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Impacts of rainfall intensity and slope gradient on rill erosion processes at loessial hillslope

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ABSTRACT

Rill erosion constitutes one of the mechanisms of soil loss by water on agricultural land. However, studies on hillslope rill erosion characteristics and its intrinsic mechanisms are still unclear. The objectives of this study were to investigate the impacts of rainfall intensity and slope gradient on hillslope rill erosion processes, rill flow hydraulic characteristics and dynamic mechanisms. A soil pan (10 m long, 1.5 m wide and 0.5 m deep and with an adjustable slope gradient of 0–30°) was subjected to rainfall simulation experiments under three rainfall intensities (50, 75 and 100 mm h^{-1}) of representative erosive rainfall and three typical slope gradients (10, 15 and 20°) on the Loess Plateau of China. The results showed that rill erosion exhibited significant contributions to hillslope soil erosion, occupying 62.2–84.8% of hillslope soil loss. The equation between the rill erosion rate with rainfall intensity and slope gradient was generated, which indicated that the impacts of rainfall intensity on hillslope rill erosion were greater than those of slope gradient. For the experimental treatments, the mean headward erosion rates varied between 2.2 and 8.2 cm min^{-1}, and they increased with an increase in either rainfall intensity or slope gradient. Most rill flow belonged to turbulent and subcritical flow regimes. The critical shear stress, the critical stream power, and the critical unit stream power of rill occurrence were 0.986 Pa, 0.207 N m^{-1} s^{-1}, and 0.002 m s^{-1}, respectively. Additionally, hillslope rill erosion was sensitive to rill flow velocity and stream power. In a word, rainfall intensity and slope gradient exhibited important impacts on rill erosion processes and its hydrodynamic characteristics. Therefore, preventing rainfall erosion and weakening slope gradient effects through conservation tillage are useful for reduction of rill erosion at loessial hillslopes.

1. Introduction

Rill erosion constitutes one of the mechanisms of soil loss by water on sloping croplands and rangelands in many areas around the world (Bewket and Sterk, 2003; Kimaro et al., 2008; Porto et al., 2014; Zheng and Tang, 1997). Agricultural productivity and environmental quality have deteriorated due to the increase in soil loss on hillslopes. Several studies (e.g., Bryan and Rockwell, 1998; Di Stefano et al., 2013) have noted that there is a marked increase in soil erosion rate coinciding with rill initiation. This increase is of obvious practical importance in soil conservation. Furthermore, rill development is also of geomorphic significance, with potential implications for the hillslope and drainage network evolution (Bryan and Rockwell, 1998).

Rill erosion is most likely a major soil erosion pattern because, rill channels transport sediment particles both detached from the interrill areas and sourced from the rill wetted perimeter (Bewket and Sterk, 2003; Bruno et al., 2008; Nearing et al., 1997). Although the knowledge of rill erosion characteristics (Bryan and Rockwell, 1998; Wirtz et al., 2012) and its influncing factors (Berger et al., 2010; Römkens et al., 2001; Wei et al., 2007) has increased, the study of rill erosion processes is still a subject of unclear description and dependence. The reported estimates (e.g., Zheng and Tang, 1997) of rill erosion on the Loess Plateau of China are extremely worrisome. Thus, a deeper insight into rill erosion processes on hillslopes of this region is essential.

Many studies have reported that rill erosion is directly controlled by combined actions of runoff and soil (Sun et al.,

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2013). Other factors may have indirect influences on rill erosion by increasing or decreasing the effects of direct factors (Wirtz et al., 2012). Rainfall intensity and slope gradient are two important influencing factors to rill erosion. Rill erosion usually increased with increasing rainfall intensity and slope gradient (Berger et al., 2010; Römkens et al., 2001). It is a general agreement that concentrated flow causes rill development (Romero et al., 2007), while raindrop impact play more significant roles in interrill erosion (Wirtz et al., 2012). On the Loess Plateau of China, rains with the features as high intensity, short duration and high frequency cause the greatest proportion of runoff and soil loss (Wei et al., 2007). Additionally, slope gradient is relatively steep and changes between 3 and 12° at the sheet erosion dominant zone and 12–25° at the rill erosion dominant zone (Zheng et al., 2005).

The intrinsic mechanisms of rill erosion are still unclear due to its complexity, especially under different physical processes (Wirtz et al., 2013). Rill erosion and development are linked to some hydraulic characteristics of channel flow, such as flow velocity, Reynolds number, Froude number, and Darcy–Weisbach resistance coefficient (An et al., 2012; Bryan and Rockwell, 1998; Reichert and Norton, 2013). Flow velocity has significant influence on magnitudes of runoff erosion and entrainment capacities (Li et al., 2006). Reynolds number is essentially a ratio of kinetic to viscous forces of flow. Froude number represents a ratio of kinetic to gravitational flow forces (Polyakov and Nearing, 2003). Then, Darcy–Weisbach resistance coefficient describes head loss due to fluid shear stress applied on the soil surface. Flow in rills is characterized by subcritical (Froude number <1) and supercritical (Froude number >1) flows, with transitional (Reynolds number = 1000–2000) and turbulent (Reynolds number >2000) flow regimes (Reichert and Norton, 2013).

It is important to evaluate the dynamic mechanisms of rill erosion because soil detachment and transport by flow are of processes of energy consumption. Shear stress, stream power, and unit stream power are basic hydrodynamic parameters (An et al., 2012). These parameters are commonly used to evaluate soil detachment rates and characterize critical dynamic conditions of soil erosion occurrence (e.g., Nearing et al., 1997; Reichert and Norton, 2013). Although studies on the dynamic mechanisms of soil erosion have been paid more attention, the hydrodynamic characteristics of rill erosion are still unclear.

Some researchers (e.g., Lei and Tang, 1998) suggest using Reynolds number as the criterion parameter of rill initiation. However, the results of Nearing et al. (1997) noted that Reynolds number was not a good predictor of rill flow hydraulic characteristics. Furthermore, Reichert and Norton (2013) noted that Darcy–Weisbach resistance coefficient seemed the best among the variables used to describe resistance to flow. Nearing et al. (1997) also reported that stream power was a consistent and appropriate predictor for unit sediment load. Thus, it is imperative to determine which parameters are optimal to characterize rill flow hydraulic characteristics and dynamic mechanisms of rill erosion.

Rainfall simulation is an ideal research method of rill erosion by replicating rill erosion processes and characteristics. An understanding of rill erosion processes is not only significant for the soil erosion prevention on sloping croplands but also of importance to soil erosion prediction models (Nearing et al., 1997; Sun et al., 2013). Therefore, a laboratory study was conducted under controlled experimental conditions. The objectives of this study are to investigate the impacts of rainfall intensity and slope gradient on rill erosion processes at the loessial hillslope, to study the rill headward erosion rate, analyze the rill flow hydraulic characteristics and dynamic mechanisms of rill erosion, and propose the most sensitive parameters for characterizing hillslope rill erosion.

2. Materials and methods

2.1. Experimental materials

The experiments were completed in the rainfall simulation laboratory of the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Yangling City, China. The experiments were conducted in a slope adjustable pan 10 m long, 1.5 m wide and 0.5 m deep, with holes (2 cm aperture) at the bottom to facilitate drainage. The slope gradient ranged from 0 to 30° with adjustment intervals of 5°. In this study, three typical slope gradients of 10, 15 and 20° on the Loess Plateau of China were designed. A down sprinkler rainfall simulator system (Zheng and Zhao, 2004) was used to apply rainfall. This rainfall simulator including three nozzles can be set to any selected rainfall intensity ranging from 30 to 350 mm h^{-1} by adjusting the nozzle size and water pressure. Three rainfall intensities (50, 75 and 100 mm h^{-1}) of representative erosive rainfall on the Loess Plateau were applied to the soil pan. The fall height of the raindrops is 18 m above the ground, which allows all raindrops to reach terminal velocity prior to impact with the soil surface. Additionally, the simulated raindrop can successfully replicate the natural raindrop size and distribution (Shen et al., 2015).

The soil used in this study was the loessial soil, classified as a *Calcic Cambisols* (USDA Taxonomy), with 28.3% sand (>50 μm), 58.1% silt (50–2 μm), 13.6% clay content (<2 μm) and 5.9 g kg^{-1} soil organic matter. The pipette method and the potassium dichromate oxidation-external heating method were used to analyze soil texture and soil organic matter, respectively. The tested soil was collected from 0 to 20 cm in the Ap horizon of a well-drained site in Ansai, Shaanxi Province, China. Impurities such as organic matter and gravels were removed from all the soil; though to keep its natural state, the soil was not passed through a sieve.

2.2. Preparation of the soil pan

Before packing the soil pan, the soil water content of the tested soil was determined and used to calculate how much soil was needed to pack the soil pan and obtain target bulk densities for different soil layers. First, a 5-cm-thick layer of sand was packed at the bottom of the soil pan, which allowed free drainage of excess water. Then, the layers over the sand layer were divided into a plow pan with a depth of 15 cm and a tilth layer with a depth of 20 cm to simulate local sloping croplands. The bulk densities for the plow pan and the tilth layer were 1.35 and 1.10 g cm^{-3}, respectively. During the packing process, both the plow pan and the tilth layer were packed in 5-cm increments, and each packed soil layer was raked lightly before the next layer was packed to ensure uniformity and continuity in the soil structure. The soil amount of each layer was kept as constant as possible to maintain similar bulk density and uniform spatial distribution of soil particles. After completion of packing the soil pan, a manual tillage on the soil pan was performed at ~20 cm depth along the contour line, which is similar to the plowing depth of croplands. After plowing, the soil pan was allowed to settle for 48 h.

2.3. Experimental procedures

Before runs, the experimental soil pan was subjected to a pre-rain with the 30 mm h^{-1} rainfall intensity until surface flow occurred. The duration of this pre-rain was ~25 min. The average soil water content before each rainfall was 23.4 ± 0.5% for all treatments. The purposes of the pre-rain were to maintain consistent soil moisture, consolidate loose soil particles by rainfall wetting, and reduce the spatial variability of surface conditions. The soil surface was covered with a plastic sheet after the pre-rain