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Effects of precipitation and different distributions of grass strips on runoff and sediment in the loess convex hillslope

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A B S T R A C T

The characteristics of runoff and sediment under different grass strip patterns are important in the study of the mechanisms regulating vegetation in convex hillslope. In this work, using a physical model of a convex hillslope as a carrier, it is analyzed the characteristics of runoff and sediment under five grass strip patterns, as well as regulation mechanism of grass strips on soil erosion through intermittent simulated rainfall experiments. The results show that some grass strip patterns significantly ($p < 0.05$) influenced both runoff and sediment yield in convex hillslope. Under different grass strip patterns, the runoff amount increased slightly, the runoff time gradually stabilized, and the sediment yield decreased sharply with the increase in rainfall episodes. The water storage and sediment reduction functions with the grass strip on the lower part of the upslope were generally clearer than those with grass on the upper part; however, positioning the grass strip closer to the lowermost end of upslope the grass strip did not clearly improve the water storage and sediment reduction functions. Appropriate positioning of the grass strips can effectively adjust the sediment concentration, and thus further reduce the runoff detachment rate, decrease average runoff velocity by 46%, and weaken the input of energy into the downslope as limiting the acceleration area of runoff rely on the appropriate position. The optimal position for grass strips in the convex hillslope was identified as 60% of the upslope length. In this location, the soil and water conservation functions of the grass strip were optimal, with the runoff and sediment reduced by 7.35% and 62.93%, respectively. The water storage function of the grass strip was weak; however, its direct sediment interception function was relatively better. The effect of vegetation patterns on soil erosion was largely through their effects on rill formation and development and density on the convex slope, especially on the downslope. Moreover, the role of vegetation not only changed the rill erosion position, more importantly, transformed the erosion pattern. This study furthers understanding of the regulation mechanism of grass strip patterns on soil erosion.

1. Introduction

Soil erosion is a complex and serious ecological environmental problem worldwide (De Baets et al., 2009; Portenga and Bierman, 2011; Zhou et al., 2016; Xu et al., 2017). In China, particularly in the loess hilly area of the Loess Plateau, soil erosion is serious and vegetation is limited, which makes this area one of the most fragile in the region and the main source area of sediment entering the Yellow River (Li et al., 2009). Many studies have demonstrated that vegetation is an efficient way in water storage and sediment reduction function, and is an effective measure for soil and water conservation (Zhou et al., 2006; Li et al., 2009; Zhou and Shangguan, 2007; Fu et al., 2011; Fu et al., 2012; Zhang et al., 2014; Zhou et al., 2016). However, the limited water resource carrying capacity in the Loess Plateau can only support a certain amount of vegetation, and excessive vegetation may cause soil dryness (e.g., the formation of a dry soil layer) and can negatively influence the soil hydrological status (Zhang et al., 2014; Zhou et al., 2016). Reasonable regulation of vegetation structure can effectively improve soil properties to help reduce and prevent soil and water loss (Fu et al., 2000; Benito et al., 2003; Pan and Shangguan, 2006, 2007). An unsuitable vegetation structure can lead to serious soil erosion (Li et al., 2007). Therefore, optimization of the configuration of limited vegetation in convex hillslope to achieve the most effective soil and water loss regulation is the key to control soil and water loss.

Existing research mostly focuses on the characteristics and regulation of erosion and sediment on the slopes; however, the influence of

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vegetation distribution patterns on erosion and sediment in whole slope-gully systems has been rarely reported (Benito et al., 2003; Pan and Shangguan, 2006, 2007; Li et al., 2009; Zhang et al., 2014). Moreover, although the effects of vegetation spatial distribution and precipitation on soil erosion in the Loess Plateau have been extensively studied, the lack of sufficiently reliable observation data has made it difficult to understand erosion characteristics and the effect of vegetation on soil erosion (Allen and Joan, 2004; Pan and Shangguan, 2006, 2007; Zhang et al., 2014), and the complex interaction among these influencing factors remains unquantified (Seeger, 2007; Nadal-Romero and Regüés, 2009; García-Ruiz et al., 2008, 2010). Even fewer studies have focused on different vegetation distribution regulation mechanisms and differences in soil and water conservation functions (Pan and Shangguan, 2006, 2007; Zhang et al., 2014; García-Ruiz, 2010). Therefore, studies of the regulation mechanisms of the vegetation distribution pattern on erosion and sedimentation characteristics in the convex hillslope of the Loess Plateau have both scientific and practical significance.

The aims of this study were: (i) to clarify the evolution hydraulic characteristics of the hydrological process of runoff and sediment in convex hillslope under different distributions of grass strips, (ii) to determine the optimal grass strip pattern and to evaluate its corresponding water storage and sediment reduction functions, and (iii) to explore grass strip regulation mechanisms and the soil and water conservation functions under different grass strip patterns in convex hillslope.

2. Experimental materials and methods

2.1. Experimental treatments and measurements

Statistical results of the typical convex hillslope geomorphic features in the Loess Plateau show that the upslope gradient is gentle (10–25°), and the downslope gradient in the loess hilly region is 25°–35°. According to the landform characteristics of convex hillslope, indoor experimental design principles, and the specific facility status in the rainfall-flood erosion laboratory, convex hillslope in the loess hilly region were generalized, and the generalized physical model of convex hillslope was established (Fig. 1).

The experiment model of the convex hillslope was constructed from steel tanks with width of 1 m, slope of 12°, and length of 8 m representing the upslope region; and another with gradient of 25° and length of 5 m, representing the downslope region (Fig. 1). The total horizontal projection area was 11.55 m^2. The length ratio of the upslope to the downslope was roughly 1.6:1.0, representing the realistic upslope to downslope ratio in the Loess Plateau (Pan and Shangguan, 2006, 2007; Li et al., 2009).

The study object was the hilly and gully region of the Loess Plateau in northern Shaanxi, with loess soil taken as the experimental soil. The particle size was obtained by a Malvern 2000 type sediment particle size analyzer (Malvern Instruments Ltd., UK). The results showed that the particles with grain size of 0.05–0.1 mm and 0.002–0.05 mm accounted for 6.21% and 91.39% of total, respectively. The soil was thus classified to be silty soil according to the soil classification standard of the United States Department of Agriculture (USDA).

Before the experiment, a 20 cm-thick natural sand layer was laid on the bottom of the steel tank to ensure the water permeability of the experimental soil was close to natural state and soil moisture infiltrated uniformly. To ensure consistency of the initial conditions, we used the tamping method and pre-wetted by spraying with water before the experiment. The soil bulk density was controlled at about 1.3 g/cm^3, and the initial soil moisture content was controlled at about 21%. Table 1 gives the initial physical parameters of the soil. Subsequently, four 5-cm experimental soil layers were laid on top of the sand layer, with a 10-cm space left for grass covering. A 10-cm grass strip was implanted in the corresponding reserved part of the slope. The gaps were filled with soil and then compacted; the grass strip was flush with and jointed closely with the bare slope part to prevent the grass strip from sliding during rainfall. The grass chosen for the experiment was wild Manila grass (Zoysiamatrella), the dimension of grass strip was 2 m × 1 m, and the root system depth was 20 cm. Two weeks before the experiments, the grass was transplanted onto the tank.

In the indoor artificially-simulated rainfall experiment, a self-designed upwards spraying rainfall device was used to generate raindrops. The pore diameters of the spray nozzles were between 1 and 6 mm. The raindrop diameter was measured with filter paper method (Best, 1950), and it reached an average of 1.5 mm and the distribution between 0.4 mm and 3.0 mm. Thus, the simulated rainfall was similar to natural precipitation in raindrop size and distribution. Rainfall from each spray nozzle covered an area of 3–4 m^2 and a total of six spray nozzles were used, among which four were positioned in the upslope and the other two in the downslope. The effective drop height of generated raindrops was 6 m, allowing raindrops to reach the design velocity. Rainfall intensities were precisely controlled through nozzle sizes and water pressure (Zhang et al., 2014). Rainfall intensity was calibrated prior to each rainfall episode to control the quantity and uniformity (Pan and Shangguan, 2006; Zhang et al., 2014). The rainfall intensity was determined with 20 small cone-shaped plastic buckets (15 cm top inner diameter and 15 cm height). They were distributed uniformly and vertically in the plot as five rows, and each bucket was 50 cm away from the sidewall. The rainfall uniformity was calculated from the following equation (Chen et al., 2005; Zhang et al., 2014):

$$K = 1 - \sum_{i=1}^{n} \frac{|P_i - \overline{p}|}{n_b} \overline{p}, \tag{1}$$

where K is rainfall uniformity; P is mean rainfall amount (mm) calculated from all small buckets; P_i is rainfall (mm) in each bucket; and n_b is the total number of buckets. Application of the equation indicated that the simulated rainfall had uniformity of ≥85% and high stability during the experiment.

2.2. Experimental design and methods

On the basis of existing research results and the actual rainstorm intensity in the study region, we used a rainfall intensity of 90 mm/h, corresponding to moderate rainfall on the Loess Plateau (Pan and Shangguan, 2006, 2007; Zhang et al., 2014; Zhou et al., 2016), to study the regulation mechanism of the grass strip patterns on runoff and sediment in convex hillslope. Intermittent rainfall events were artificially simulated; three successive rainfall events were simulated for each grass strip pattern, with the rainfall event interval of 24 h. Two repetitions of the intermittent rainfall experiments were conducted for each grass strip patterns to reduce errors caused by randomness. The statistical test showed that there was no significant difference in average rainfall amounts and sediment yields between the two replicated tests under controlled experimental conditions.

In this study, according to the observation of the experiment, we found serious crusting in the third simulated rainfall event, which can lead to sealing and flattening of surface in soils and thus a significant reduction of surface roughness and a certain increase of surficial density. It in turn resulted in increased runoff depth and intensity, which reduces splash erosion. There are many existing studies describing such process and the consequences (Regües and Torri, 2002; Casermeiro et al., 2004; Vásquez-Méndez et al., 2010). Therefore, the runoff and sediment data from the third rainfall event is eliminated in the calculations from this study. Thus, we used only the experimental data from the first two simulated rainfall events. All experiments were recorded from runoff generation time, and the runoff duration was defined as 30 min, as runoff had reached a stable state after 30 min according to the actual controlled experimental conditions. The runoff and sediment in the storage bucket were collected every minute and the runoff

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