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Runoff and erosion processes on bare slopes in the Karst Rocky Desertification Area

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ABSTRACT

Underground pore fissure and bedrock bareness are the main factors that lead to complicated mechanisms of soil erosion in karst regions. The objectives of this study were as follows: a) to measure runoff and sediment generated from the surface and underground in the karst bare slope; and b) to analyse the impacts of underground pore fissures and bedrock bareness rates on soil erosion. To achieve these objectives, we designed an experiment in which underground pore fissure degrees and bedrock bareness rates were varied, and their impacts on soil erosion were measured. The results showed that i) runoff and sediment yields from the surface and underground increased with increasing rainfall intensity, and the surface runoff was much more easily generated when the rainfall intensity was greater; ii) surface runoff yield first increased and then decreased with increasing bedrock bareness rates, while the runoff yield in underground pore fissures increased with increasing bedrock bareness rates; thus, sediment production on the surface and in underground pore fissures showed the same pattern, i.e., first decreased and then increased; iii) the surface runoff and sediment generally decreased with increasing degrees of underground pore fissures, while that of underground pore fissures presented a different pattern; and iv) rainfall intensity, bedrock bareness rates and underground pore fissure degrees were the important factors affecting soil erosion processes in karst bare slopes because the bedrock bareness rates and underground pore fissure degrees were the main factors causing the uneven distribution of runoff and sediment on soil surfaces and underground. Therefore, soil and water loss in underground pore fissures was the special pattern and main difference in soil erosion processes in the karst region compared with other regions. These results have theoretical and practical significance for understanding soil erosion mechanisms and controlling soil and water loss in karst regions.

1. Introduction

Soil erosion has become a severe environmental and social issue throughout the world (Higgitt, 1991; Oldeman, 1994). Karst landscapes represent an important facet of the earth's geodiversity, and their area reaches approximately 22 million square kilometres. The area of karst landscapes accounts for 12% of the total land area in the world, mainly distributed in the world's three carbonate rocks: the area from the Alps on the coast of the Mediterranean to the Central Plateau of France and to the Ural Mountains of Russia; the southwest karst mountains of China and Northern Vietnam; and finally, the karst mountainous areas in Indiana and Kentucky of the middle eastern United States, Kentucky, Cuba, Jamaica and the south of Australia (Liu, 2009). The Karst Region of Southwest China, centred in Guizhou Province, is the greatest one among the three distribution regions, located at the range of N 22°00´ ~ 30°04´ and E 100°34´ ~ 114°10´ with an area of 0.54 million square kilometres, in which carbonate bare areas in Guizhou, Yunnan, Hunan and Guangxi provinces reached 0.37 million square kilometres, accounting for 36% of the total area in this region (Li et al., 2002).

Long-term karstification forms the surface and underground double layer space structure in the karst region, in which the surface is rugged complex terrain and the underground is a large underground river system (Cao and Yuan, 2005). Under the interaction of natural factors (rainfall and geological geomorphology) and human activities, the surface presents a rocky desertification landscape with a shallow soil layer, discontinuous regolith and even large areas of bare rock (Chen et al., 2011), in which bedrock bareness is the most obvious indication of karst rocky desertification. Moreover, the underground is characterised by sinkholes, sinking streams, closed depressions, subterranean drainage, caves and fissures. Much water and soil could enter the underground rivers along with the fissures and ponors (Williams, 1987; Peng and Wang, 2012; Dai et al., 2015). Related studies indicate that

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soil loss is the main factor causing karst rocky desertification, considered one of the most serious ecological, geological and environmental problems in Southwest China (Wang, 2003). The soil erosion process in the karst region is very complex because the soil is not only washed away by surface runoff but also eroded underground via pore fissures, funnels and holes (Zhang et al., 2011; Chen et al., 2012; Peng et al., 2016).

Currently, many studies on karst mainly focus on geomorphological processes (Ford and Williams, 1989), hydrologic processes (Bögli, 1980), ecosystem vulnerability (Ehrefld, 2000) and ecological reconstruction (Kobza and Jim, 2004; Costanza et al., 1997). Moreover, studies on soil erosion in the karst region mainly focus on surface erosion (Li et al., 2011; Chen et al., 2011; Peng and Wang, 2012; Yang et al., 2011; Feng et al., 2016; Huang et al., 2016). Karst in Southwest China has always been a concern of domestic and foreign scholars. For example, Dr. Marjorie M. Sweeting, an internationally famous karst geomorphology scientist, has visited Guizhou five times to observe and study karst landforms and analyse the formation of Guizhou's conical karst (Sweeting, 1992; Sweeting, 1993). However, because of the great difficulty of monitoring underground leakage of soil and water directly, little attention has been paid to the soil erosion process and its quantitative analysis in this region. Zhang et al. (2011) posited that soil loss on karst slopes included ground and underground soil losses, and the latter may be the predominant factor leading to soil loss and rocky desertification. Zhou et al. (2012) built a conceptual creep model, revealing a detailed inference of the creep mechanism in the underground soil loss and suggesting that underground leakage was the main mode of soil loss. However, others argue that underground soil loss develops slowly and can be prevented by controlling soil collapse (Wang et al., 2014), and they proposed the erosion-creep-collapse mechanism of underground soil loss. In addition, the isotope ^{137}Cs tracing method was applied to describe the soil leakage phenomena qualitatively and quantitatively in karst regions and indicated that the soil leakage phenomena varied depending on the processes acting at the small, medium, and large spatial scales (Wei et al., 2016). In short, the important physical processes of soil erosion on karst slopes are still unclear but represent a significant cause of rocky desertification under natural forces, especially concerning soil erosion processes under the surface and underground double layer space structure in the karst region.

As one of the key ecological zones in China, the complex erosion mechanisms and serious soil and water losses in the fragile karst mountainous areas in Southwest China restrict its ecological restoration and reconstruction. Therefore, taking the 25° bare slope in the karst region as an example, this study represents an initial effort to study the soil erosion processes by artificial rainfall simulation tests based on simulating the double layer space structure with surface micro topography and underground pore fissures. Hence, this study specifically aims to analyse and reveal the runoff and sediment yield characteristics on the surface and underground of karst bare slopes under different rainfall intensities, bedrock bareness rates and underground pore fissure degree conditions and to further explore the influencing factors. These results from the present study have important theoretical and practical significance to reveal soil erosion mechanisms, control soil and water loss and promote healthy and sustainable development in the karst region.

2. Materials and methods

2.1. Experimental materials

Experimental soil was collected from a typical karst region (26°28′32″N, 106°42′02″E), located in Huaxi district, Guizhou province in China (Fig. 1). The experimental soil is a calcareous clay loam developed from carbonate rocks, and the soil particle compositions are shown in Table 1. Based on several field investigations, karst bare slopes were simulated in the laboratory according to natural conditions. First, carbonate rocks with a size of ≥35 cm were collected and randomly arranged in a steel tank with a length of 4.0 m and a width of 1.5 m (Dai et al., 2011); meanwhile, soil was homogenously backfilled in the space of rocks layer-by-layer according to field measured soil compaction until the bed rock bareness rate reached the designed levels. The soil surface was then levelled with a special board, and the boundary was compacted by hand to reduce edge effects. After soil preparation, the underground pore fissure degrees were adjusted by changing the contact area of holes between the movable tank floor and fixed tank floor to the designed level before the beginning of every experiment.

2.2. Experimental designs

Bedrock bareness rates, underground pore fissure degrees, soil thickness and soil layer characteristics and rainfall intensity were considered as simulation factors in this study based on field surveys and literature analysis. The experimental slope is 25°. Bare bedrock on the slope was simulated by limestone rocks with a diameter of >35 cm randomly arranged in the steel test tank. The bedrock bareness rate is the ratio of bare bedrock to horizontal projected area of slope, including 10%, 20%, 30%, 40% and 50%, amounting to 9, 18, 27, 36 and 44 pieces of limestone, respectively (Peng et al., 2016). Because of the complicated transporting process of runoff and sediment in pore fissures under the soil layer, drainage holes at the bottom of the tank were used to simulate pore fissures under the soil layer in order to analyse the amount of runoff and sediment that can enter into underground pore fissures during the soil erosion process. The underground pore fissure degree is the ratio of underground pore fissures to floor area of steel tank, including 1%, 2%, 3%, 4% and 5%. The total depth of the soil layer was 30 cm, and the soil layer was divided into 3 sub-layers, from the lower to upper parts. Soil compactness was 1070, 760 and 410 kPa for the lower sub-layer, median sub-layer and upper sub-layer, respectively. Based on erosive rainfall (approximately 15 mm) in the karst area of Guizhou province, the rainfall intensities were 0.5, 0.8, 1.3, 2.0, 2.5 and 3.0 mm/min; the rainfall duration was 90 min for every rainfall event. After a rainfall event finished, surface soil with a thickness of 10 cm was replaced with fresh soil in order to conduct the next rainfall event. Each rainfall test was repeated three times.

2.3. Rainfall simulation

Rainfall simulation experiments were conducted at a rainfall laboratory in Guizhou University, Guiyang. The rainfall simulator (Model: QYJY-502) is a portable fully automatic simulator with four stainless steel down-sprayers made by Xi'an Qingyuan Measurement and Control Technology Co., Ltd. The rainfall simulator is similar to that described by Cerdà (1998); the final raindrop velocity matched the natural rainfall characteristics; the height of the sprayer was 6 m; the rain intensity could be controlled remotely or adjusted manually and ranged from 10 to 200 mm/h; adjustment time was <30 s and adjustment precision was 7 mm/h; the effective rainfall area was 6.5 m × 6.5 m; and the raindrop distribution uniformity was >85%. The length, width and depth of the steel tank was 4 m, 1.5 m and 0.35 m, respectively (Fig. 2). The slope could be adjusted from 0 to 45°. At the bottom of tank, drainage holes with a diameter of 5 cm were uniformly formed for free-drainage of infiltrating water, which became underground pore fissure runoff. Meanwhile, smaller holes at the bottom edge of the tank were also formed for free-drainage of interface runoff, which did not become underground fissure runoff. The porosity of drainage holes at the bottom of tank could be adjusted from 0 to 6% to simulate varied pore fissure degrees of underground bedrock. Surface runoff and underground runoff were collected at the lower end of the steel tank.