Original Research

Core Ideas

- Runoff simulation was conducted on different sides of rock outcrops.
- Rock outcrops shaped the water flow paths differently on their three sides.
- Outcrop runoff will contribute greatly to soil loss, rock dissolution, and biodiversity.

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Infiltration Patterns and Ecological Function of Outcrop Runoff in Epikarst Areas of Southern China

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Rock outcrops (ROCs), a widespread surface component in a karst landscape, play a unique, hydrological role in the infiltration and redistribution of precipitation. This experiment aimed to explore water pathways of outcrop runoff and their ecological functions in epikarst by applying the dye tracer Brilliant Blue FCF on three sides of rocks—the uphill sides, the downhill sides, and the lateral sides—to simulate the outcrop runoff under a rainfall intensity of 100 mm h⁻¹, combined with a soil loss survey and soil property measurements. Our results showed that the outcrop runoff infiltration in three directions (i.e., lateral flow into the soil, vertical flow, and lateral spread at the soil-rock interface) differed greatly on the three sides of the ROCs. Deep but narrow vertical flow was the most common infiltration pattern on the uphill sides; long but shallow lateral flow toward downslope dominated outcrop runoff movement on the lateral sides. However, on the downhill sides, the vertical flow at the soil-rock interface was quantitatively equal to the lateral flow to soil. The difference in outcrop runoff infiltration at the three sides of ROCs may help to reveal the mechanisms of soil erosion as well as rock dissolution and biodiversity in a karst environment.

Abbreviations: ROC, rock outcrop; SWC, soil water content; WL, laterally distributed water; WV, vertically distributed water.

Soil water infiltration is an important part of the terrestrial hydrological cycle by which surface water and groundwater are connected in the process of water transport (Bouwer, 1986; Hillel, 1998, p. 385–426). This infiltration is greatly affected by the soil surface components (Lv and Wu, 2008) and is frequently considered an important index of the risk of soil erosion (Pan and Bergsma, 1995). Karst landscapes, where rock outcrops (ROCs) are frequent geologic features, occupy 12 to 15% of the global land surface (Ford and Williams, 2007; Palmer, 1991). However, only a few quantitative experiments have been conducted to evaluate the effect of ROCs on water infiltration and soil loss in a karst environment (Li et al., 2014; Sohrt et al., 2014; Wang et al., 2016a).

Soil crust can directly affect water infiltration by blocking the soil water channel, increasing surface sealing, and then increasing runoff susceptibility sharply (Morin et al., 1989). Preferential flow paths generated by soil swelling and shrinking processes (Alakukku et al., 2010) or by soil fauna such as ants or earthworms (Mitchell et al., 1995) have been found helpful to increase a soil's effective porosity and have shown significant positive correlations with the infiltration rate of the topsoil. Besides, non-soil components, such as litter and well-developed roots, could reduce the soil density to increase the soil's hydraulic conductivity (Scanlan, 2009; Jia, 1990). Rock fragments could lead to significant variations in the topsoil's physical properties, even to some extent modifying underground water recharge and runoff generation (Brakensiek and Rawls, 1994).

However, these factors are small in size and lie on the soil's surface or are embedded in the earth. Rock outcrops in epikarst usually have large bulk, often stretching from the ground surface to the bedrock, and possess characteristics that differ from a nonlimestone area (Yuan, 1997). Rock outcrops are usually surrounded by visible voids at the soil–rock interface (Laine-Kaulio et al., 2015), which could avoid soil surface sealing, increase the saturated hydraulic conductivity, and are expected to strongly promote the process of rainfall infiltration in the vadose zone (Wilcox et al., 1988). Wang et al. (2016a) found that ROCs can receive a great quantity of rainwater and redistribute about half of this water into the soil. The outcrop runoff quickly percolates into the fractured bedrock via narrow preferential flow paths at the soil-rock interface (Sohrt et al., 2014); however, meanwhile, due to the strong funnel effect of ROCs, the generated runoff may exceed the conductivity of the near soil and laterally spread into a larger area (Lange et al., 2003). Therefore, a series of questions should be raised: How much water from outcrop runoff will spread into the soil? How much water percolates into the bedrock and how is the amount related to the direction of infiltration, i.e., the orientation of the soil-rock interface? Outcrop runoff is one of the promising research issues in the realm of rocky desertification control and vegetation restoration (Bai et al., 2013), while the effect of ROCs on water infiltration has not yet been well explored.

Complex water movement related to infiltration events is rather difficult to measure in the field (Allaire et al., 2009). Dyes are commonly used to trace the flow paths of water (Schwärzel et al., 2012), and Brilliant Blue FCF has proved to be one of the most practical tracers for this task (Flury and Flühler, 1994). Dye tracer application followed by soil water content (SWC) measurement can provide a clear pathway of water flow in the soil and serve as a method of quantifying water distribution (Alaoui and Goetz, 2008). In this study, we applied dye tracers at the uphill sides, downhill sides, and lateral sides of the ROCs on a plot of sloping farmland. We combined this with subsequent excavation of the dye-stained soil profile and measurement of soil properties. Our objectives were (i) to trace the flow paths of the outcrop runoff, (ii) to evaluate the effects of the ROCs on water infiltration at different orientations, and (iii) to discover the connection between outcrop runoff and soil erosion.

Materials and Methods Study Site

The study was performed in Mengzi County, Yunnan Province, southwestern China (Fig. 1a). Mengzi County has a total land area of 2228 km², and the proportion of land under intense rocky desertification is about 44.65% (Li et al., 2017). It is located at the edge of the Yunnan–Guizhou Plateau, and the topography is dominated by mountains and basins (Fig. 1b). This area has a subtropical monsoon climate with clear wet and dry seasons. Droughts and water shortages are prominent during the winter and spring. Heavy rainfalls and rainstorms become more frequent in the rainy season, which is from May to October.

The experimental plot selected comprised sloping farmland in a small township (23°47′46″ N, 103°48′2″ E), with an elevation of approximately 2010 m asl, which represents the typical conditions of farmland in this area. The rainfall averages approximately 800 mm yr⁻¹, and >70% of rainfall is concentrated in the period from July to September. The mean annual temperature is 13.6°C, and the annual evaporation is 1478 mm. Bare rocks cover most parts of the area, and we randomly selected some rocks for in-site dye tracer application. The ROCs were about 100 cm in height and had the shape of a cone or a pyramid with a gradient of 70%. Due to the mosaic structure of ROCs and soil patches, the geology of the selected area is quite complex. The mean gradients of the farmland and the rock surface were 10 and 70%, respectively. The dominant soil type is typic black lithomorphic isohumosol (Gong et al., 2007), and the shallow soil layers starting from the top are an eluvial horizon (A horizon), transition horizon (A/B horizon), illuvial horizon (B horizon), and parent material (C horizon). The major field crops are apple trees planted several years ago, and herbicides have been frequently applied to control weeds. The experimental plot had not been plowed for many years, thus, prior to the experiment, the topsoil structure and surrounding rocks had seldom been destroyed by agricultural cultivation. The experiment was performed in June, when rainfall had continued for a few days and soil cracks were not found in the field. The soil's physical properties in the sloping farmland are shown in Table 1.

Measurements

Soil Loss

As the result of soil loss, the soil–rock interface will be gradually exposed, and a clear boundary will emerge between the new and previously exposed soil–rock interface (Fig. 2c). The width of the newly exposed soil–rock surface could be used as an indicator to calculate the thickness of soil loss, similar to the steel rod method (Mutchler et al., 1988). Before the dyeing experiment, the herbs and litter surrounding outcrops were carefully cut off along



Fig. 1. (a) Location of the study site in Mengzi County, Yunnan Province, southwestern China, and (b) a view of the sloping farmland near a karst basin showing that the land's surface is characterized by exposed rocks and low plant coverage.

Table 1. Soil properties on three sides of rock outcrops. Due to the limited infiltration depth of the dye tracer, the depth of the B-horizon soil was ignored.

Soil horizon	Soil depth	Rock slope	Soil slope	Soil bulk density	Soil porosity	Soil water content
501110112011	Johr depth	Rock slope	5011 stope	2	Johr porosity	Son water content
	cm	°		g cm ⁻⁵	%	-
<u>Uphill sides</u>						
А	$16.5\pm5.3^{\dagger}$	73.6 ± 4.5	3.3 ± 1.7	1.14 ± 0.05	56.87 ± 1.87	22.73 ± 3.99
В	-	-	-	1.46 ± 0.03	44.87 ± 1.14	30.30 ± 4.58
<u>Downhill sides</u>						
А	5.7 ± 2.5	73.0 ± 4.1	4.6 ± 1.7	1.15 ± 0.07	56.64 ± 2.70	26.68 ± 6.51
В	-	-	-	1.44 ± 0.04	45.48 ± 1.63	33.95 ± 4.54
<u>Lateral sides</u>						
А	9.7 ± 3.8	69.1 ± 6.2	21.1 ± 3.9	1.15 ± 0.03	56.67 ± 0.97	24.32 ± 5.81
В	-	-	-	1.44 ± 0.05	45.83 ± 1.90	32.32 ± 3.61
† Mean ± standard deviation.						

the rocks, and 18 rocks were randomly selected to measure the gradient of the rock surface and nearby soil surface, as well as the height difference at the uphill, downhill, and lateral sides of the ROCs. We measured six replications on the same side of a rock, and each measurement was 5 cm apart (Fig. 2c). We then calculated the soil loss thickness as

$$b_{\rm U} = \sin\left(i_{\rm U}^{\rm rock} + i_{\rm U}^{\rm soil}\right) d_{\rm U}$$
^[1]

$$b_{\rm D} = \sin\left(i_{\rm D}^{\rm rock} - i_{\rm D}^{\rm soil}\right) d_{\rm D}$$
^[2]

$$b_{\rm L} = \sin\left(i_{\rm L}^{\rm rock}\right) d_{\rm L} \tag{3}$$

where $h_{\rm U}$, $h_{\rm D}$, and $h_{\rm L}$ are the soil thickness (cm), $d_{\rm U}$, $d_{\rm D}$, and $d_{\rm L}$ are the width of the newly exposed soil–rock surface (cm), and $i_{\rm U}^{\rm rock}$, $i_{\rm D}^{\rm rock}$, and $i_{\rm L}^{\rm rock}$ are the gradient of the rock surface (%)



Fig. 2. Measurements of soil loss conducted at (a) the uphill sides, the downhill sides, and (b) the lateral sides of each rock outcrop, and (c) the width of the newly exposed rock surface, which was determined by the average of six measurements, each 5 cm apart. According to the angles shown in (a) and (b), it can been proved that $A = a_1 + a_2$ and $B = b_1 - b_2$, where a_1 and b_1 are the rock gradients and a_2 and b_2 are soil surface slopes.

at the uphill, downhill, and lateral sides of the ROCs, respectively, while $i_{\rm U}^{\rm soil}$ and $i_{\rm D}^{\rm soil}$ are the gradient of the soil surface (%) at the uphill and downhill sides of the ROCs, respectively. These equation calculations of soil loss thickness are illustrated by Fig. 2.

Runoff Water Simulation and Dye Tracer Application

Brilliant Blue FCF at 10 g L^{-1} as recommended for a karst soil dye tracer (Zhao et al., 2017) was applied, which was higher than the normal use of 3 to 5 g L^{-1} (Flury and Flühler, 1994), to ensure good visibility in the soils and to compensate for absorption by the rocks and soils. Brilliant Blue FCF (250 mL) was applied on the rock surface by a 15-cm perforated sprinkler line during a period of 5 min. The experimental design included three treatments with 10 replications, i.e., the dye tracer applications were conducted at three positions successively (uphill sides, downhill sides, and lateral sides) of each of the 10 selected ROCs. The spraying device was mounted to a metal stand, and the perforated sprinkler line was fixed close to the ground (Fig. 3). The rainwater-collecting area above the 15-cm-long perforated sprinkler line was approximately 300 cm^2 [(15 cm × 100 cm)/(2 tan 70°)], and the outcrop runoff was simulated under a rainfall intensity of 100 mm h⁻¹. The highmagnitude rainfall event was designed for the purpose of creating a great variety of infiltrating paths.

Soil Excavation and Picture Shooting

Immediately after the application of the dye tracer, a picture was taken of the dye-stained area on the soil surface. Next, a trench perpendicular to the rock was excavated 10 cm outside the dye zone to measure the SWC using a Theta Probe–ML2 (Delta-T Devices) and bulk density using metal rings, which represent the pre-experiment soil conditions unaffected by the dyeing experiment. The measurements were made horizontally and vertically at 5-cm increments (Fig. 3c). In addition, the average soil porosity of the soil–rock interface and soil matrix was calculated (10 cm away from the rock) to analyze the spatial variability of the soil texture.

Next, a vertical soil profile was prepared through the center of the dye infiltration zone. A high-resolution photograph of the soil profile, with a calibrated scale and number tag placed aside, was taken to measure the characteristics of the stain pattern. The SWC of the dye-stained areas in the soil profile were also measured at horizontal and vertical 5-cm increments (Fig. 3c and 4b), which were then compared with the soil unaffected by dye tracer to quantify the distribution of outcrop runoff.

Finally, all the stained soil was removed, and photos were taken to record the dye-stained zone on the rock surface. Because of the destructive excavation of the dye tracer experiment, study of the flow paths cannot be repeated at the same location.

Photograph Processing

All photographs were rectified by lens correction to eliminate distortion and ensure that the images of the dye-stained sections were vertical and perpendicular to the horizon. Then, the photographs were processed with the color replaced and were converted into a black-and-white binary pattern. The photographs were clipped and the resolution set to 1 pixel mm⁻¹, which allowed calculation of the dye-stained area with millimeter precision (Fig. 4c). The image processing was performed in Adobe Photoshop CS 6.0.

The dye-stained area of the soil profile was divided into two branches: the vertical flow at the soil–rock interface and the lateral flow into the soil patch (Fig. 4c). Diagonal division was adopted for the overlap area of the vertical and lateral flow. Then the depth, length, and dye-stained area of the vertical and lateral flows were measured. A three-dimensional reference system was used as a tool to facilitate the later description and comparison of all the



Fig. 3. Device and design of the dye tracer application: (a) 250 mL of dye tracer solution in the water bag was applied via a 15-cm-long perforated sprinkler line with the spraying device hung on a metal stand, and the intensity of spraying was controlled by a flow regulator; (b) locations of the sprinkling experiments, where dye applications were successively conducted at the uphill, downhill, and lateral sides of the rocks, and (c) a three-dimensional reference system was used to describe the infiltration direction of the dye tracer, where the *x* axis horizontally orients to the soil, the *y* axis vertically points to the bedrock, and the *z* axis is laterally tangent to the rock surface. The properties of unaffected soil were measured 10 cm away from the dye-stained zone.





one-dimensional parameters (i.e., length, width, and depth), but it must be noted that all these parameters should be converted to projected lengths at the coordinate axis. The dye-stained area on the rock surface was divided into left and right parts by the y axis, and the width of each part was measured separately to analyze the symmetry of outcrop runoff infiltration.

Finally, the black-and-white binary pattern was interpreted into a (0,1) digital matrix with Matlab 7.0, where 1 represents the black, colored area and 0 represents the white, uncolored area. The total number of elements classified as 1 was calculated with Excel 2010 to determine the dye-stained area of each part.

Water Distribution

The water distribution of the outcrop runoff was also divided into two branches: water vertically distributed at the soil–rock interface (WV) and water laterally distributed into the soil (WL). We used the ratio WV/WL to compare the infiltration characteristics of outcrop runoff on different sides of the ROCs, where larger values of this ratio correspond to greater vertical (preferential) flow relative to the total outcrop runoff. The individual water distribution was quantified by the volume of each branch and each corresponding increment of SWC coming from the dye application.

Results Soil Properties and Soil Loss

There is a significant difference in the depth of the A horizon on the three sides of the ROCs (Table 1). The A horizon at the uphill sides of the ROCs is much deeper than that of the lateral and downhill sides. Because the dye tracer had not penetrated across the B horizon, the thickness of this soil layer was not measured. At the time of the study, cracks were almost nonexistent in the B horizon. The mean gradient of the soil surface at the lateral sides of the ROCs was 21.1%, which is much greater than the uphill (3.3%) and the downhill (4.6%) sides. The soil porosity at the soil–rock interface was found to be significantly higher than that of the soil matrix (paired-samples *t*-test, p > 0.05), but the soil porosity at the soil–rock interface on the three sides of the ROCs was not significantly different from each other.

The mean soil loss at the downhill sides (8.59 cm) of the rocks was significantly greater than at the uphill sides (5.87 cm) and the lateral sides (6.64 cm) (Fig. 5). The maximum thickness of soil loss was found at the downhill sides (10.5 cm), and the minimum was at the uphill sides (4.0 cm). Thus, the downhill sides of the rocks were determined to represent the most severe area of soil loss.

Vertical Flow along the Soil–Rock Interface

The flow paths revealed by the dye tracer indicate that outcrop runoff vertically and preferentially flowed along the soil–rock interface. However, infiltration depths measured along the individual directions, as shown in Fig. 6, indicate that the depth of vertical flow (on the *y* axis) was significantly different on the three sides of the ROCs. Results show that the deepest penetration for vertical flow was at the uphill sides of the ROCs, with an average of 41.4 cm, followed by the downhill sides at an average of 30.2 cm. The shallowest depth was observed at the lateral sides of the ROCs: a mere 24.4 cm. Similarly, regarding the aspect of water distribution, the vertical flow at the uphill sides (68.00%)



Fig. 5. Soil loss thickness at the uphill, lateral, and downhill sides of the rock outcrops. *Significant at p < 0.05; **significant at p < 0.01.





was also significantly larger than at the downhill sides (47.74%) and the lateral sides (20.48%) (Fig. 7a). Consequently, both the dye-stained pattern and the water distribution indicate that vertical flow at the soil–rock interface plays a dominant role at the uphill sides of the ROCs.

From the dye-stained area on the rock surfaces, we found that the width of vertical flow at the z axis surpassed 15 cm (the width of the perforated sprinkler line), which means that the vertical flow could also gradually spread outside its original boundary to invade a large area. At the uphill sides and the downhill sides, the dye-stained area on the rock surface was almost bilaterally symmetrical. By paired *t*-test (p < 0.05), no significant difference was found in the width of the dye-stained area at the two sides of the *y* axis. However, at the lateral sides, the width of the dye-stained zone on the upper side was significantly smaller than on the lower side. This reveals that the vertical flow at the lateral sides of the rocks had greatly inclined toward the downslope. Finally, on the uphill sides of the ROCs, some fissures or holes on the rock surface were discovered, and a small quantity of dye tracer was found to have leaked out through the fracture structure (Fig. 8a and 8b).

Lateral Flow into Soil Patches

The lateral flow was significantly different on the three sides of the ROCs. The mean length of lateral flow along the *x* axis was smaller on the uphill sides (10.2 cm) than the downhill sides (14.9 cm) and the lateral sides (14.6 cm), but there was no significant difference between the latter two sides. One thing worthy of note is that the lateral flow on the lateral sides was not significant on the *x*- axis but particularly long on the *z* axis downslope, which reached as much as 46 cm long. Correlational analysis revealed that the length of downslope flow is related to the slope gradient (p < 0.05, r = 0.695).

Water distribution shows that lateral flow on the uphill sides amounted to only about 27.15% of the applied dye tracer solution



Fig. 7. Water distribution of (a) water vertically distributed at the soil-rock interface (WV) and (b) water laterally distributed within the soil (WL). *Significant at p < 0.05; **significant at p < 0.01.

(Fig. 7b). on the downhill and lateral sides, the distribution of the lateral flow was 45.73 and 66.13%, respectively. Thus, the corresponding WV/WL ratios are, in decreasing order, 2.50 on the uphill sides, 1.04 on the downhill sides, and finally 0.31 on the lateral sides.

The dye-stained soil profile shows that the dye distributed on the topsoil can also vertically penetrate into the soil through preferential flow, but the infiltration depth is merely restricted to the thin upper part of the B horizon (Fig. 8c). The B horizon, with low porosity, can hinder the infiltration of outcrop runoff, so the dye-stained width of vertical flow decreased sharply with the soil depth (Fig. 4). Additionally, on the downhill sides, a portion of water was found to laterally branch off from the soil–rock interface and shunt into the A/B horizon (Fig. 8d).

Discussion

Rock outcrops, part of a karst landscape, can intercept or collect a great quantity of water during rainfall and release the water to nearby soil patches via outcrop runoff. Our results showed that outcrop runoff penetrates deep along the soil–rock interface and expands laterally along the rock surface and into the surrounding soils in various proportions on the three sides of the ROCs (i.e., the uphill sides, the downhill sides, and the lateral sides).

At the uphill sides of the ROCs, deep but narrow vertical flow was the most common infiltration pattern of outcrop runoff. Most of the applied water ended up emptying into the ground along the soil–rock interface, and only a small part was distributed into the nearby soil patches. On the contrary, long but shallow lateral flow along the rock surface dominated the outcrop runoff movement on the lateral sides, and most of the applied water was distributed to the topsoil. However, on the downhill sides of the ROCs, the vertical flow at the soil–rock interface was quantitatively equal to the lateral flow into the soil (i.e., the ratio of WV/WL was close to unity). Various factors may contribute to this difference. First, ROCs are considered to have a blocking function to water and soil erosion (Yang, 1990), which ensured that the A horizon on the uphill sides was much thicker than on the lateral sides and especially the downhill sides. The porous A horizon can provide a more unobstructed pathway for the vertical flow of outcrop runoff. Thicker A horizons promote deeper infiltration of vertical flow, which explains why the infiltration on the uphill sides was much deeper than on the other two sides of the rocks. The slope is always the main topographic factor causing great surface runoff (Meyer, 1984) and is obviously the reason for the outstanding lateral flow on the lateral sides of the ROCs. Similarly, the upsloping angle made it difficult for the outcrop runoff to flow laterally on the uphill sides of the ROCs. Although no special infiltration features were found on



Fig. 8. Particular flow paths of dye infiltration: (a) flow through ground fissures, (b) flow through holes on the rock surface, (c) preferential flow of dye on the soil surface, and (d) interflow along the A/B horizon.

the downhill sides, the flow pattern there was also formed by the coupling of slope and soil porosity.

On the uphill sides of the ROCs selected, soil sinkage occurred, although long-distance surface runoff was not clearly present there. An idea of "soil loss" has been posed by researchers to explain the phenomenon of soil disappearing without direct scouring by rain (Li et al., 2001). Rock outcrops differ from general non-soil components like rock fragments; they are large and especially can locally podzolize soil at the soil-rock interface through preferential flow (Backnäs et al., 2012; Bogner et al., 2012). Sohrt et al. (2014) found that the soil samples near ROCs have a larger particle size and higher organic C content than the soil matrix. In our study, the ROCs were also found capable of increasing the soil porosity. In karst hard clay, the high hydraulic conductivity of the soil-rock interface was the key factor to trigger deep water infiltration during rainstorm events (Sohrt et al., 2014), which may impact soil erosion. On the one hand, the rapid vertical penetration can, to some extent, reduce scouring of the soil surface by surface runoff, resulting in the reduction of soil erosion. On the other hand, it can also increase the risk of underground leakage of soil and water. Based on the infiltration pattern of outcrop runoff on different sides of the ROCs, we speculate that the deep leakage may act as the main style of soil and water loss on the uphill sides, and the strength, due to the blockage to surface runoff, may probably surpass even that on the lateral and downhill sides.

Soil loss in karstified regions is always the result of combined surface runoff and underground leakage. The current study focused mainly not only on the general trends of soil loss but also on a quantitative description. Analyzing the details of outcrop runoff may help to dissect the soil loss process in karstified regions. In our experimental plot, the downhill sides of ROCs turned out to be the worst-hit areas in terms of soil loss, which differed from the conclusion of Yang (1990), who determined that it is the lateral sides that will lose the most soil due to fluvial erosion. However, based on the water flow movement, we deduced that the relatively upper outcrop runoff (especially on the two lateral sides of ROCs) could unite at the downhill sides. The intensified outcrop runoff, we inferred, is expected to strengthen the scouring of topsoil and accelerate the soil loss. Besides, the interflow along the A/B horizon probably played a part in soil erosion on the downhill sides of the ROCs. Schwärzel et al. (2012) found that, due to the resistance of the compacted clay-enriched B horizon, vertical stem flow had been guided downslope. An in situ dye tracer application experiment at a hillslope showed that the lateral interflow above the B horizon was an essential component of runoff generation as well as a regulation of the response of the hillslope to high-magnitude rainfall events (Laine-Kaulio et al., 2015). In the dry season, the clay-rich subsoil was usually full of large cracks caused by soil shrinkage (Hendrickx and Flury, 2001). However, because our study took place after a short, rainy couple of days, soil cracks were not observed in the B horizon. Therefore, at the downslope sides where the A horizon was the thinnest, the

B horizon was able to serve as a restricting layer to hinder deep infiltration of outcrop runoff. Ultimately, the interflow at the A/B horizon triggered shear failure and made the topsoil there vulnerable to being flushed away.

Rock outcrops are generally viewed as having negative ecological functions because the weathered rock-soil dual entity with low water storage made plants suffer from severe water scarcity (Wang et al., 2016a, 2016b). However, in seriously rocky desertification areas, there frequently appeared a special landscape of "root bouldering" or "tree bouldering" (rocks were tightly surrounded by trees or a root system). Plants tend to expand their roots at the soil-rock interface in shallow karst soils to compete for the cracks or fissures surrounding rocks (Poot and Lambers, 2008). Stable isotope techniques proved that plants could capture the fissure water and use it as the main, or even the only, water source in the dry season (Deng et al., 2012; Rose et al., 2003). It stands to reason that ROCs are a highly important area in the niche competition of plant life and thus change the spatial patterns of natural plant communities. On the other hand, the fissures and holes appearing on rock surfaces on the uphill sides embody the significance of the high-rate outcrop runoff in the dissolution of carbonate rocks. Water erosion is the major driving force that causes dissolving spatial differences in rocks of uniform lithology (Williams, 1983). The strong, deep leakage of water at the uphill sides of ROCs was able to intensify the dissolution toward the insides of the rocks. Once the ROCs were punched like a sieve, soil crept into the cave-fissure systems, and the generated pipe erosion weakened the soil water's spatial heterogeneity formed by the blockage of the ROCs. Besides, because our experimental premise was that all the applied dye solution would be distributed in a discoverable area, the dye tracer that escaped from the fissures or holes (Fig. 4a) may affect the resulting accuracy of the outcrop runoff distribution.

Considering the complex flow pattern of outcrop runoff, ROCs must play a unique role in the redistribution of water and nutrients. Göransson et al. (2014) defined the redistribution function of ROCs to precipitation as "the funnel effect," and they found that ROCs had created N hotspots and N/P heterogeneity. Wang et al. (2016b) proved that ROCs can greatly increase the organic C and nutrient content in nearby soil patches. The different distribution patterns of outcrop runoff are expected to affect the water utilization strategy of plants and contribute to biodiversity. In our study, the half-closed funnel effect varied greatly on the different sides of the ROCs, so there may be a relatively suitable location for plants to choose as a shelter in a stressful karst environment. Certainly, the choice was made after a trade-off of water, nutrients, sunlight, and other factors.

The primary goal of this outcrop runoff study was to discover its dynamic change under different space-time conditions. Although dye tracer application is an economical and convenient method to investigate flow paths of soil water infiltration, the destructive excavations for the preparation of dye-stained soil profiles always make the dye application unable to be repeated at the same position. Our study was implemented by independent dye applications at a small scale, which may be not very well in line with the actual situation of outcrop runoff. In addition, the discontinuous outcrop runoff could self-organize and incorporate into well-connected networks (Laine-Kaulio et al., 2015), and the distribution of the outcrop runoff might gradually change during rainfall. This means that the results of our simulation experiment might be valid for only the initial stage of a rainfall event.

To solve the problem, high-density electrical resistivity tomography should be introduced to this soil hydrological process which satisfies the necessities of three-dimensional, nondestructive, and real-time measurement. This technique has the potential to become a revolutionary tool for the dynamic observation of outcrop runoff as well as the establishment of an infiltration model. In the future, research of outcrop runoff should be conducted on greater space and time scales, combined with real-time monitoring of soil and water loss, to investigate the more functional role of the ROCs in a karst environment.

Conclusion

Outcrop water runoff will penetrate deep and expand laterally along the soil-rock interface and move laterally into the soil at varying proportions on the three sides of the ROCs: the uphill sides, the downhill sides, and the lateral sides. On the uphill sides of the ROCs, most of the applied water flowed vertically into the ground along the soil-rock interface, and only a small part was distributed into the nearby soil patches. On the contrary, at the lateral sides, long but shallow lateral flow toward downslope dominated outcrop runoff movements, and most of the applied water was distributed to the topsoil. However, on the downhill sides of the ROCs, the water's vertical flow at the soil-rock interface was quantitatively equal to the lateral flow into the soil. These results will bring clues to understanding surface soil and water erosion as well as underground leakage. The results will also allow a deeper understanding of the process of rocky desertification and provide valuable information for rational land utilization as well as water and soil conservation, which will guide afforestation efforts in karstified regions.

Our study focused merely on the flow pattern of outcrop runoff on different sides of ROCs. The influence of other factors on outcrop runoff infiltration (e.g., soil moisture, ROC size, rainfall intensity, and so on) are yet to be explored. Because the limited sample of rocks selected may be unable to generalize all the cases of outcrop runoff infiltration at the slope scale, more complex experiments are needed to further evaluate the functions of outcrop runoff in a karst ecosystem, which would be an enormous undertaking.

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