Field studies on the slope length effect of grass cover and rainfall intensity on erosion on typical watersheds of the Loess Plateau, China

Zimiao He [a], Peiqing Xiao [b], Guodong Jia [a], Shi long Hao[b], Ziqiang Liu [c], Xinxiao Yu [a]

[a] Key Laboratory of State Forestry Administration on Soil and Water Conservation, College of Soil and Water Conservation, Beijing Forestry University, Beijing 100083, China

[b] Yellow River Institute of Hydraulic Research Key Laboratory of Soil and Water Loss Process and Control on the Loess Plateau of Ministry of Water Resources, 450003, Zhengzhou China

[c] Co-Innovation Center for Sustainable Forestry in Southern China, Nanjing Forestry University, Nanjing, 210037, China

*Corresponding author at: College of Soil and Water Conservation, Beijing Forestry University, No. 35 Qinghua East Road, Haidian District, Beijing 100083, China. E-mail address: yuxinxiao112@126.com.

Yellow River Institute of Hydraulic Research Key Laboratory of Soil and Water Loss Process and Control on the Loess Plateau of Ministry of Water Resources, 450003, Zhengzhou China. E-mail address: peiqingxiao@163.com

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Abstract

Slope length is an important topographic factor for controlling soil erosion and pivotal parameters in the soil erosion model. The impact of slope length on soil erosion was studied under different grassland and different rainfall intensity through simulated rainfall experiments. The experiment included five rainfall intensity treatments (1, 1.5, 2, 2.5 and 3 mm h^{-1}), four grass cover treatments (0, 30%, 60% and 90%) and five slope length treatments (2, 4, 6, 8 and 10 m). The results show that the rate of soil loss increased exponentially with increasing slope length under 0 and 30% grass cover. Under high grass covers (60% and 90%), the slope length increased sedimentation

from runoff and reduced slope erosion.The increase of slope length led to enhancement of soil loss as rainfall intensity increased. At 1 mm min^{-1} rainfall intensity, natural grass slopes (60%) controlled soil loss very well and were not affected by slope length. At 1.5–2 mm min^{-1}rainfall intensity, the soil erosion increased with slope length, but the overall soil erosion amount was small. This indicates that grass cover at 10 m slope length had a good impact on soil erosion. When the rainfall intensity exceeded 2 mm min^{-1}, soil loss increased with slope length. Regression analysis showed that soil erosion was more strongly related to grass cover and rainfall intensity than to slope length.

Keywords: slope length, grass cover, rainfall intensity, soil loss, Loess Plateau

1. Introduction

Soil erosion is a worldwide form of soil degradation that seriously threatens the sustainable development of ecosystems. It destroys the soil structure and causes soil fertility decline and ground surface fragmentation, which is closely related to water pollution and sedimentation of rivers and reservoirs (Fang et al., 2016). Soil erosion is affected by many factors, such as rainfall characteristics, ground cover, ground morphology, soil characteristics, etc. (Zhang et al, 2018), It is essential to research on the mechanism and control factors of soil erosion process under multi-factor interaction for improving erosion management, mitigating land degradation and promoting the sustainability of land-water ecosystems.

Slope is an important source of sediment for erosion. The contribution of erosion in sloping farmland to soil loss could reach 60% in the heavily eroded Loess Plateau, (Zheng et al., 1989).The Chinese government encourages the conversion of sloped arable land into grassland, bush or forest through the implementation of the Project of Returning Farmland to Forest and Grass(Jia et al., 2017) to protect soil and water resources and restore the damaged environment (Sidle et al., 2007). The role of vegetation in controlling soil erosion has received widespread attention from researchers (Wang et al., 2019). The interception of the vegetation canopy reduces the final velocity of the raindrops and the number of raindrops that reach the soil surface (Marques et al., 2007). The vegetation litter increases the slope surface roughness and delays the flow velocity (Leighton-Boyce et al., 2007). The vegetation roots could improve soil parameters, such as soil porosity, bulk density and organic matter content (Zhao et al., 2017), thereby increasing the soil infiltration volume and infiltration depth (Zhang et al., 2016). The roots could also enhance the water-stable aggregate content and the network bonding of the root system increases erosion resistance of the soil (Wang et al., 2016). However, the increase in vegetation coverage (especially for artificial forests and grasslands that were previously farmland) has increased the use of soil moisture and triggered the appearance of dry soil layers (Jia et al., 2020). Feng et al.(2016) evaluated the threshold of vegetation capacity on the Loess Plateau (China) and found that the vegetation was approaching sustainable water resource limits. Breshears et al. (2005) indicated that long-term drying of soil profiles may lead to land degradation and drought. In addition, the severe dry layer of soil will weaken the exchange of surface soil water and groundwater, thereby affecting the sustainability of the regional water cycle and ecosystem (Turkeltaub et al., 2018). Therefore, it is essential to analyze the ecological environmental impacts under different vegetation coverage.

The main motive force for soil erosion comes from rainfall, and the soil erosion across large areas of the world is caused by strong or extreme rainfall events (Wang et al., 2019). The impact of rainfall on soil erosion is mainly manifested in four aspects. The first is the splashing of soil particles by rainfall, which promotes soil erosion (Ziadat et al., 2013). The second is that rainfall characteristics control the generation and amount of runoff on slopes (Serrano-Muel et al., 2013). Thirdly, the impact of raindrops increases the turbulence of runoff and enhances the sediment transport capacity of runoff (Shen et al., 2016). Fourth, rainfall intensity has an impact on the surface soil structure, which in turn affects slope infiltration and runoff (Feng et al., 2012). Rachman et al. (2003) believed that rainfall intensity seriously affected runoff and soil erosion processes. Studies in arid environments have shown that little rainfall intensity (1–2 mm min^{-1}) could occur runoff, while rainfall intensity above 2 mm min^{-1} occurs floods (Salameh et al., 1991). Wu et al. (2017) reported soil erosion under four erosion degrees, and found that soil properties and rainfall intensity and duration control the erosion process and sediment delivery.

Slope length is an important topographic factor affecting erosion and sediment transport (Cook, 1937; Qin et al., 2018). It determines the changes along the slope water flow energy by changing the rain-receiving area, which affects the movement of water and sediment. There are currently three different views on the effect of slope length on erosion. One view is that the sand content in the runoff increases with the slope length, and the flow energy is mostly consumed by carrying sediment, resulting in weaker erosion (Xu et al., 2009). The second view is that as the water depth gradually increases from uphill to downhill, erosion correspondingly increases (Kara et al., 2010). The third view is that the amount of erosion changes as a wave with the increase of the slope length (Zheng et al., 1989). Bagarello and Ferro (2010) analyzed the natural rainfall data in the wild plots and showed that in the range of 11–33 m in slope length, the erosion modulus of the inter rill erosion was proportional to the power of the slope length. Cai (1989) reported that the amount of soil erosion initially increased with the length of the slope; however, when the slope length exceeded a certain value, it gradually decreased with the extension of the slope length. Liu et al. (2019) showed that the soil loss of forest, shrub and grass-covered slopes weakened with slope length, and short slopes responded more quickly to this change. Due to the influence of topography, vegetation coverage, rainfall intensity and other factors, the results of different experiments are not the same, all of which complicate the relationship between slope length and erosion intensity.

In the context of ecological restoration, the effect of slope length on soil erosion of grass slopes with different coverage and rainfall intensity is discussed. The specific objectives were to: (1) investigate the impact of slope length on soil loss, (2) determine the change of these effects with grass cover and rainfall intensity, and (3) quantify the relationship of soil loss with slope length, grass cover and rainfall intensity.

2. Materials and methods

2.1. Experimental site

The experiment was in the Luoyugou watershed (34° 34′ - 34° 40′N, 105° 30′ -

105° 40′E; 1199.8–1896.9 m elevation),which is a typical region in western China(Fig. 1). The density of the gully was 3.54 km/km^2 and the average slope was 18°. Annual average temperature in this region ranges between 7-11 °C. Annual average precipitation is about 533.7 mm, with about 80% occurring between May and October (Qin et al., 2018). Precipitation in this area, predominantly classified as heavy rain, occurs over a small area, characterized by a short duration and high intensity. The main types of soil in the study area are cinnamon soil, black loess soil and red clay. Soil in the study area has a poor resistance to soil erosion and it is readily broken. The average annual erosion modulus in the study area is 5510 t/(km2.a)(Chen et al., 2011).

After an in-situ investigation and comparison, 10 experimental plots were selected on the slope of a natural wasteland (tillage had been abandoned for around 20 years) in the lower reaches of the Luoyugou watershed. The slope of the plots was 15° and the elevation was 1500 m. The plots were 10 m long and 2 m wide. The natural vegetation is mainly grasses, mainly Coronilla varia and Poa sphondylodes. Two sites were treated as bare slopes, three were designated as high-cover grass slopes through usual protection (multiple watering), and three were designated as low-cover grass slopes through usual protection (trimming), and the other two are not treatment, they are all natural grassland. The experiment was conducted from June to September 2019. Table 1 describes the vegetation status of the experiment site.

2.2.Experimental set-up

The rainfall device is the QYJY-501(Qing yuan, Xi'an, China). Five groups of rainfall nozzles were established, each having three different aperture sizes. During rainfall simulation, different rainfall intensities were achieved using different nozzle combinations and pressures. Rainfall intensity was controlled using real-time rain gauge data feedback. With respect to raindrop velocity and raindrop size, rainfall generated by the simulation device had more than 80% similarity with natural rainfall. At the same time, a Thies LAM Laser Raindrop Spectrometer was used to record the velocity and size of raindrops during the rainfall experiments.

2.3. Experimental treatments

In accordance with local seasonal rainfall (Qin et al., 2018) and temporal distribution of extreme rainfall in the Loess Plateau (Zhang et al., 2020), five rainfall intensities were replicated (1, 1.5, 2, 2.5 and 3 mm/h) on four slope types: bare slope, lowly covered grass slope (30%), natural grass slope (60%) and highly covered grass slope (90%). Regarding the design of the slope length, the first 10m slope length test was carried out, and then the 8m, 6m, 4m and 2m slope length experiments were carried out in sequence.Use marble slabs to divided the slope in turn along the slope to obtain runoff plots of different lengths. The day before the experiment, a WET soil moisture meter was used to measure the soil moisture content. According to the measured value, the water spray method was used to ensure the same soil moisture content. According to the method used by Zhao et al. (2016), the eroded surface was repaired with equivalent sand. In the rain experiment, the use of a wind net could reduce any impact caused by wind.

Time required for runoff to be generated was recorded and all flow discharge from each plot was collected at the outlet every 2 minutes, including all suspended and bed sediments. Once rainfall had been simulated for 60 min, runoff samples were measured volumetrically and allowed to stand for 12 h, after which most of the clean water was poured out. Then, the drying method is used to obtain the weight of the sediment.

2.4. Data analysis

The slope length effect of soil erosion (*ELI*) at a given grass cover and rainfall intensity is defined as the ratio of the soil erosion rate to the reduction rate at the 2 m slope length. The *ELI* was calculated by:

$$ELI = (SLR_i - SLR_2) / SLR_2 \tag{7}$$

where SLR_i is the soil loss rate of the i^{th} slope length (g m^{-2} min^{-1}) and SLR_2 is the soil loss rate at the length of the 2 m slope (g m^{-2} min^{-1}).

The relationship between soil loss rate and grass cover, rainfall intensity and slope was analyzed with multiple regression analysis.

3. Results

3.1. Soil erosion process

The soil erosion process responded differently to different treatments(Figure 2). The soil loss process was divided into two stages: rapid increase and stable fluctuation.Grass cover reduced the rate of increase and duration in the first stage and the fluctuation range in the second stage, The higher the coverage rate, the greater the effect. Rainfall intensity had the opposite effect. Under different slope lengths, compared with bare slopes, the average soil loss of grass slopes reduced by 47%–90%, and the average reduction was 70%. Compared with the rainfall intensity of 1 mm min^{-1}, the average soil erosion of other rainfall intensity increased by 2–13 times, and the average increased by 7 times.

3.2. Changes in the impact of slope length on soil loss with grass cover

The effects of grass cover and slope length on soil loss rate were analyzed under the 1.5 mm min^{-1} rainfall intensity. the average soil loss rate increased with slope length (Table 2). However, this trend was altered by changes in grass cover. When the grass cover was 0 or 30%, the soil loss rate power function increased with slope length , and the increase of slope length promoted soil loss. However, at 60% grass cover, the soil erosion rate peaked at a slope length of 8 m, and at 90% grass cover, the soil erosion rate peaked at a slope length of 6 m.Under bare slope, 30%, 60% and 90% grass cover, compared with 2m slope length, the maximum increase rate of soil loss rate was 775% (10 m), 930% (8 m) and 225% (6 m) and 475% (4 m) .

3.3. Changes in the impact of slope length on soil loss with rainfall intensity

The impacts of rainfall intensity and slope length on soil loss rate were analyzed under natural restoration of grass slopes (60% coverage). At 1 mm min^{-1} rainfall intensity, the average soil loss rate showed an increasing–decreasing–increasing fluctuation with slope length . With the increase of rainfall intensity, the average soil loss rate gradually changed to increasing with slope length (Figure 4). Under the rainfall intensity of 1, 1.5, 2, 2.5 and 3 mm min^{-1}, compared with the slope length of 2 m, the maximum increase rate of soil loss rate was 3% (10 m), 225% (8 m), 237% (10 m), 373% (8 m) and 497% (10 m), and the maximum decrease rate of soil erosion rate was 56% (4 m) under 1 mm min^{-1} rainfall intensity (Table 3).

3.4. The relationship between grass cover, rainfall intensity and slope length and soil loss rate

The impact of slope length on soil erosion varied with grass cover and rainfall intensity. In order to further analyze the effect of slope length, grass cover and rainfall intensity on soil erosion, a nonlinear regression analysis of the relationship between soil loss rate and slope length, grass cover and rainfall intensity was performed. The fitting equations were:

$$Z = 19.1836x^{-0.2124}e^{0.1917y} \quad (R^2 = 0.8416,\ n = 20) \qquad (8)$$

$$Z = 2.8327I^{2.5912}e^{0.1436y} \quad (R^2 = 0.8651,\ n = 25) \qquad (9)$$

where Z is the soil loss rate (g m^{-2} min^{-1}), x is the grass cover (%), y is the slope length (m), and I is the rainfall intensity (mm min^{-1}). Comparison of the standard regression coefficients of slope length with grass cover and rainfall intensity reveals that compared with slope length, the relationship between soil loss and grass cover and rainfall intensity is stronger.

4. Discussion

4.1. Influence of the slope length on the effect of grass cover on soil loss

Slope length is an important topographic factor affecting erosion. The average soil loss rate increased with slope length. The effect of slope length on soil loss was attributed to the increased rain area and the increase in water flow (Cai, 1989; An et al., 2019).On the one hand, the large rain area and the long flow path corresponding to the long slope increase the chance of raindrop splash and water flow erosion, and enhance confluence of slope runoff and intensity of runoff erosion. On the other hand, long slopes could increase the infiltration of slope runoff and thus reduce the amount of slope runoff (Panagos et al., 2015; Schmidt et al., 2019). The longer slope also is associated with a longer runoff carrying distance for sediment, and thus more energy is consumed (Xu et al., 2009). In this study, the slope runoff rate, runoff depth and slope flow velocity increased with the slope length (Table 2), indicating that as the slope length increases, the sediment delivery capacity increases. However, the rate of increase gradually slowed, indicating that the effect of increasing infiltration and energy consumption on the long slope gradually increased.

Ecological restoration of vegetation is an important measure to prevent and control soil erosion on slope (Vannoppen et al., 2015). In the study, grass slopes reduced soil loss by about 70%. Grass cover also changed the trend of soil loss with slope length (Figure 3， Table 2). On bare slopes and under low grass cover, long slopes promote erosion. However, high grass cover increases slope roughness (Zhao et al., 2017), promotes runoff infiltration (Wu et al., 2016) and retards the development of slope hydrological connectivity (Durán et al., 2008). Thus, a short slope is insufficient for runoff to converge into a larger runoff and for velocity to increase (Table 2). A long slope has not yet played a role in the process of erosion. Therefore, at 1.5mm / min rainfall intensity, the soil erosion of 60% grass slope in the range of 10m slope length showed a downward trend (Figure 3c), indicating that 60% grass slope have a good control effect on soil loss with a slope length of 10 m. The 90% grass-covered slopes have better control effect on soil erosion, because there is no significant difference in the amount of soil erosion in plots with different slope lengths (Figure 3d). Quantifying the impact of slope length and grass cover on soil erosion revealed that the impact of grass cover on soil loss was greater than the slope length, which is similar to the results of Bircher et al. (2019). The interception of grass canopy and the change of root system on soil properties also have positive significance for the control of soil erosion (Biddoccu et al., 2016). Grass and its roots effectively reduce soil erodibility and increase the critical shear force (Table 4).

4.2. Influence of the slope length on the impact of rainfall intensity on soil loss

The effect of slope length on soil loss on ecologically restored grassland slopes varied with rainfall intensity. The greater the rainfall intensity, the greater the increase in soil loss with slope length (Figure 4,Table 3). This result was similar to the reports of Wu et al. (2017). The impact of rainfall on slope erosion is mainly due to the effect of raindrops on the loose topsoil and the potential erosive force of runoff (Liu, et al., 2016). In this study, the relationship between rainfall erosivity and soil erosion rate was not significant, because grass cover responded differently to rainfall erosion at different rainfall intensities (Figure 5a). However, the soil loss rate increased significantly with the increase of water flow power, following a power function (R^2 = 0.8095, P < 0.01) (Figure 5b). Reichert and Norton (2013) and Wang et al. (2019) showed that the flow power is the best hydrodynamic parameter to characterize the dynamic mechanism of slope erosion. However, rainfall intensity also has an important effect on soil properties (soil compaction and sealing) (Shen et al., 2016). In the current study, it was found that the critical runoff shear force decreases as the rainfall intensity increases (Table 4). Vaezi et al. (2017) showed that heavy rainfall intensity promoted soil compaction and sealing, which is consistent with our research results.

The impact of rainfall intensity on soil erosion was greater than the slope length, which is consistent with the reports of Fu et al. (2019). The presence of grass cover could intercept rainfall (Yang et al., 2017), increase soil infiltration (Mei et al., 2018), and block the direct effect of rainfall on soil (Bracken et al., 2013), thereby delaying the intensity of rainfall the impact of slope length erosion. Some previous studies have shown that there is a critical rainfall intensity for soil erosion. When the rainfall intensity is greater than the critical rainfall intensity, the erosion is further intensified under the influence of the slope length factor ((Diodato, 2004; Fu et al., 2013). In the current study, the correlation between runoff speed, soil loss and slope length was not significant under the 1 mm min^{-1} rainfall intensity (Table 3 and Figure 4a). This indicates that the ecologically restored grass cover could control soil loss very well without affecting by slope length. At 1.5 - 2 mm min^{-1} rainfall intensity, the total amount of soil erosion was small, indicating that the grass recovered ecologically within this rainfall intensity range has a good control effect on soil loss within a slope length of 10m. However, the amount of soil loss increased drastically with slope length when the rainfall intensity is greater than 2 mm min^{-1}. Chen et al. (2011)] pointed out that the slope length effects of soil loss were different with different I_{30} (maximum 30 min rain intensity). When I_{30}> 0.21 mm min^{-1}, as the slope length increases in the range of 20-60m, the amount of soil erosion first increased and then stabilized. Xing et al. (2016) showed that soil loss increased with slope length. The increase of rainfall intensity would increase the amount of soil loss, but did not affect the relationship between soil loss and slope length. It could be seen that the rainfall erosion responds differently to the slope length under different factors such as different study areas and different rain intensities. In combination with the conclusions of previous research, the slope length of the experimental design runoff plot in this study was small (the longest was only 10 m). Therefore, the effect of slope length on erosion on sloping farmland under the background of ecological restoration needs to be further explored in subsequent experiments.

5. Conclusions

Study of the influence of slope length on the process of runoff and erosion can provide an important theoretical basis for the deployment of soil erosion prevention measures on slopes. Under different treatments, the soil loss process was divided into two stages: rapid increase and stable fluctuation. The average soil loss rate increased with slope length. Grass cover changed the trend of soil loss with slope length; at 0 and 30% grass cover, long slopes promoted erosion. When the grass coverage reaches 60% and above, the change of slope length has little impact on the erosion process. The increase of rainfall intensity led to the enhancement of soil loss due to the increase of slope length. At 1 mm min^{-1} rainfall intensity, natural grass slopes (60%) were able to control soil loss very well and were not affected by slope length. At 1.5 - 2 mm min^{-1} rainfall intensities, the overall soil erosion amount was small. This indicates that grass cover within 10 m slope length had a good control on soil erosion. the soil loss increased drastically with slope length when the rainfall intensity is greater than 2 mm min^{-1}. Regression analysis showed that the relationship between soil loss, grass cover and rainfall intensity was stronger than that between soil loss and slope length.

References

[1]. An, M., Han, Y., Xu, L., Wang, X., Ao, C., & Pang, D. 2019. KINEROS2-based simulation of total nitrogen loss on slopes under rainfall events. CATENA, 177, 13–21. doi:10.1016/j.catena.2019.01.039

[2]. Bagarello, V., & Ferro, V. 2010. Analysis of soil loss data from plots of differing length for the Sparacia experimental area, Sicily, Italy. Biosystems Engineering, 105(3), 411–422. doi:10.1016/j.biosystemseng.2009.12.015

[3]. Biddoccu, M., Ferraris, S., Opsi, F., & Cavallo, E. 2016. Long-term monitoring of soil management effects on runoff and soil erosion in sloping vineyards in Alto Monferrato (North–West Italy). Soil and Tillage Research, 155, 176–189. doi:10.1016/j.still.2015.07.005

[4]. Bircher, P., Liniger, H. P., & Prasuhn, V. 2019. Comparing different multiple flow algorithms to calculate RUSLE factors of slope length (L) and slope steepness (S) in Switzerland. Geomorphology, 106850. doi:10.1016/j.geomorph.2019.106850

[5]. Bracken, L. J., Wainwright, J., Ali, G. A., Tetzlaff, D., Smith, M. W., Reaney, S. M., & Roy, A. G. 2013. Concepts of hydrological connectivity: Research approaches, pathways and future agendas. Earth-Science Reviews, 119, 17–34. doi:10.1016/j.earscirev.2013.02.001

[6]. Breshears, D. D., Cobb, N. S., Rich, P. M., et al. 2005. Regional vegetation die-off in response to global-change-type drought. *Proceedings of the National Academy of Sciences*, **102**(42), 15144–15148. doi:10.1073/pnas.0505734102

[7]. Cai Q.G. 1989.Effect of slope length on the slope erosion process. Sediment Research,(4):84-91.

[8]. Chen X.A., Cai Q.G., Zhang L.C., et al.2011. Impact of slope length on soil erosion under different rainfall intensity in a hilly Loess region on the Loess plateau. *Chinese Journal of Soil Science*, **42**(3): 721－725.

[9]. Chen, Y. , Wang, F. , Liu, G. , Xinxiao, Y. U. , Jia, G. , & Gan, P. 2011. Modified vegetation-erosion dynamics model and its application in typical watersheds in the loess plateau. *International Journal of Sediment Research*(01), 81-89. doi:10.1016/s1001-6279(11)60077-2

[10]. Cook, H. L. 1937. The Nature and Controlling Variables of the Water Erosion Process. *Soil Science Society of America Journal*, **1**(C), 487. doi:10.2136/sssaj1937.036159950001000000008

[11]. Diodato, N. 2004. Estimating RUSLE's rainfall factor in the part of Italy with

a Mediterranean rainfall regime. *Hydrology and Earth System Sciences*, **8**(1), 103–107. doi:10.5194/hess-8-103-2004

[12]. Durán Zuazo, V. H., & Rodríguez Pleguezuelo, C. R. 2008. Soil-erosion and runoff prevention by plant covers. A review. *Agronomy for Sustainable Development*, **28**(1), 65–86. doi:10.1051/agro:2007062

[13]. Feng, X., Fu, B., Piao, S., Wang, S., Ciais, P., Zeng, Z., … Wu, B. 2016. Revegetation in China's Loess Plateau is approaching sustainable water resource limits. *Nature Climate Change*, **6**(11), 1019–1022. doi:10.1038/nclimate3092

[14]. Feng, X., Vico, G., & Porporato, A. 2012. On the effects of seasonality on soil water balance and plant growth. *Water Resources Research*, **48**(5). doi:10.1029/2011wr011263

[15]. Fu X.T., Zhang, L.P. 2014. Impact of slope length on soil erosion of sloping farmland with crop in red soil hilly region. *CSAE*, **30**(5): 91－98.doi: 10.3969/j.issn.1002-6819.2014.05.012

[16]. Fu, G., Yu, J., Yu, X., Ouyang, R., Zhang, Y., Wang, P., … Min, L. 2013. Temporal variation of extreme rainfall events in China, 1961–2009. *Journal of Hydrology*, **487**, 48–59. doi:10.1016/j.jhydrol.2013.02.021

[17]. Fu, X. T., Zhang, L. P., & Wang, Y. 2019. Effect of Slope Length and Rainfall Intensity on Runoff and Erosion Conversion from Laboratory to Field. *Water Resources*, **46**(4), 530–541. doi:10.1134/s0097807819040080

[18]. Jia, X., Wang, Y., Shao, M., Luo, Y., & Zhang, C. 2017. Estimating regional losses of soil water due to the conversion of agricultural land to forest in China's Loess Plateau. *Ecohydrology*, **10**(6), e1851. doi:10.1002/eco.1851

[19]. Jia, X., Zhao, C., Wang, Y., Zhu, Y., Wei, X., & Shao, M. 2020. Traditional dry soil layer index method overestimates soil desiccation severity following conversion of cropland into forest and grassland on China's Loess Plateau. *Agriculture, Ecosystems & Environment*, **291**, 106794. doi:10.1016/j.agee.2019.106794

[20]. Kara, Ö., Şensoy, H., & Bolat, İ. 2010. Slope length effects on microbial

biomass and activity of eroded sediments. *Journal of Soils and Sediments*, **10**(3), 434–439. doi:10.1007/s11368-010-0192-8

[21]. Leighton-Boyce, G., Doerr, S. H., Shakesby, R. A., et al.2007. Quantifying the impact of soil water repellency on overland flow generation and erosion: a new approach using rainfall simulation and wetting agent on in situ soil. *Hydrological Processes*, **21**, 2337-2345. doi:10.1002/hyp.6744

[22]. Liu, J., Gao, G., Wang, S., & Fu, B. 2019. Combined effects of rainfall regime and plot length on runoff and soil loss in the Loess Plateau of China. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, 1–10. doi:10.1017/s1755691018000531

[23]. Liu, Y., Wu, G.-L., Ding, L.-M., Tian, F.-P., & Shi, Z.-H. 2016. Diversity-Productivity Trade-off During Converting Cropland to Perennial Grassland in the Semi-arid Areas of China. *Land Degradation & Development*, **28**(2), 699–707. doi:10.1002/ldr.2561

[24]. Marques, M. J., Bienes, R., Jiménez, L., & Pérez-Rodríguez, R. 2007. Effect of vegetal cover on runoff and soil erosion under light intensity events. Rainfall simulation over USLE plots. *Science of The Total Environment*, **378**(1-2), 161–165. doi:10.1016/j.scitotenv.2007.01.043

[25]. Mei, X., Zhu, Q., Ma, L., Zhang, D., Wang, Y., & Hao, W. 2018. Effect of stand origin and slope position on infiltration pattern and preferential flow on a Loess hillslope. *Land Degradation & Development*, **29**(5), 1353–1365. doi:10.1002/ldr.2928

[26]. Panagos, P., Borrelli, P., & Meusburger, K. 2015. A New European Slope Length and Steepness Factor (LS-Factor) for Modeling Soil Erosion by Water. *Geosciences*, **5**(2), 117–126. doi:10.3390/geosciences5020117

[27]. Qin, RJ. Li, GF. Li, P. 2018. Impacts of Precipitation and Land Use Change on Runoff and Sediment in Luoyugou Watershed. *Journal of Soil and Water Conservation*.**2018**,32(05),29-34+40

[28]. Qin, W., Guo, Q., Cao, W., Yin, Z., Yan, Q., Shan, Z., & Zheng, F. 2018. A new RUSLE slope length factor and its application to soil erosion assessment in a

Loess Plateau watershed. *Soil and Tillage Research*, **182**, 10–24. doi:10.1016/j.still.2018.04.004

[29]. Rachman, A., Anderson, S. H., Gantzer, C. J., & Thompson, A. L. 2003. Influence of Long-term Cropping Systems on Soil Physical Properties Related to Soil Erodibility. *Soil Science Society of America Journal*, **67**(2), 637. doi:10.2136/sssaj2003.6370

[30]. Reichert, J. M., & Norton, L. D. 2013. Rill and interrill erodibility and sediment characteristics of clayey Australian Vertosols and a Ferrosol. *Soil Research*, **51**(1), 1. doi:10.1071/sr12243

[31]. Salameh E, Remawi O, Bannayan H. 1991. Groundwater artificial recharge in Jordan. Water Research and Study Center, University of Jordan: Amman, Jordan

[32]. Schmidt, S., Tresch, S., & Meusburger, K. 2019. Modification of the RUSLE slope length and steepness factor (LS-factor) based on rainfall experiments at steep alpine grasslands. *MethodsX*. doi:10.1016/j.mex.2019.01.004

[33]. Serrano-Muela, M. P., Nadal-Romero, E., Lana-Renault, N., González-Hidalgo, J. C., López-Moreno, J. I., Beguería, S., … García-Ruiz, J. M. 2013. An Exceptional Rainfall Event in the Central Western Pyrenees: Spatial Patterns in Discharge and Impact. *Land Degradation & Developmen*t, **26**(3), 249–262. doi:10.1002/ldr.2221

[34]. Shen, H., Zheng, F., Wen, L., Han, Y., & Hu, W. 2016. Impacts of rainfall intensity and slope gradient on rill erosion processes at loessial hillslope. *Soil and Tillage Research*, **155**, 429–436. doi:10.1016/j.still.2015.09.011

[35]. Sidle, R. C., Hirano, T., Gomi, T., & Terajima, T. 2007. Hortonian overland flow from Japanese forest plantations—an aberration, the real thing, or something in between? *Hydrological Processes*, **21**(23), 3237–3247. doi:10.1002/hyp.6876

[36]. Turkeltaub, T., Jia, X., Zhu, Y., Shao, M.-A., & Binley, A. 2018. Recharge and Nitrate Transport Through the Deep Vadose Zone of the Loess Plateau: A Regional-Scale Model Investigation. *Water Resources Research*, **54**(7), 4332–4346. doi:10.1029/2017wr022190

[37]. Vaezi, A. R., Ahmadi, M., & Cerdà, A. 2017. Contribution of raindrop impact to the change of soil physical properties and water erosion under semi-arid rainfalls. *Science of The Total Environment*, **583**, 382–392. doi:10.1016/j.scitotenv.2017.01.078

[38]. Vannoppen, W., Vanmaercke, M., De Baets, S., & Poesen, J. 2015. A review of the mechanical effects of plant roots on concentrated flow erosion rates. *Earth-Science Reviews*, **150**, 666–678. doi:10.1016/j.earscirev.2015.08.011

[39]. Wang, L., Zhang, G., Wang, X., & Zhu, P. 2019. Soil loss response to plant the litter incorporation rate under simulated rainfall conditions. *Land Degradation & Development*. doi:10.1002/ldr.3304

[40]. Wang, Z.-J., Jiao, J.-Y., Rayburg, S., Wang, Q.-L., & Su, Y. 2016. Soil erosion resistance of "Grain for Green" vegetation types under extreme rainfall conditions on the Loess Plateau, China. *CATENA*, **141**, 109–116. doi:10.1016/j.catena.2016.02.025

[41]. Wu, G.-L., Yang, Z., Cui, Z., Liu, Y., Fang, N.-F., & Shi, Z.-H. 2016. Mixed artificial grasslands with more roots improved mine soil infiltration capacity. *Journal of Hydrology*, **535**, 54–60. doi:10.1016/j.jhydrol.2016.01.059

[42]. Wu, X., Wei, Y., Wang, J., Xia, J., Cai, C., Wu, L., … Wei, Z. 2017. Effects of erosion degree and rainfall intensity on erosion processes for Ultisols derived from quaternary red clay. *Agriculture, Ecosystems & Environment*, **249**, 226–236. doi:10.1016/j.agee.2017.08.023

[43]. Xing, W., Yang, P., Ren, S., Ao, C., Li, X., & Gao, W. (2016). Slope length effects on processes of total nitrogen loss under simulated rainfall. *CATENA*, **139**, 73–81. doi:10.1016/j.catena.2015.12.008

[44]. Xu, X.-L., Liu, W., Kong, Y.-P., Zhang, K.-L., Yu, B., & Chen, J.-D. 2009. Runoff and water erosion on road side-slopes: Effects of rainfall characteristics and slope length. T*ransportation Research Part D: Transport and Environment*, **14**(7), 497–501. doi:10.1016/j.trd.2009.05.006

[45]. Yang, D., Xiong, D., Zhang, B., Guo, M., Su, Z., Dong, Y., … Lu, X. 2017. Effect of grass basal diameter on hydraulic properties and sediment yield

processes in gully beds in the dry-hot valley region of Southwest China. *CATENA*, **152**, 299–310. doi:10.1016/j.catena.2017.01.023

[46]. Zhang, J., Gao, G., Fu, B., Wang, C., Gupta, H. V., Zhang, X., & Li, R. 2020. A universal multifractal approach to assessment of spatiotemporal extreme precipitation over the Loess Plateau of China. *Hydrology and Earth System Sciences*, **24**(2), 809–826. doi:10.5194/hess-24-809-2020

[47]. Zhang, K., Yu, Y., Dong, J., Yang, Q., & Xu, X. 2019. Adapting & testing use of USLE K factor for agricultural soils in China. *Agriculture, Ecosystems & Environment*, **269**, 148–155. doi:10.1016/j.agee.2018.09.033

[48]. Zhang, X., Zhao, W., Liu, Y., Fang, X., & Feng, Q. 2016. The relationships between grasslands and soil moisture on the Loess Plateau of China: A review. *CATENA*, **145**, 56–67. doi:10.1016/j.catena.2016.05.022

[49]. Zhang, Z., Li, M., Si, B., & Feng, H. 2018. Deep rooted apple trees decrease groundwater recharge in the highland region of the Loess Plateau, China. *Science of The Total Environment*, **622**, 584–593. doi:10.1016/j.scitotenv.2017.11.230

[50]. Zhao, C., Gao, J., Huang, Y., Wang, G., & Xu, Z. 2016. The Contribution of Astragalus adsurgens Roots and Canopy to Water Erosion Control in the Water-Wind Crisscrossed Erosion Region of the Loess Plateau, China. *Land Degradation & Development*, **28**(1), 265–273. doi:10.1002/ldr.2508

[51]. Zhao, D., Xu, M., Liu, G., Ma, L., Zhang, S., Xiao, T., & Peng, G. 2017. Effect of vegetation type on microstructure of soil aggregates on the Loess Plateau, China. *Agriculture, Ecosystems & Environment*, **242**, 1–8. doi:10.1016/j.agee.2017.03.014

[52]. Zheng F.L., Tang K.L., Zhou P.H. 1989. Study on factors affecting rill erosion on cultivated slope land. *Acta Pedologica Sinica*, **26**(2): 109－116.

[53]. Ziadat, F. M., & Taimeh, A. Y. 2013. Effect of rainfall intensity, slope, land use and antecedent soil moisture on soil erosion in an arid environment. *Land Degradation & Development*, **24**, 582-590. doi:10.1002/ldr.2239

Table 1 Stratification of the soil physical properties for the different soil layers

Plot	Canopy characteristics	Root characteristics at the soil depth of 0-100 cm
0		
30	EN:12.5cm;CV:20.3cm； 14.23g/m^2	EN:26.6cm,dia<0.5mm; CV:72.5cm,dia4-10mm;28.74g/m^2
60	EN:12.2cm;CV:21.5cm； 87.26g/m^2	EN:32.5cm,dia<0.5mm; CV:69.3cm,dia4-10mm; 170.43g/m^2
90	EN:12.8cm;CV:19.6cm； 165.68g/m^2	EN:35.5cm,dia<0.5mm; CV:80.3cm,dia4-10mm; 325.43g/m^2

EN: Eriophorum comosum Nees, CV: Coronilla varia Linn,

Table 2 Runoff erosion characteristics under different grass cover

Grass-cover （%）	Slope length （m）	RR (mm min^{-1})	RRD (mm)	U (m s^{-1})	SLR (g m^{-2} min^{-1})	SC (g L^{-1})
	2	0.96	1.46	0.13	19.19	13.37
	4	0.97	2.33	0.24	47.28	53.39
0	6	0.99	3.04	0.27	103.52	101.06
	8	1.04	3.26	0.30	102.41	92.95
	10	1.08	3.94	0.41	167.95	224.41
	2	0.87	1.69	0.12	8.05	9.69
	4	0.89	2.70	0.19	30.26	30.20
30	6	0.92	3.39	0.23	52.89	49.57
	8	0.95	3.81	0.27	61.51	58.15
	10	0.99	4.83	0.31	82.89	142.36
	2	0.59	1.66	0.12	8.83	9.03
	4	0.64	3.25	0.16	14.27	14.67
60	6	0.71	3.82	0.22	18.81	18.81
	8	0.76	3.82	0.28	28.70	24.87
	10	0.75	4.34	0.27	24.87	15.32
	2	0.35	1.73	0.10	2.42	3.30
	4	0.39	2.68	0.15	5.18	5.50
90	6	0.46	3.41	0.17	10.71	12.31
	8	0.53	3.41	0.17	7.34	8.37
	10	0.51	3.88	0.20	13.91	14.44

Notes: U, flow velocity; RR,runoff rate; RRD, Runoff depth; SC, sediment concentration; SLR, soil loss rate; SR, the efficiency of reducing soil loss.

Table 3 Runoff erosion characteristics under different rainfall intensity

Rainfall intensity （mm/min）	Slope length (mm)	RR (mm min^{-1})	RRD (mm)	U (m s^{-1})	SLR (g m^{-2} min^{-1})	SC (g L^{-1})
	2	0.4	1.61	0.12	13.21	10.10
	4	0.45	2.44	0.15	5.86	4.00
1	6	0.51	3.08	0.20	8.39	6.50
	8	0.58	3.45	0.17	6.13	4.07
	10	0.63	4.05	0.25	13.61	11.01
	2	0.59	1.66	0.12	8.83	9.03
	4	0.64	3.25	0.16	14.27	14.67
1.5	6	0.71	3.82	0.22	18.81	18.81
	8	0.76	3.82	0.28	28.70	24.87
	10	0.75	4.34	0.27	24.87	15.32
	2	0.93	2.29	0.10	10.74	12.25
	4	0.97	3.11	0.17	20.62	19.98
2	6	1.02	3.45	0.18	18.57	28.61
	8	1.08	3.86	0.22	28.10	31.25
	10	1.14	4.31	0.25	36.23	26.98
	2	1.43	2.03	0.11	28.10	35.45
	4	1.47	2.85	0.16	70.08	91.66
2.5	6	1.51	3.49	0.18	87.18	88.72
	8	1.56	3.60	0.24	132.80	86.56
	10	1.62	3.75	0.25	122.15	88.22
	2	1.85	1.65	0.11	27.69	32.44
	4	1.89	3.30	0.18	83.82	74.49
3	6	1.93	4.20	0.23	90.99	31.75
	8	1.98	4.43	0.25	147.21	147.65
	10	2.03	4.61	0.29	160.36	165.39

Notes: U, flow velocity; RR,runoff rate; RRD, Runoff depth; SC, sediment concentration; SLR, soil loss rate; SR, the efficiency of reducing soil loss.

Table 4 Fitting of runoff shear and soil loss rate

Influencing factors	Factor conditions	Fitting equation	R^2	Critical runoff shear stress($N*m^{-2}$)
grass-cover（%）	0	$y=31.874\tau-27.289$	0.717	0.856
	30	$y=12.108\tau-16.848$	0.719	1.388
	60	$y=2.333\tau-4.861$	0.740	2.130
	90	$y=0.726\tau-1.928$	0.708	2.714
rainfall intensity（mm/min）	1	$y=1.156\tau-3.510$	0.649	2.917
	1.5	$y=2.333\tau-4.861$	0.740	2.130
	2	$y=2.286\tau-4.733$	0.772	2.070
	2.5	$y=6.424\tau-11.280$	0.672	1.756
	3	$y=6.875\tau-11.545$	0.814	1.678