shrub, but the differences between forest and shrub in runoff and between grass and forest in soil loss did not reach significant levels. Secondly, rainfall regimes had an important effect on runoff and soil loss under different land uses. The lowest runoff coefficients and the highest soil loss in regime 2 were found in shrub and forest land, respectively, which differed from that of regime 1. In total, rainfall regime 1 had the highest runoff coefficient of 0.84–2.06 %, followed by regime 3 with 0.33–0.88 % and regime 2 with 0.04–0.06 %. Soil loss in forest and grass land had a different order of regime 3 > regime 1 > regime 2. Thirdly, both the runoff coefficient and soil loss decreased with increasing plot length, while the effect of slope length on runoff/soil loss were influenced by land use type and rainfall regimes.

KEY WORDS: erosion, land use, rainfall intensity, runoff coefficient, slope length.

Soil loss causes many serious environmental problems, such as land degradation, the reduction of agricultural productivity, water shortage and other socio-economic problems, especially in semi-arid regions (Pimentel *et al*. 1995; Zuazo & Pleguezuelo 2008). Rainfall, topography, soil properties and vegetation are widely recognised as the primary factors influencing runoff and soil loss (Chirino *et al*. 2006; Parsons *et al*. 2006; Kinnell 2007; Sadeghi *et al*. 2013). The Universal Soil Loss Equation and its revised version (USLE and RUSLE) are commonly used to predict annual soil loss by water (Wischmeier & Smith 1978; Kinnell 2005). Rainfall erosivity (EI_{30}), slope length and vegetation are the basic parameters used in the USLE and RUSLE (Liu *et al*. 2000; Kinnell 2007; Gao *et al*. 2012). With comprehensive consideration of the combined and interactive effects of vegetation cover, rainfall characteristic and slope length, the prediction of runoff and soil loss can be improved effectively.

Vegetation restoration is recognised as the most efficient measure to control runoff and soil loss (Elwell & Stocking 1976; Feng *et al*. 2012; Lu *et al*. 2012). Runoff and soil loss have been shown to decrease linearly or exponentially with vegetation coverage (Crockford & Richardson 2000; Chirino *et al*. 2006; Allen *et al*. 2014). The amount of runoff and soil loss varies with different types of vegetation cover, due to their various morphologies and structure (Bochet *et al*. 1998; Calder 2001). Nunes *et al*. (2011) showed that shrub land and areas of recovering oak forest resulted in less runoff and soil loss than pasture land, whereas Fusun *et al*. (2013) found that a high coverage of grass was more efficient in preventing runoff and soil loss in land restoration projects than shrubs and forests. Similar effects of high vegetation coverage on limiting runoff and soil loss were also observed in dry grassland, thorn shrub land and afforested tree land (Chirino *et al*. 2006). Variations in runoff and soil loss may result from the presence of different plant species, as well as regional and climatic differences.

Rainfall is the drive for runoff and the source of kinetic energy for erosion (Parsons & Stone 2006). Rainfall characteristics, such as rainfall depth, duration, average intensity, maximum 10-min (I_{10}) or 30-min intensity (I_{30}), and the overall rainfall pattern, had great effects on runoff and soil erosion (Cammeraat 2004; Frauenfeld & Truman 2004; Dunkerley 2010; Ran *et al*. 2012; Wei *et al*. 2014; Zhou *et al*. 2016). Among these indices, the maximum I_{30} was commonly used to predict soil erosion, which presented more explanatory power for runoff and soil loss than the average intensity (Millward & Mersey 1999; Angel *et al*. 2005; Xu *et al*. 2009; Dunkerley 2010; Gao *et al*. 2012). Many studies had used rainfall depth, duration and maximum I_{30} to classify rainfall events into different regimes (Fang *et al*. 2012; Peng & Wang 2012; Liu *et al*. 2016). For example, Wei *et al*. (2007) divided rainfall events into three regimes and investigated their effects on runoff and soil loss in five land use types, from 1986 to 1999. Liu *et al*. (2016) and Peng & Wang (2012) classified rainfall into five regimes to investigate their effects on runoff and soil loss under different types of vegetation cover.

In general, runoff and soil loss also have a strong spatial scale dependency (Parsons *et al*. 2006; Mayor *et al*. 2011;

 doi:10.1017/S1755691018000531

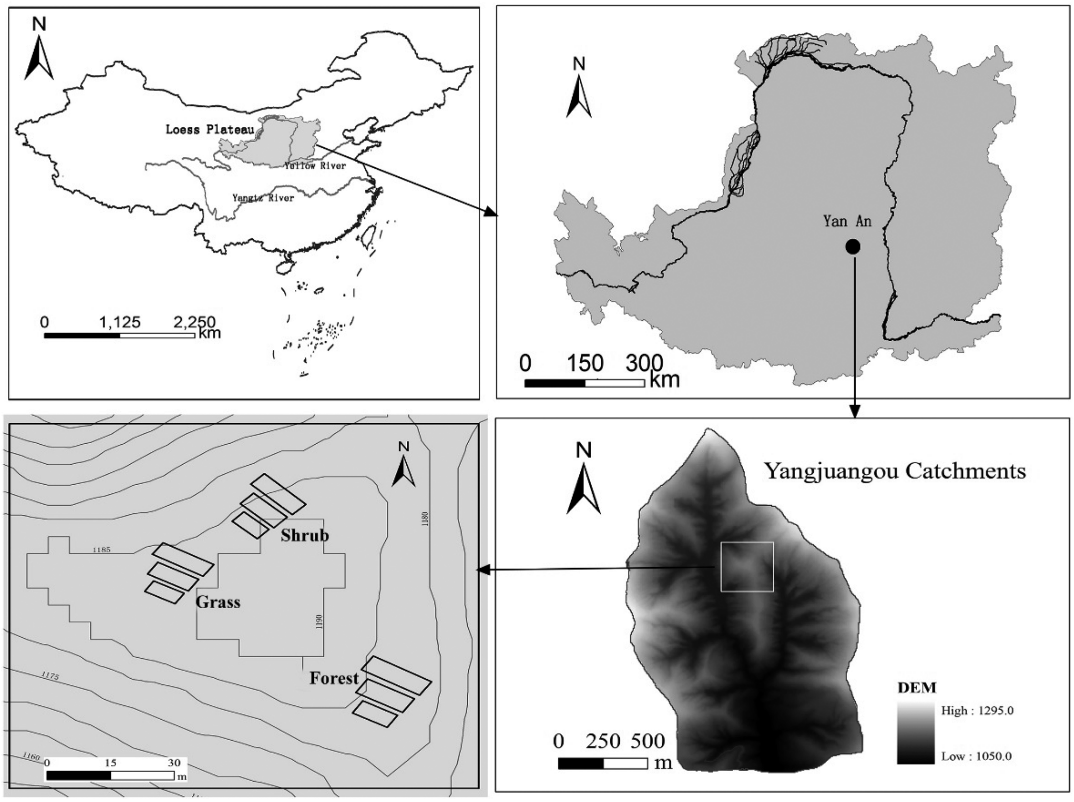

Figure 1 Location of the study area and distribution of the three runoff plot groups.

Sadeghi *et al.* 2013). The inter-influences of vegetation on soil erosion change with scale, which affects processes of the generation and redistribution of runoff, and sediment movement (e.g., delivery, transport and storage) (Puigdefabregas *et al.* 1999; Boix-Fayos *et al.* 2006). Smets *et al.* (2008) found that the effectiveness of vegetation in controlling runoff and soil loss reduction was reduced with increasing plot length, and vegetation factors had more effect in plots longer than 11 m. The effects of rainfall on runoff and erosion generation were also closely related to the studied scale (Cammeraat 2004; Mayor *et al.* 2011).

Understanding the responses of runoff and soil loss to changes in rainfall under different land uses is crucial to land management, especially in the areas with severe erosion, such as the Loess Plateau in China. Many studies have been conducted to investigate the effects of vegetation restoration after 1999 (initiation of the Grain-for-Green project) on soil erosion in the Loess Plateau of China (Fu *et al.* 2011; Feng *et al.* 2012; Lu *et al.* 2012; Zhou *et al.* 2012; Zhao *et al.* 2013). For example, Liu *et al.* (2012) found that runoff and soil loss varied with plot scale, but depended on the type of vegetation cover adopted in the vegetation restoration projects. Chen *et al.* (2011) found that the effects of slope length on soil erosion changed with the rainfall intensity in the Loess Plateau. Fang *et al.* (2008) and Wei *et al.* (2007) presented the responses of runoff and soil loss to rainfall regimes at different plot scales and under different land uses, before the Grain-for-Green project was implemented in the Loess Plateau. However, few studies have considered the response of runoff and soil loss with different slope lengths and land uses to rainfall patterns change after implementing the Grain-for-Green project in the Loess Plateau of China (Fang *et al.* 2008; Xin *et al.* 2008; Zhang *et al.* 2014). The interaction effects of rainfall pattern and slope length on runoff and soil loss are still unclear.

In this study, runoff and soil loss were measured under three land uses – forest, shrub and grass – with different plot lengths, from 2008 to 2016. Fifty-nine rainfall events with production of runoff and soil loss were classified into three regimes and were used to analyse the variation of runoff and soil loss induced by rainfall pattern and plot length among different land uses. The aims of this study were to: (1) investigate the effects of rainfall regimes on runoff and soil loss among different land uses; (2) determine the responses of runoff and soil loss to plot length changes under different land uses; and (3) detect the interactive effects of rainfall regimes and plot length on the differences of runoff and soil loss between land uses.

1. Materials and methods

1.1. Study area

This study was conducted in the Yangjuangou catchment [36°42′N, 109°31′E], which is located in the central region of the Loess Plateau, Shaanxi Province, China (Fig. 1). The catchment has a total area of 2.02 km^2, with the elevation ranging from 1050 to 1298 m. The catchment has a semi-arid climate, with an average annual precipitation of 535 mm and an average annual air temperature of 14 °C. The soil type in the study area is a Calcaric Cambisol, which is characterised by a uniform texture, with a maximum depth of approximately 200 m (Li *et al.* 2003). The dominant vegetation in the catchment consists of replanted vegetation due to the Grain-for-Green project, which was launched in 1999, and is dominated by *Robinia pseudoacacia*, *Prunus armeniaca*, *Spiraea pubescens*, *Artemisia sacrorum*, *Andropogon* and *Artemisia scoparia*. This catchment experienced severe soil erosion, with a mean soil erosion rate of 62.73 $t\,ha^{-1}\,y^{-1}$ from 1992 to 1996 and 36.41 $t\,ha^{-1}\,y^{-1}$ in 2006 (Liu *et al.* 2012).

https://doi.org/10.1017/S1755691018000531 Published online by Cambridge University Press

1.2. Field experiment

Event runoff and soil loss were measured from 2008 to 2016 (except for 2010) under three land uses – forest, shrub and grass – commonly used in ecological restoration projects (Fig. 2), including (1) abandoned cropland covered by forests (*Prunus armeniaca*), (2) native shrub land (*Spiraea pubescens*) with very sparse wood and (3) dense grass (*Andropogon L.* and *Artemisia scoparia*). Three runoff plot groups with different land cover types were installed in the catchment in 2008.

(a)

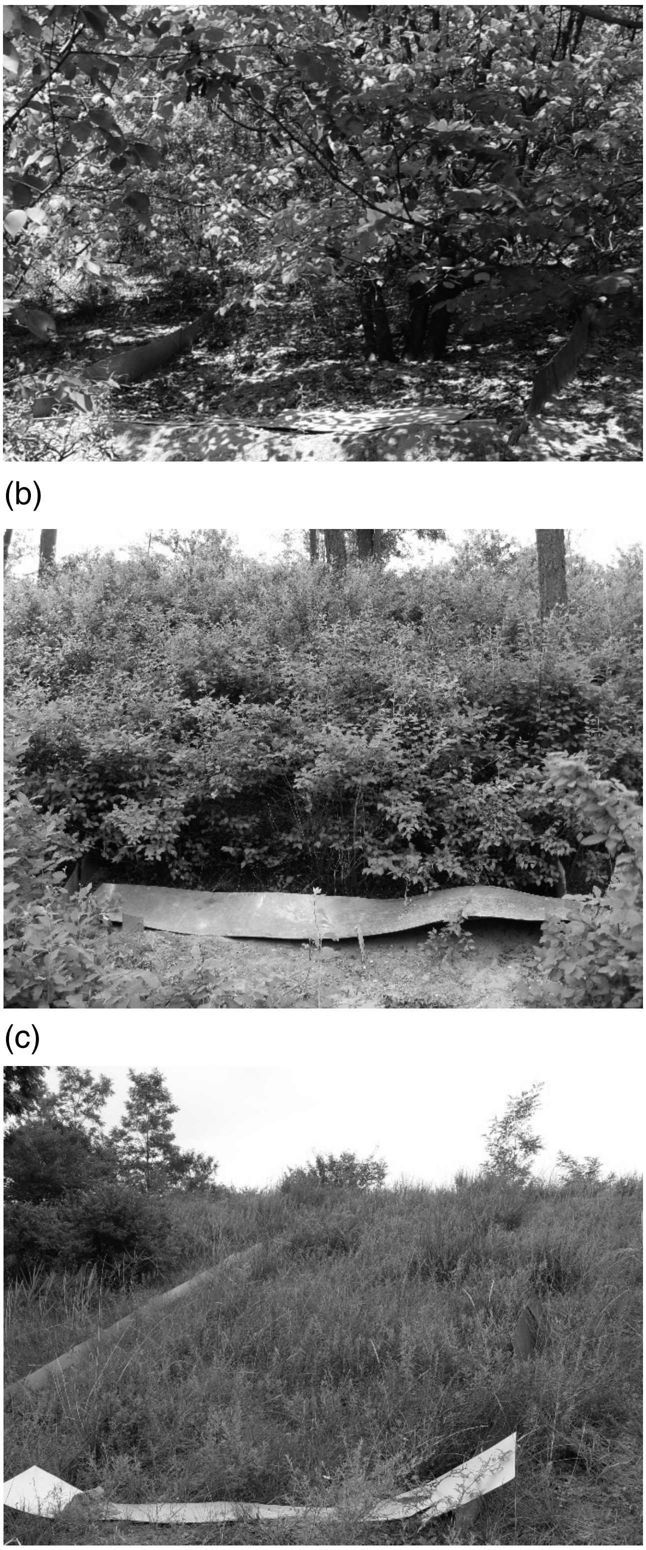

Figure 2 Photographs of the three plot groups with different land uses. (a) Forest; (b) Shrub; (c) Grass.

Each group included three closed runoff plots with a fixed width of 2 m and lengths of 5, 9 and 13 m. Group 1 plots (forest) had been abandoned for 16 years, and Group 2 (shrub) and Group 3 (grass) had been abandoned for 33 years (Liu *et al*. 2012). Forest land had a high canopy of 10–15 m and large leaf area, and was planted in rows at interval distances of 2.5–5 m, which had thinner litter cover and sparse, deep roots. Shrub land had a higher coverage (more than 80 %), with a canopy height of 1–2 m; it had thick and wide litter cover and dense roots. Grass land was dominated by dense tussock (*Artemisia scoparia*) and beard grass (*Andropogon L.*), but also included other grass species, showing greater species richness. It had a low canopy of less than 1 m, and bare areas were imbedded between tussock, where litter was distributed according to the patch-bare mosaic pattern of grass. The grass land had the densest roots in the surface soil. The slope gradient of all plots was approximately 22 °. Polyvinyl chloride (PVC) sheets (at a depth of 50 cm) were used at the boundaries of runoff plots to prevent surface water flowing from lateral seepage during rainfall. A collection system consisting of water channels and water containers was installed at the bottom boundary of each plot.

Rainfall depth and timing was measured during 2008–2016 using tipping-bucket rain gauges (RG3-M, Onset Computer Corp., Bourne, MA, USA), with an accuracy of 0.2 mm. Runoff and sediment samples were collected after each rainfall event. Runoff volume was measured by collecting the water in the containers. Representative samples of runoff containing sediment were shaken vigorously to create a homogeneous mixture in the containers. The mixed water was then poured into plastic bottles and taken to the laboratory to separate sediment from water. After settling for 24 h, the excess water was decanted and the residual sample was dried in an oven at 105 °C for 24 h and weighed. A total of 59 erosive rainfall events producing runoff were observed during the study period.

1.3. Data analysis

The runoff coefficients for each rainfall event were calculated as the ratio of runoff depth to rainfall depth in each plot. Soil loss rates were calculated as the amount of sediment exported per square meter. A clustering methodology was used to classify rainfall events into different rainfall regimes. This analysis method could separate and classify rainfall events based on their characteristics (Yeh *et al*. 2000). In general, clustering can be achieved by two methods: the K-means method and the hierarchical method (Hong 2003). In this study, the K-means method was selected due to the large number of rainfall events. Three rainfall regimes were classified based on the variables of rainfall depth, duration and maximum I_{30} (Wei *et al*. 2007; Liu *et al*. 2016). Rainfall regime 1 was characterised by a high intensity, short duration and low rainfall depth. Rainfall regime 2 had a low intensity, long duration and high depth. Rainfall regime 3 had a moderate intensity, duration and depth. With natural logarithm transformation data for passing the normality test, a one-way analysis of variance (ANOVA) with a least-square difference (LSD) post-hoc test was used to determine whether runoff and soil loss differed significantly among different vegetation, rainfall regimes and plot lengths. The level of significance was set at 95 % confidence interval ($P = 0.05$).

2. Results

2.1. Rainfall regimes

In this study, three rainfall regimes were obtained using K-means clustering from 59 rainfall events based on rainfall depth, duration and maximum I_{30} (Table 1). The rainfall

https://doi.org/10.1017/S1755691018000531 Published online by Cambridge University Press

Table 1 Statistical features of different rainfall regimes. Abbreviations: P = rainfall depth; D = duration; I_{30} = the maximum 30-min intensity.

Rainfall regime	Eigenvalue	Max.	Min.	Mean	Standard deviation	Variation of coefficient	Sum	Frequency
1	P (mm)	46.20	1.50	13.94	10.46	0.75	404.30	29
	D (min)	496.62	15.15	205.89	174.08	0.85	5970.92	
	I_{30} (mm min^{-1})	0.71	0.03	0.30	0.13	0.42		
2	P (mm)	82.60	13.00	40.43	22.99	0.57	283.00	7
	D (min)	1952.30	1460.00	1711.97	211.11	0.12	11983.78	
	I_{30} (mm min^{-1})	0.38	0.03	0.13	0.09	0.67		
3	P (mm)	91.80	3.40	29.37	22.47	0.76	675.60	23
	D (min)	1261.10	539.70	828.99	209.37	0.25	19066.87	
	I_{30} (mm min^{-1})	0.71	0.03	0.27	0.14	0.52		

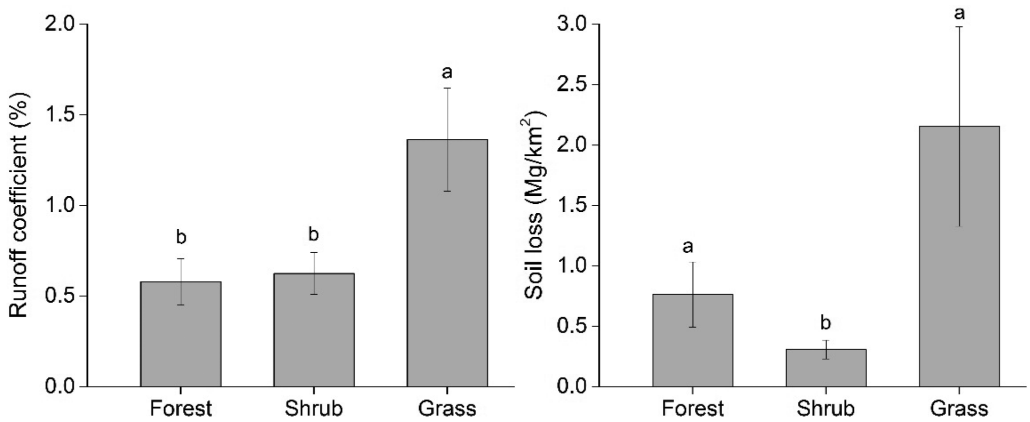

Figure 3 Mean runoff coefficient and soil loss of each rainfall event during 2008–2016 under different land uses with forest, shrub and grass. The same letter on two bars indicates no significant difference ($P < 0.05$) in runoff coefficient and soil loss between different land uses. The error bar represents standard error.

events in regime 1 had a low rainfall depth of 13.94 mm, a short duration of 205.89 min and a high maximum I_{30} of 0.30 mm/min. They were observed 29 times during the study period, and accounted for 49 % of all events. The three eigenvalues of seven rainfall events in regime 2 were the opposite to those in regime 1; they had a high rainfall depth of 40.43 mm, a long duration of 1711.97 min and a low intensity of 0.15 mm min^{-1}. The rainfall events in regime 3 had a moderate rainfall depth (29.37 mm), duration (828.99 min) and intensity (0.27 mm min^{-1}), and accounted for 39 % of the total events. Thus, extreme rainfall events with a short duration, low rainfall depth and high-intensity storms were classified as regime 1, while those with the opposite characteristics were classed as regime 2. Other events with moderate rainfall eigenvalues were regarded as regime 3.

2.2. Runoff and soil loss under different land uses

Figure 3 presents the mean runoff coefficient and mean soil loss during 2008–2016 under the three land uses, forest, shrub and grass. Grass land had the largest runoff coefficient (1.36 %) and soil loss (2.15 Mg km^{-2}). The lowest runoff coefficient was found in forest land (0.58 %), and shrub land had a moderate runoff coefficient of 0.62 %. In contrast, shrub land had the lowest soil loss of 0.31 Mg km^{-2}, accounting for only approximately 14 % of that in grass land. A moderate level of soil loss occurred in forest land (0.76 Mg km^{-2}), which accounted for approximately 35 % of that in grass land. The runoff coefficient and soil loss of grass land were significantly greater than that of shrub land, but there were no significant differences between forest and shrub land in runoff coefficient, and between grass and forest land in soil loss. The results indicated that grass land produces significantly more runoff and soil loss than shrub land and, thus, forest and dense shrub cover have a significant effect on reducing runoff and soil loss, respectively.

2.3. Runoff and soil loss under different rainfall regimes

The differences in the runoff coefficient and soil loss among the three land uses – forest, shrub and grass – under different rainfall regimes are shown in Figure 4. The rainfall events of regime 2 produced the lowest runoff coefficient of 0.04–0.06 % and the lowest soil loss of 0.01–0.03 Mg/km^2 under each land use. The highest runoff coefficient of 0.84–2.06 % in different land uses was found under regime 1 events, followed by events of regime 3 with 0.33–0.88 %. The soil loss of shrub land was highest under regime 1 events (0.45 Mg km^{-2}), whereas for forest land and grass land, regime 3 events produced the highest soil loss of 1.17 and 2.81 Mg km^{-2}, respectively.

The differences in runoff and soil loss among different land uses were influenced by rainfall regimes. The order of the runoff coefficient in the three land uses induced by regime 1 events was the same as the average level shown in Figure 3 (forest < shrub < grass), while under regime 2 and regime 3 events, shrub land produced the lowest runoff coefficient. For soil loss, rainfall events of regime 2 produced a different order (shrub < grass < forest) from that under regime 1 and regime 3 (shrub < forest < grass). Regime 1 and regime 3 resulted in significant differences in the runoff coefficient and soil loss among different types of land uses, while the differences of runoff coefficient in regime 2 did not reach a significant level ($P < 0.05$), indicating that the effects of land use in reducing runoff are likely to be crucial during high-intensity rainfall. Moreover, the highest variation in the runoff coefficient and soil loss induced by the different rainfall regimes was found in shrub land, indicating that the effect of shrubs on preventing

https://doi.org/10.1017/S1755691018000531 Published online by Cambridge University Press

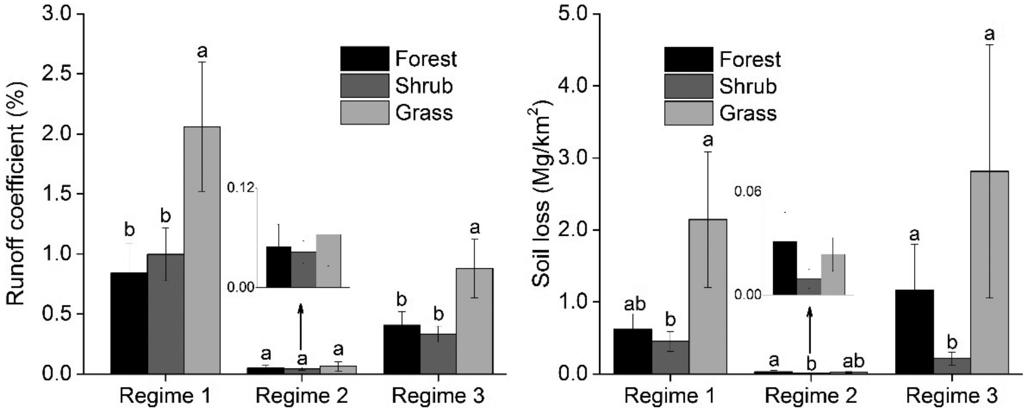

Figure 4 Mean runoff coefficient and soil loss of each land use under different rainfall regimes. The same letter on two bars indicates no significant difference in runoff coefficient and soil loss ($P < 0.05$) between different rainfall regimes. The error bar represents standard error.

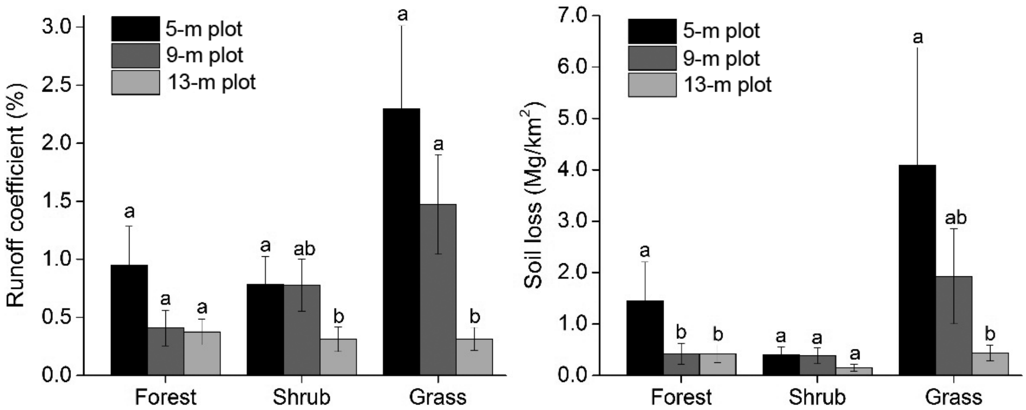

Figure 5 Mean runoff coefficient and soil loss of each land use at different plot lengths. The same letter on two bars indicates no significant difference in runoff coefficient and soil loss ($P < 0.05$) between different plot lengths. The error bar represents standard error.

soil and water loss was highly sensitive to the changes in rainfall.

2.4. Runoff and soil loss under different plot lengths

Figure 5 shows the scale characteristics of runoff and soil loss under different land uses. As shown in Figure 5, the runoff coefficients for the 13-m plots in shrub and grass land were significantly lower than the 5- and 9-m plots, but there were no significant differences between the 5- and 9-m plots. Soil loss in the 5-m plots of forest and grass land was significantly higher than that of the 9- and 13-m plots of forest and grass land, respectively, while no significant differences were found between the 9- and 13-m plots. There were no significant differences among plots with different plot lengths in the runoff coefficient for forest land and soil loss in shrub land.

Generally, the 5-m plots had the highest runoff coefficient and soil loss in each land use, followed by the 9- and 13-m plots. However, changes in runoff and soil loss with plot lengths were different between land uses. For forest land, the runoff coefficients and soil loss in the 9- and 13-m plots were similar (0.4 % and 0.4 Mg km^{-2}, respectively), accounting for only 43 % and 29 % of the values in the 5-m plot, respectively. For shrub land, the runoff coefficients and soil loss in the 5- and 9-m plots had similar values of 0.8 % and 0.4 Mg km^{-2}, which were 2.5 and 2.6 times higher, respectively, than the values in the 13-m plots. For grass land, the runoff and soil loss decreased with plot lengths, exhibiting the largest variation among different plot lengths. These results indicated that the effect of plot length on runoff and soil loss was limited by land use types, and grass land was found to have the strongest response of runoff and soil loss to slope length change.

2.5. Scale characteristics of runoff and soil loss under different rainfall regimes

The effects of slope length on runoff and soil loss induced by different rainfall regimes under each type of land use were also captured (Fig. 6). Under regime 1 events, runoff coefficient and soil loss decreased with plot length in each land use. The same trends (5-m plot > 9-m plot > 13-m plot) occurred under regime 3 events, except for the soil loss in shrub land (9-m plot > 5-m plot > 13-m plot). The scale characteristics of runoff and soil loss under regime 2 events were complex. The interaction of rainfall regime and slope length was also affected by land uses. The runoff coefficient and soil loss in forest land and the runoff coefficient in shrub land decreased with plot length. However, for the soil loss in shrub land and the runoff coefficient and soil loss in grass land, the order was 9-m plot > 5-m plot > 13-m plot. Consequently, the effects of plot length on runoff and soil loss under different land uses were influenced by rainfall regimes. Runoff and soil loss induced by regime 2 events were most sensitive to plot length change.

2.6. Mean annual soil loss during 2008–2016

Figure 7 shows the mean annual soil loss rate for different land uses under different rainfall regimes during 2008–2016. The data were calculated using the average values of soil loss in each year and the corresponding rainfall regime, where the soil loss of each land use was the summation value of the three

https://doi.org/10.1017/S1755691018000531 Published online by Cambridge University Press

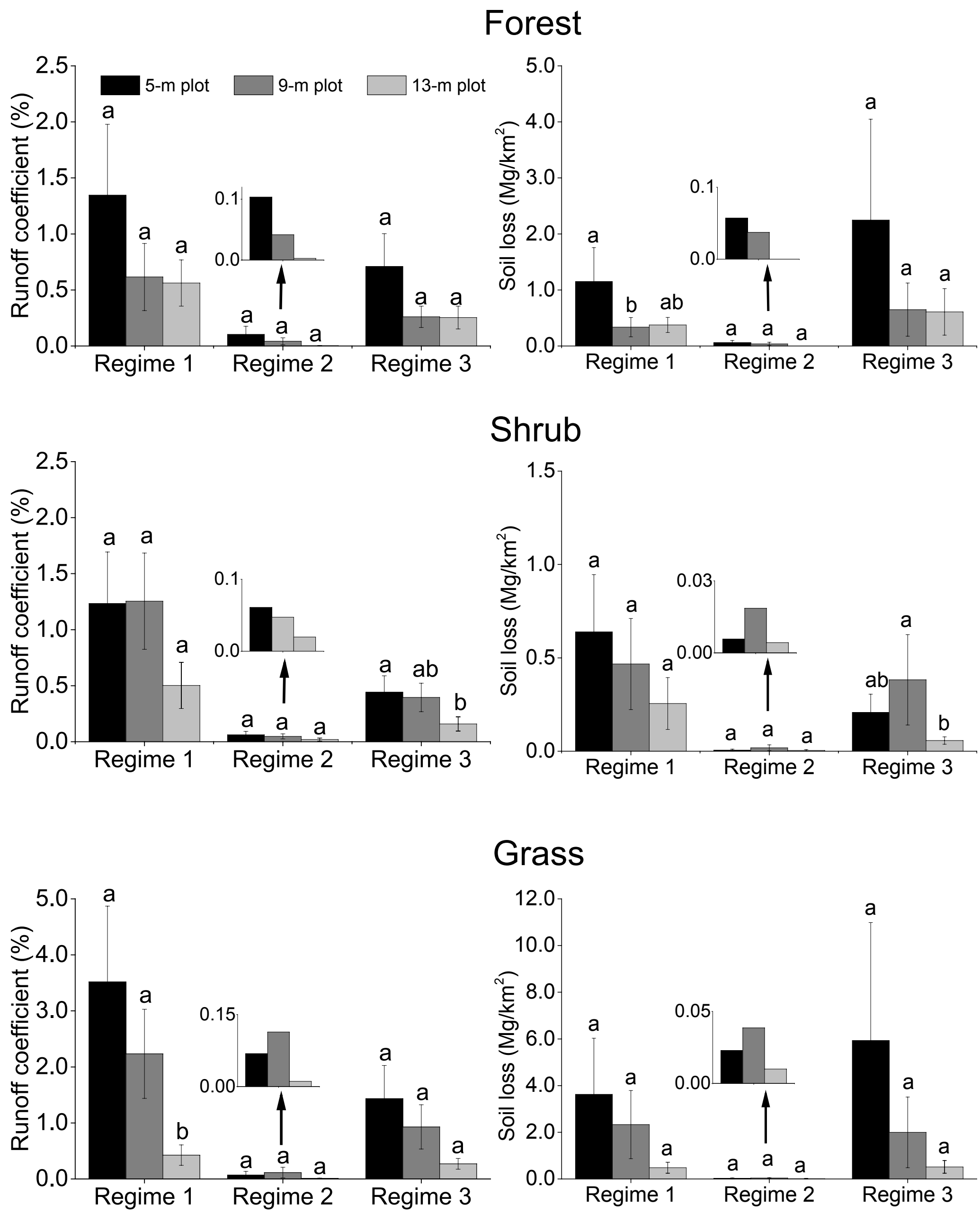

Figure 6 Scale characteristics of runoff coefficient and soil loss induced by different rainfall regimes for each land use. The same letter on two bars indicates no significant difference in runoff coefficient and soil loss ($P < 0.05$) between different rainfall regimes. The error bar represents standard error.

plots with different lengths. The change trends of mean annual soil loss for forest land and grass land were similar. Soil loss in rainfall regime 1 was always higher than that of regime 3 during 2008–2016, except for 2009 and 2016. The highest values of mean annual soil loss in regime 1 and regime 3 were 4.53 Mg km^{-2} and 13.93 Mg km^{-2} for forest land, and 21.96 Mg km^{-2} and 30.91 Mg km^{-2} for grass land in 2016, respectively. For shrub land, soil loss in regime 1 always higher than that of regime 3. However, the highest value of 5.44 Mg km^{-2} in regime 1 was found in 2008, and regime 3 still produced the highest soil loss of 2.39 Mg km^{-2} in 2016.

3. Discussion

3.1. Effects of rainfall regimes on runoff and soil loss under different land uses

As shown in Figure 4, rainfall regimes had a significant effect on runoff and soil loss under different land uses. Rainfall with a low depth, short duration and high I_{30} (regime 1) had the greatest effect on runoff generation, while rainfall with a high depth, long duration and low I_{30} (regime 2) had the least effect on runoff and soil loss generation. Rainfall with moderate depth, duration and I_{30} (regime 3) caused the most severe soil loss for grass and forest cover. Other studies in arid and semi-arid regions also reported similar phenomenon (Wei *et al.* 2007; Fang *et al.* 2008).

The results could be explained by the mechanism of runoff generation being mainly attributed to excess infiltration in the Loess Plateau of China; runoff only occurred when rainfall intensity was higher than the infiltration rate (Shi & Shao 2000; Kang *et al.* 2001). I_{30} is recognised as the most significant rainfall index related to runoff and soil loss in arid and semi-arid areas (Angel *et al.* 2005; Xu *et al.* 2009; Dunkerley 2010). Therefore, regime 1 events with the highest I_{30} resulted in the largest runoff coefficient. In contrast, the lower intensity and long duration of regime 2 events resulted in more infiltration, leading to a lower runoff coefficient. However, in other areas,

https://doi.org/10.1017/S1755691018000531 Published online by Cambridge University Press

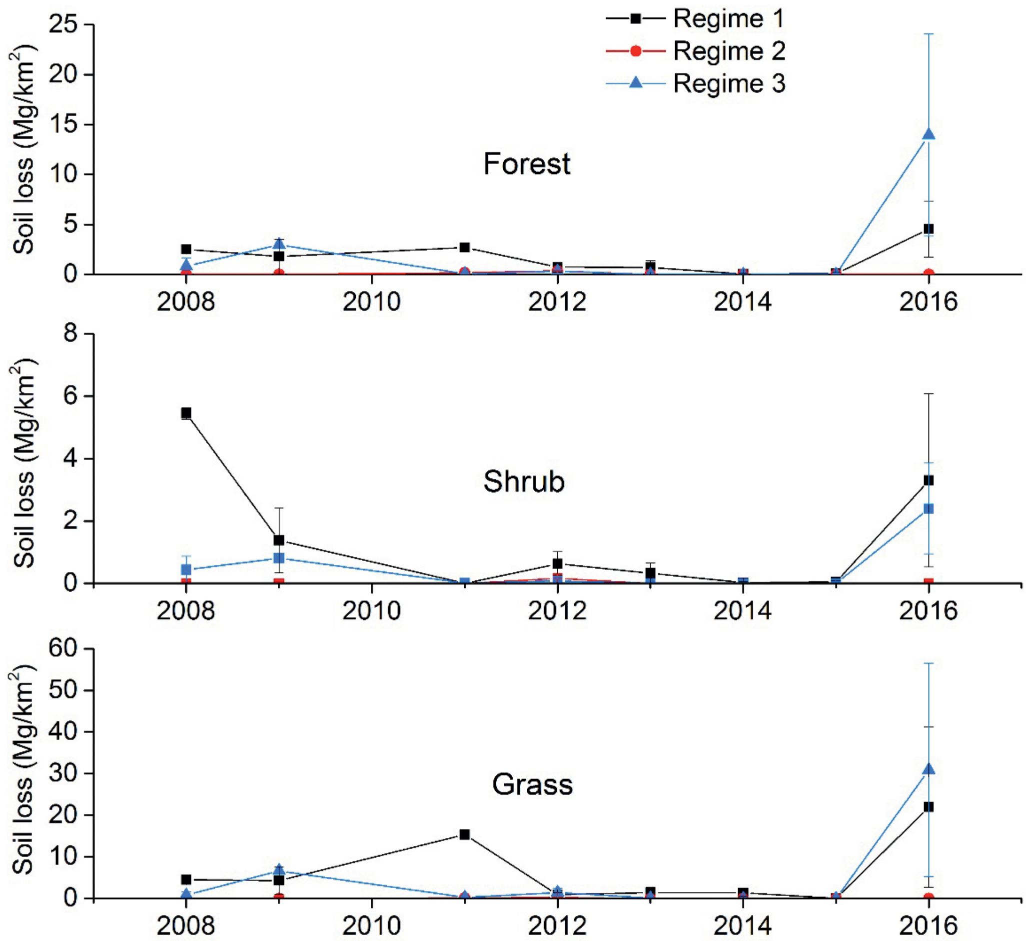

Figure 7 Mean annual soil loss of different land uses under different rainfall regimes during 2008–2016. The error bar represents standard error.

such as humid and semi-humid regions, due to the saturation and Hortonian mechanisms for the generation of runoff, rainfall with a high annual rainfall depth (regime 3) created the most surface runoff (Peng & Wang 2012; Liu *et al*. 2016).

It should be noted that most soil loss under grass and forest cover was induced by regime 3 events with moderate I_{30}, instead of regime 1 events with the highest I_{30}. This result is not consistent with some previous studies (Wei *et al*. 2007; Peng & Wang 2012). Annual soil loss from 2008 to 2016 under each vegetation type is shown in Figure 7 to address this abnormal behaviour. In most years (except for 2009 and 2016), regime 1 events usually induced more soil loss than regime 3 events under grass and forest cover. Based on the observed data, we found that extreme erosion events played a critical role in the soil loss difference induced by different rainfall events. For example, one rainfall event (classed as regime 3 event), which took place on August 15, 2016, resulted in 52.74 Mg km^{-2} and 20.74 Mg km^{-2} of soil loss in grass land and forest land, respectively, which was more than 41 and 56% of total soil loss in the corresponding plots induced by regime 1 events during the study period. Previous studies also showed that extreme erosion events were responsible for the high soil loss in the Loess Plateau of China (Shi & Shao 2000; Wei *et al*. 2009). Heavy rain storms often caused 1.5–53.1 times higher erosion rates than the mean annual rates, which accounted for more than 50%, or even 75%, of annual soil erosion (Shi & Shao 2000; Cheng *et al*. 2002; González-Hidalgo *et al*. 2007; Ramos & Martinez-Casasnovas 2009; Wei *et al*. 2009). In addition, the effects of extreme rainfall events on runoff and soil loss were also influenced by other factors such as plant growth stage, vegetation cover and cultivated landscapes (Boardman 2015).

The rainfall regimes resulted in a complex order of runoff and soil loss between different land uses. Plant morphology and vegetation structure significantly affected the processes of runoff generation and accumulation, as well as soil detachment and transport (Bochet *et al*. 1998; Calder 2001), which were responsible for the different orders of runoff and soil loss under different rainfall regimes (Fig. 4). Forest and shrub cover had a greater canopy height and generated more litter cover than grass cover, which significantly reduces raindrop kinetic energy and intercepts more rainfall to delay the generation of runoff (Calder 2001; Smets *et al*. 2008; Li *et al*. 2014). The ability of vegetation in controlling runoff and soil loss was influenced by rainfall intensity. Shrub land had the highest canopy coverage and produced the thickest litter layer, which effectively reduced runoff and soil loss during low-intensity rainfall (i.e., regimes 2 and 3 events) (Calder 2001; Smets *et al*. 2008; Li *et al*. 2014), resulting in the lowest levels of runoff and soil loss. However, previous studies have proposed that a flow channel for runoff might be formed by excess litter cover, thus preventing water infiltration when high-intensity rainfall events occurred (Findeling *et al*. 2003; Li *et al*. 2014). Therefore, shrub cover produced more runoff than forest cover under regime 1 events. The thick litter layer can also greatly limit sediment detachment (Pannkuk & Robichaud 2003; Li *et al*. 2014), resulting in low soil loss during regime 1 events. In addition, the time of land abandoned also influenced the processes of runoff and soil loss generation. Under shrub land and forest land, vegetation coverage increased with plant

https://doi.org/10.1017/S1755691018000531 Published online by Cambridge University Press

growth years (Wei *et al.* 2007). Soil organic carbon and soil water-stable aggregate also increased with the increase in years of returning cultivated land to black locust land (Sun *et al.* 2017). In this study, shrub land that has been abandoned for the longest presented the lowest runoff levels for regime 2 and 3, and the lowest soil loss, due to its having the highest vegetation coverage and soil anti-erodibility.

3.2. Response of runoff and soil loss to plot length under different land uses

The runoff and soil loss orders in plots with different lengths (5-m plot > 9-m plot > 13-m plot) were almost the same under the three land uses (Fig. 5). Ghahramani & Ishikawa (2013) also found that runoff decreased with increasing slope length. The connectivity, distance of runoff pathway and time of runoff were crucial to the amount of runoff and soil loss, which were limited by the slope length and affected by the type of vegetation cover and litter layer (Parsons *et al.* 2006; Ghahramani & Ishikawa 2013). Increasing infiltration with increasing slope length has been recognised as the main factor contributing to the scale effects of runoff (Mayor *et al.* 2011; Ghahramani & Ishikawa 2013). Therefore, due to the key role of vegetation in controlling infiltration, runoff and soil loss at different scales were related to the type of vegetation cover (Cammeraat 2004). Grass land was found to have the most significant effect of slope length on runoff and soil loss. Shrub land produced slight variations in runoff and soil loss between plots with lengths of 5 and 9 m, while forest cover plots with lengths of 9 and 13 m had similar levels of runoff and soil loss. Therefore, the effect of slope length on runoff and soil loss was mainly determined by the type of land use.

3.3. Combined effects of rainfall regime and plot length on runoff and soil loss

Many studies found that the scale effects of runoff and soil loss were influenced by rainfall intensity (Chaplot & Le Bissonnais 2003; Cammeraat 2004; Xu *et al.* 2009; Ghahramani & Ishikawa 2013). The thresholds of rainfall depth and intensity for runoff generation increase with increasing plot length, and runoff may only occur in long plots under sufficient high rainfall amount and intensity (Cammeraat 2004; Mayor *et al.* 2011). In this study, runoff and soil loss under different land uses were shown to be affected by both the rainfall regime and plot length. The slope length characteristics of runoff at different rainfall regimes under forest and shrub cover showed a similar trend (a decrease with slope length increased), which differed from the behaviour for soil loss. Different slope length effects of runoff were observed under grass cover when experiencing rainfall events with a low intensity (regime 2).

It was found that rainfall events with a high intensity reduced the scale effects of runoff (Fang *et al.* 2008; Sadeghi *et al.* 2013), while the scale effects of soil loss were amplified (Liu *et al.* 2000). However, the effects of rainfall intensity on the scale characteristics of runoff and soil loss were affected by land uses. Vegetation structures, such as canopy height, litter layer and plant roots, can alter rainfall erosive kinetic energy and soil properties, and then directly or indirectly affect the generation of runoff and soil loss (Quinton *et al.* 1997; Crockford & Richardson 2000; Gyssels *et al.* 2005; Zuazo & Pleguezuelo 2008; Li *et al.* 2014). For forest and shrub land, high-intensity rainfall generated the least response of runoff and soil loss to slope length change, whereas low-intensity rainfall led to the largest response. For grass land, rainfall with moderate intensity resulted in the least variation in runoff and the largest variation in soil loss when slope length changed, whereas low-intensity rainfall generated the converse result, which does not correspond to the previous studies. As a result, we found that land uses could influence the effect of rainfall intensity on the response of runoff and soil loss to slope length.

4. Conclusion

This study investigated the combined effects of rainfall regimes and plot length on runoff and soil loss among different land uses with forest, shrub and grass in the Loess Plateau. Fifty-nine rainfall events recorded from 2008 to 2016 were divided into three rainfall regimes using K-means clustering based on rainfall depth, duration and maximum I_{30}. Regime 1 events were the most frequent type of rainfall, with high intensity, short duration and low rainfall depth. Regime 2 events were the least frequent type of rainfall, with the opposite characteristics to those in regime 1 events. Regime 3 events had moderate level of rainfall indices between those of regime 1 and 2 events.

The order of mean runoff under the three land uses was grass > shrub > forest, while, for soil loss, the order was grass > forest > shrub. However, the differences between forest and shrub in runoff and between grass and forest in soil loss did not reach significant level. Rainfall regimes had an important effect on runoff and soil loss under different land uses. The orders of runoff among land uses under regimes 2 and 3 events were different from that of regime 1, and only regime 2 events resulted in the change of the order of soil loss. Moreover, runoff and soil loss varied considerably between the different rainfall regimes. Runoff under rainfall regime 1 was the greatest, followed by regimes 3 and 2. Soil loss followed the same order under shrub land, while, under grass and forest land, the order became regime 3 > regime 1 > regime 2. Runoff and soil loss under shrub land showed the most sensitivity to the change of rainfall regimes.

Runoff and soil loss decreased with increasing plot length, while these effects were influenced by land use type and were highly dependent on the rainfall regime. For forest and shrub land, runoff under all rainfall regimes showed a similar response to slope length change, but different effects of slope length on soil loss were found under regimes 2 and 3. For grass land, regime 2 resulted in different effects of slope length on both runoff and soil loss from other regimes. Consequently, the complex relationship of rainfall pattern–land use–slope length to runoff and soil loss still requires further investigation.

5. Acknowledgements

This research was financially supported by the National Natural Science Foundation of China (no. 41390464), the National Key Research and Development Program (no. 2016YFC0501602) and the Youth Innovation Promotion Association CAS (no. 2016040).

6. References

Allen, S. T., Brooks, J. R., Keim, R. F., Bond, B. J. & McDonnell, J. J. 2014. The role of pre- event canopy storage in throughfall and stemflow by using isotopic tracers. *Ecohydrology: Ecosystems, Land and Water Process Interactions, Ecohydrogeomorphology* **7**, 858–68.

Angel, J. R., Palecki, M. A. & Hollinger, S. E. 2005. Storm precipitation in the United States. Part ii: soil erosion characteristics. *Journal of Applied Meteorology* **44**, 947–59.

Boardman, J. 2015. Extreme rainfall and its impact on cultivated landscapes with particular reference to Britain. *Earth Surface Processes and Landforms* **40**, 2121–30.

Bochet, E., Rubio, J. L. & Poesen, J. 1998. Relative efficiency of three representative matorral species in reducing water erosion at the microscale in a semi-arid climate (Valencia, Spain). *Geomorphology* **23**, 139–50.

Boix-Fayos, C., Martinez-Mena, M., Arnau-Rosalen, E., Calvo-Cases, A., Castillo, V. & Albaladejo, J. 2006. Measuring soil erosion by field plots: understanding the sources of variation. *Earth-Science Reviews* **78**, 267–85.

Calder, I. R. 2001. Canopy processes: implications for transpiration, interception and splash induced erosion, ultimately for forest management and water resources. *Plant Ecology* **153**, 203–14.

Cammeraat, E. L. H. 2004. Scale dependent thresholds in hydrological and erosion response of a semi-arid catchment in southeast Spain. *Agriculture Ecosystems & Environment* **104**, 317–32.

Chaplot, V. A. M. & Le Bissonnais, Y. 2003. Runoff features for interrill erosion at different rainfall intensities, slope lengths, and gradients in an agricultural loessial hillslope. *Soil Science Society of America Journal* **67**, 844–51.

Chen, X. A., Cai, Q. G., Zhang, L. C., Zheng, M., Qi. J. Y. & Li, J. L. 2011. Impact of slope length on soil erosion under different rainfall intensity in a hilly loess region on the Loess Plateau. *Journal of Soil Science* **42**, 721–25.

Cheng, J. D., Lin, L. L. & Lu, H. S. 2002. Influences of forests on water flows from headwater watersheds in Taiwan. *Forest Ecology and Management* **165**, 11–28.

Chirino, E., Bonet, A., Bellot, J. & Sanchez, J. R. 2006. Effects of 30-year-old Aleppo pine plantations on runoff, soil erosion, and plant diversity in a semi-arid landscape in south eastern Spain. *Catena* **65**, 19–29.

Crockford, R. H. & Richardson, D. P. 2000. Partitioning of rainfall into throughfall, stemflow and interception: effect of forest type, ground cover and climate. *Hydrological Processes* **14**, 2903–20.

Dunkerley, D. 2010. How do the rain rates of sub-event intervals such as the maximum 5-and 15-min rates (i-5 or i-30) relate to the properties of the enclosing rainfall event? *Hydrological Processes* **24**, 2425–39.

Elwell, H. A. & Stocking, M. A. 1976. Vegetal cover to estimate soil erosion hazard in Rhodesia. *Geoderma* **15**, 61–70.

Fang, H. Y., Cai, Q. G., Chen, H. & Li, Q. Y. 2008. Effect of rainfall regime and slope on runoff in a gullied loess region on the Loess Plateau in China. *Environmental Management* **42**, 402–11.

Fang, N. F., Shi, Z. H., Li, L., Guo, Z. L., Liu, Q. J. & Ai, L. 2012. The effects of rainfall regimes and land use changes on runoff and soil loss in a small mountainous watershed. *Catena* **99**, 1–8.

Feng, X. M., Sun, G., Fu, B. J., Su, C. H., Liu, Y. & Lamparski, H. 2012. Regional effects of vegetation restoration on water yield across the Loess Plateau, China. *Hydrology and Earth System Sciences* **16**, 2617–28.

Findeling, A., Ruy, S. & Scopel, E. 2003. Modeling the effects of a partial residue mulch on runoff using a physically based approach. *Journal of Hydrology* **275**, 49–66.

Frauenfeld, B. & Truman, C. 2004. Variable rainfall intensity effects on runoff and interrill erosion from two coastal plain ultisols in Georgia. *Soil Science* **169**, 143–54.

Fu, B. J., Liu, Y., Lu, Y. H., He, C. S., Zeng, Y. & Wu, B. F. 2011. Assessing the soil erosion control service of ecosystems change in the Loess Plateau of China. *Ecological Complexity* **8**, 284–93.

Fusun, S., Jinniu, W., Tao, L., Yan, W., Haixia, G. & Ning, W. 2013. Effects of different types of vegetation recovery on runoff and soil erosion on a Wenchuan earthquake-triggered landslide, China. *Journal of Soil and Water Conservation* **68**, 138–45.

Gao, G. Y., Fu, B. J., Lu, Y. H., Liu, Y., Wang, S. & Zhou, J. 2012. Coupling the modified SCS-CN and RUSLE models to simulate hydrological effects of restoring vegetation in the Loess Plateau of China. *Hydrology and Earth System Sciences* **16**, 2347–64.

Ghahramani, A. & Ishikawa, Y. 2013. Water flux and sediment transport within a forested landscape: the role of connectivity, subsurface flow, and slope length scale on transport mechanism. *Hydrological Processes* **27**, 4091–102.

González-Hidalgo, J. C., Peña-Monné, J. L. & de Luis, M. 2007. A review of daily soil erosion in western Mediterranean areas. *Catena* **71**, 193–99.

Gyssels, G., Poesen, J., Bochet, E. & Li, Y. 2005. Impact of plant roots on the resistance of soils to erosion by water: a review. *Progress in Physical Geography* **29**, 189–217.

Hong, N. 2003. *Products and servicing solution teaching book for SPSS of Windows Statistical*, 300–11. Beijing: Tsinghua University Press and Communication University Press.

Kang, S. Z., Zhang, L., Song, X. Y., Zhang, S. H., Liu, X. Z., Liang, Y. L. & Zheng, S. Q. 2001. Runoff and sediment loss responses to rainfall and land use in two agricultural catchments on the Loess Plateau of China. *Hydrological Processes* **15**, 977–88.

Kinnell, P. I. A. 2005. Why the universal soil loss equation and the revised version of it do not predict event erosion well. *Hydrological Processes* **19**, 851–54.

Kinnell, P. I. A. 2007. Runoff dependent erosivity and slope length factors suitable for modelling annual erosion using the universal soil loss equation. *Hydrological Processes* **21**, 2681–89.

Li, X., Niu, J. & Xie, B. 2014. The effect of leaf litter cover on surface runoff and soil erosion in northern China. *Plos One* **9**, 1–15.

Li, Y., Poesen, J., Yang, J. C., Fu, B. & Zhang, J. H. 2003. Evaluating gully erosion using cs-137 and pb-210/cs-137 ratio in a reservoir catchment. *Soil & Tillage Research* **69**, 107–15.

Liu, B. Y., Nearing, M. A., Shi, P. J. & Jia, Z. W. 2000. Slope length effects on soil loss for steep slopes. *Soil Science Society of America Journal* **64**, 1759–63.

Liu, Y., Fu, B. J., Lu, Y. H., Wang, Z. & Gao, G. Y. 2012. Hydrological responses and soil erosion potential of abandoned cropland in the Loess Plateau, China. *Geomorphology* **138**, 404–14.

Liu, Y. J., Yang, J., Hu, J. M., Tang, C. J. & Zheng, H. J. 2016. Characteristics of the surface-subsurface flow generation and sediment yield to the rainfall regime and land-cover by long-term in-situ observation in the red soil region, southern China. *Journal of Hydrology* **539**, 457–67.

Lu, Y. H., Fu, B. J., Feng, X. M., Zeng, Y., Liu, Y., Chang, R. Y., Sun, G. & Wu, B. F. 2012. A policy-driven large scale ecological restoration: quantifying ecosystem services changes in the Loess Plateau of China. *Plos One* **7**, 1–10.

Mayor, A. G., Bautista, S. & Bellot, J. 2011. Scale-dependent variation in runoff and sediment yield in a semiarid Mediterranean catchment. *Journal of Hydrology* **397**, 128–35.

Millward, A. A. & Mersey, J. E. 1999. Adapting the RUSLE to model soil erosion potential in a mountainous tropical watershed. *Catena* **38**, 109–29.

Nunes, A. N., De Almeida, A. C. & Coelho, C. O. 2011. Impacts of land use and cover type on runoff and soil erosion in a marginal area of Portugal. *Applied Geography* **31**, 687–99.

Pannkuk, C. D. & Robichaud, P. R. 2003. Effectiveness of needle cast at reducing erosion after forest fires. *Water Resources Research* **39**, 1–9.

Parsons, A. J., Brazier, R. E., Wainwright, J. & Powell, D. M. 2006. Scale relationships in hillslope runoff and erosion. *Earth Surface Processes and Landforms* **31**, 1384–93.

Parsons, A. J. & Stone, P. M. 2006. Effects of intra-storm variations in rainfall intensity on interrill runoff and erosion. *Catena* **67**, 68–78.

Peng, T. & Wang, S. J. 2012. Effects of land use, land cover and rainfall regimes on the surface runoff and soil loss on karst slopes in southwest China. *Catena* **90**, 53–62.

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R. & Blair, R. 1995. Environmental and economic costs of soil erosion and conservation benefits. *Science* **267**, 1117–23.

Puigdefabregas, J., Sole, A., Gutierrez, L., del Barrio, G. & Boer, M. 1999. Scales and processes of water and sediment redistribution in drylands: results from the Rambla Honda field site in southeast Spain. *Earth-Science Reviews* **48**, 39–70.

Quinton, J. N., Edwards, G. M. & Morgan, R. P. C. 1997. The influence of vegetation species and plant properties on runoff and soil erosion: results from a rainfall simulation study in south east Spain. *Soil Use and Management* **13**, 143–48.

Ramos, M. C. & Martinez-Casasnovas, J. A. 2009. Impacts of annual precipitation extremes on soil and nutrient losses in vineyards of NE Spain. *Hydrological Processes* **23**, 224–35.

Ran, Q., Su, D., Li, P. & He, Z. 2012. Experimental study of the impact of rainfall characteristics on runoff generation and soil erosion. *Journal of Hydrology* **424–25**, 99–111.

Sadeghi, S. H. R., Seghaleh, M. B. & Rangavar, A. S. 2013. Plot sizes dependency of runoff and sediment yield estimates from a small watershed. Catena **102**, 55–61.

Shi, H. & Shao, M. G. 2000. Soil and water loss from the Loess Plateau in China. *Journal of Arid Environments* **45**, 9–20.

Smets, T., Poesen, J. & Bochet, E. 2008. Impact of plot length on the effectiveness of different soil-surface covers in reducing runoff and soil loss by water. *Progress in Physical Geography* **32**, 654–77.

Sun, L., Zhang G. H., Wang, B. & Luan, L. L. 2017. Soil erosion resistance of black locust land with different ages of returning farmland on Loess Plateau. *Transactions of the Chinese Society of Agricultural Engineering* **33**, 191–97. [In Chinese.]

Wei, W., Chen, L. D., Fu, B. J., Huang, Z. L., Wu, D. P. & Gui, L. D. 2007. The effect of land uses and rainfall regimes on runoff and soil erosion in the semi-arid loess hilly area, China. *Journal of Hydrology* **335**, 247–58.

https://doi.org/10.1017/S1755691018000531 Published online by Cambridge University Press

Wei, W., Chen, L. D., Fu, B. J., Lu, Y. H. & Gong, J. 2009. Responses of water erosion to rainfall extremes and vegetation types in a loess semiarid hilly area, NW China. *Hydrological Processes* **23**, 1780–91.

Wei, W., Jia, F. Y., Yang, L., Chen, L. D., Zhang, H. D. & Yu, Y. 2014. Effects of surficial condition and rainfall intensity on runoff in a loess hilly area, China. *Journal of Hydrology* **513**, 115–26.

Wischmeier, W. H. & Smith, D. D. 1978. Predicting rainfall erosion losses: a guide to conservation planning, 537. Washington: US Department of Agriculture, Agricultural Research Service, Agriculture Handbook.

Xin, Z. B., Xu, J. X. & Zheng, W. 2008. Spatiotemporal variations of vegetation cover on the Chinese Loess Plateau (1981–2006): impacts of climate changes and human activities. *Science in China Series D-Earth Sciences* **51**, 67–78.

Xu, X. L., Liu, W., Kong, Y. P., Zhang, K. L., Yu, B. F. & Chen, J. D. 2009. Runoff and water erosion on road side-slopes: effects of rainfall characteristics and slope length. *Transportation Research Part D-Transport and Environment* **14**, 497–501.

Yeh, H. Y., Wensel, L. C. & Turnblom, E. C. 2000. An objective approach for classifying precipitation patterns to study climatic effects on tree growth. *Forest Ecology and Management* **139**, 41–50.

Zhang, G. H., Liu, G. B., Yi, L. & Zhang, P. C. 2014. Effects of patterned *Artemisia capillaris* on overland flow resistance under varied rainfall intensities in the Loess Plateau of China. *Journal of Hydrology and Hydromechanics* **62**, 334–42.

Zhao, G., Mu, X., Wen, Z., Wang, F. & Gao, P. 2013. Soil erosion, conservation, and eco-environment changes in the Loess Plateau of China. *Land Degradation & Development* **24**, 499–510.

Zhou, D., Zhao, S. & Zhu, C. 2012. The Grain for Green Project induced land cover change in the Loess Plateau: a case study with Ansai County, Shanxi Province, China. *Ecological Indicators* **23**, 88–94.

Zhou, J., Fu, B., Gao, G., Lü, Y., Liu, Y., Lü, N. & Wang, S. 2016. Effects of precipitation and restoration vegetation on soil erosion in a semi-arid environment in the Loess Plateau, China. *Catena* **137**, 1–11.

Zuazo, V. H. D. & Pleguezuelo, C. R. R. 2008. Soil-erosion and runoff prevention by plant covers. A review. *Agronomy for Sustainable Development* **28**, 65–86.

MS received 6 December 2016. Accepted for publication 3 August 2017