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

Hao Chen[a], Xiaoping Zhang[a,*], Muratjan Abla[a], Du Lü[a], Rui Yan[a], Qingfu Ren[a], Zhiyong Ren[c], Yahui Yang[a], Wenhui Zhao[a], Pengfei Lin[a], Baoyuan Liu[a], Xihua Yang[b]

[a] *State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi 712100, China*
[b] *New South Wales Office of Environment and Heritage, PO Box 644, Parramatta, NSW 2124, Australia*
[c] *The Monitoring Center of Soil and Water Conservation, Shanxi 030000, China*

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A B S T R A C T

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

* Corresponding author at: Institute of Soil and Water Conservation, Northwest A&F University, No. 26 Xinong Road, Yangling, Shaanxi 712100, China.
*E-mail address:* zhangxp@ms.iswc.ac.cn (X. Zhang).

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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