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Distinguishing transport-limited and detachment-limited processes of interrill erosion on steep slopes in the Chinese loessial region

Bing Wu[a,c], Zhanli Wang[a,b,*], Qingwei Zhang[b], Nan Shen[b]

[a] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, China
[b] 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
[c] University of Chinese Academy of Sciences, Beijing 100049, China

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ABSTRACT

Distinguishing transport- and detachment-limited processes of interrill erosion on the basis of the ratio of interrill erosion rate (*Q*) to splash detachment rate (*D*) was investigated to fully understand interrill erosion processes. A modified experimental device was used to measure interrill erosion and splash detachment rates simultaneously at 12.23%, 17.63%, 26.8%, 36.4%, 40.40% and 46.63% slope gradients under rainfall intensities of 48 and 120 mm h^{-1}. Results showed that the transport-limited ($Q < D$), detachment-limited ($Q > D$), and transport- and detachment-limited ($Q < D$ & $Q > D$) processes were respectively included in individual rainfall event, which were influenced by slope gradient and rainfall intensity, and the transport-limited process changed to a detachment-limited process early when the slope gradients were steep. Furthermore, the ratio of interrill erosion rate to splash detachment rate under rainfall intensities of 48 and 120 mm h^{-1} increased from 0.006 to 36.91 and from 0.14 to 15.65 as the slope gradient increased from 12.23% to 46.63%, respectively. The research findings emphasise the importance of quantifying transport- and detachment-limited processes on steep slopes.

1. Introduction

The Loess Plateau in northwest China has suffered from serious soil erosion in recent decades (Shi and Shao, 2000; Liu et al., 2012; Zhao et al., 2013; Tian et al., 2016). Ellison (1944, 1947) defined soil erosion as “a process of detachment and transportation of soil materials” and suggested that (1) soil detachment by rainfall, (2) transport by rainfall, (3) detachment by runoff and (4) transport by runoff are considered as separate but interrelated phases of the process of soil erosion by water. Such processes are affected by many soil and cover factors (Asadi et al., 2007). Many researchers have focused on the soil erosion processes, and several process-based erosion prediction models (Smith et al., 1995; De Roo et al., 1996; Morgan et al., 1998; Flanagan et al., 2001) have been established to help predict the intensity and assess the rate of soil erosion in a particular area. Thus, in the Loess Plateau in China, soil erosion processes also need to be understood and evaluated to make a decision regarding soil erosion control in the area.

Several studies also investigated the effects of various slopes or rainfall intensities on interrill erosion processes (McCool et al., 1987; Nearing et al., 1989; Kinnell, 1993; Liu et al., 1994, 2015; Zhang and Hosoyamada, 1996; Zhang et al., 1998; Fox and Bryan, 2000; Bulygin et al., 2002; Wei et al., 2009; Yuan et al., 2015; Zhang and Wang, 2017). McCool et al. (1987) found that interrill erosion rate can be predicted as a linear function of the sine of slope gradient. This finding was consistent with the report of Liu et al. (1994). Nearing et al. (1989) discovered that a power function exist between interrill erosion rate and rainfall intensity, and that interrill erosion rate varied directly with the square of rainfall intensity. Kinnell (1993) observed that interrill erosion rate varied directly with rainfall intensity rather than the square of rainfall intensity when certain factors (e.g. flow discharge) are also considered. Zhang and Hosoyamada (1996) suggested that the interrill erosion rate can be predicted as a polynomial function of slope gradient's sine. Zhang et al. (1998) suggested that the interrill erosion rate can be predicted as a power function of slope gradient percentage. This finding was consistent with the reports of Fox and Bryan (2000) and Bulygin et al. (2002). Wei et al. (2016) suggested that the interrill erosion can be predicted as a power function of rainfall intensities. Yuan et al. (2015) and Liu et al. (2015) found that slope is an important factor in interrill erosion. Zhang and Wang (2017) suggested that the interrill erosion increases as rainfall intensity increases for a steep

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[*] Corresponding author at: State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources, Yangling, Shaanxi 712100, China.
E-mail address: zwang@nwsuaf.edu.cn (Z. Wang).

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slope.

The main processes in interrill erosion are the detachment of soil material by raindrop impact and the transport of sediment by overland flow (Watson and Laflen, 1986; Kinnell, 2006). A more concentrated overland flow further transports most of the sediments removed from the interrill area (Young and Wiersma, 1973; Nearing, 1991; Levy et al., 1994). Thus, interrill erosion can be described as a combination of two sub-processes, namely, splash and wash dynamics, which were considered in several erosion models, such as the Limburg soil erosion model (LISEM) (De Roo et al., 1996), the European soil erosion model (EUROSEM) (Morgan et al., 1998) and the terrace erosion and sediment transport model (TEST) (Van Dijk and Bruijnzeel, 2003), and many previous erosion studies have investigated the interaction between various erosion processes, including the interaction between raindrop and surface flow on different slope gradients. Bryan (1974) partitioned the total splash and wash on a slope of 36.4% and found that the former was smaller than the latter. Bryan (1979) measured the downslope splashed material of eight soils at ten slopes from 5.24% to 57.7% and proved that the magnitude of splash and wash contribution to soil erosion varies among different soil types. Bradford et al. (1987) measured the effect of surface sealing on infiltration, runoff and soil loss for 20 soils with different soil textures ranging from sand to clay. The wash and splash erosions were measured for near-saturated soils in 0.14 m^2 pans exposed to laboratory-simulated rainfall with an intensity of approximately 63 mm h^{-1} for one hour; the wash and splash amounts decreased with time due to surface sealing, with the decrease in wash being much smaller than the decrease in splash. Grosh and Jarrett (1994) measured interrill erosion on 5%, 15%, 25%, 45%, 65% and 85% slopes. Interrill erosion and runoff were measured in a 0.504 m^2 box filled with disturbed Hagerstown silty clay loam under 20 min of simulated 92 mm h^{-1} rainfall intensity. The combined wash and splash loss in a 1 m^2 area was found to increase linearly with the slope. Sutherland et al. (1996) and Wan et al. (1996) reported that the total splash is greater than the wash on slopes from 8.7% to 36.4%. Mermut et al. (1997) also found that the total splash loss is much higher than the wash loss when a 30-cm diameter cylindrical soil tray is used. Van Dijk et al. (2003) observed that the total splash was higher than the wash on 0%, 8.7%, 26.78% and 83.85% slopes under natural rainfall. Fu et al. (2011) measured interrill splash and wash at 9%, 18%, 27%, 36%, 47%, 58%, 70%, 84% and 100% slopes under a 67 mm h^{-1} constant rainfall intensity in a laboratory setting and found that the total splash and wash losses all increase with the slope and then decrease after reaching a maximum value. Bryan and Luk (1981) partitioned downslope splash and wash and found that the downslope splash is less than the wash on 22.16% slope. Wei et al. (2016) measured interrill splash and wash on 17.6% slope under rainfall intensities of 50 and 100 mm h^{-1} and found that the total splash was smaller than the wash.

Overall, the effects of various slopes or rainfall intensities on interrill erosion and the splash contribution to interrill erosion were evaluated in previous studies. However, the soil pans in most studies had no border area and most studies were conducted under gentle slope. Agassi and Bradford (1999) suggested the necessity of a buffer area surrounding the central test area such that any redistribution of splash does not result in a net loss of splashed soil within the test area. Any splash leaving the test area must be balanced by an input of splash from the surrounding areas. Cao et al. (2015) reported that landform in the Loess Plateau is characterised by its steep slope gradient. Hence, an accurate observation of the interrelation between the splash detachment rate and interrill erosion rate in rainfall processes using the bordered soil pan area on steep slopes is necessary, on the basis of which the splash detachment and wash processes can be separately quantified to distinguish transport-limited and detachment-limited processes of interrill erosion, severed for clarifying processes of interrill erosion and laying the foundation for developing processes-based interrill erosion model.

The objectives of this study were to distinguish detachment-limited and transport-limited processes of interrill erosion under different slope gradients and rainfall intensities in the loessial region of China. The results can deeply reveal interrill erosion processes and provide a scientific basis for soil erosion control in the area.

2. Materials and methods

2.1. Experiment equipment

2.1.1. Simulated rainfall device

In this study, the experiments were conducted in the Simulation Rainfall Hall of the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau at the Institute of Soil and Water Conservation, Chinese Academy of Science and Ministry of Water Resources in China. A rainfall simulator system with two-side nozzles was used to produce simulated rainfall. This rainfall simulator could be set to any rainfall intensity (30–350 mm h^{-1}), by changing the water pressure and nozzle sizes. Tap water from these nozzles was approximately 16 m above the soil surface in all experiments. The raindrop size and distribution of simulated rainfall with greater than 90% uniformity were similar to those of natural rainfall, which was consistent with Shen et al. (2016).

2.1.2. Soil pan

The soil pan used in this study was modified from the soil pan designed by Meyer and Harmon (1989) and Bradford and Foster (1996), which could separately measure the splash detachment rate and interrill erosion rate on hillslopes. Each experiment soil pan with metal frames was 140 cm long, 120 cm wide and 25 cm deep. The test area was 80 cm long, 60 cm wide and 25 cm deep. The splash detachment collecting area on both sides of the test area was 80 cm long and 3.5 cm wide. A 30 cm-wide border area around the test plot was filled with soil in the same manner as the test area to equalize the opportunity for splash onto and off the area. The slope gradient for the soil pan could be adjusted between 0% and 84% (Fig. 1).

2.2. Study site and test soil

The study site was located in Ansai County (109°19′ E, 36°51′ N), Shaanxi Province, China, which is a typical loessial region with hills and gullies on the Loess Plateau. The mean altitude of the region is approximately 1200 m. The region has a typical semiarid continental climate, with an average annual temperature of 8.8 °C. Its mean annual precipitation is 500 mm, of which 60% or more falls between July and September as high-intensity rainstorms. The soil is classified as a typical loessial soil, representing the most common soil type on the Loess Plateau. It is highly erodible and susceptible to erosive forces.

The test soil was collected from a depth of 0 cm–25 cm at the farming layer of cropland. It consisted of 70.09% sand (diameter: 0.02–2.0 mm), 21.42% silt (diameter: 0.002–0.02 mm) and 8.49% clay (diameter: < 0.002 mm). Thus the test soil was sandy loam based on the soil texture classification system of United States Department of Agriculture. The median grain diameter of the test soil was 0.039 mm. The soil organic matter content of the test soil was 0.3%–0.6%.

2.3. Setup

Soil erosion in the research area of the Loess Plateau was produced by rainstorm. The rainfall intensity for 1 h of rainfall was from 11.9 mm h^{-1} to more than 250 mm h^{-1} (Wang and Jiao, 1996). Thus, two rainfall intensities (48 and 120 mm h^{-1}), which were in the range of rainfall intensity in the Loess Plateau of China, were selected in this study. Accordingly, six slope gradients (12.23%, 17.63%, 26.8%, 36.4%, 40.40% and 46.63%) were designed in our study. Before packing the soil, the water content of the soil was adjusted into 14%, which is the typical level during flood season on the Loess Plateau when