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Response of soil particles around bedrock outcrops to sorting of rock surface flow derived outcrops in a rocky desertification area

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Soils around bedrock outcrops, even if they are protected by vegetation to some extent after ecological restoration, are prone to being washed away by rock surface flow (RSF) derived from these outcrops in rocky desertification land. However, the extent of the scouring scale and sorting effect of RSF on the soils around outcrops remains unknown. To solve this problem, a series of soils around bedrock outcrops exposed in sloping farmland (SF, without RSF), abandoned land (AL, 1 year of RSF) and shrub–grassland (SG, 5 years of RSF) were examined by the laser diffraction method in a natural ecological restoration area of rocky desertification, where the duration of the RSF is also the time for ecological restoration. It was found that the RSF had a limited effect on the particle size distribution of the soils, only having a significant scouring effect on the soils at the rock–soil interface within a horizontal distance of 2 cm from the outcrops and an insignificant effect on the soils far away from the outcrops in terms of horizontal distance (10 cm and 20 cm). The particle size distributions of the soil around the outcrops were related to erosion caused by the RSF, but mainly benefited from ecological restoration. Compared with SF, the fine particle content in the soils around the outcrops significantly decreased in AL, but significantly increased in SG. Within a short period (1 year) after natural recovery, the RSF had a reduced effect on the fine particles of the soil around the outcrops; however, this did not occur after a long period (5 years). The results of this study further explain the influence of the RSF on soil erosion and leakage loss in karst areas.

Keywords Rock surface flow, Soil around outcrops, Rock–soil interface, Particle sorting, Rocky desertification

The sustainability of ecological restoration in karst areas has become an important research topic in recent years^{1–3}. As one of the largest and most continuously distributed karst rock areas in the world, southwestern China suffers from extremely imbalanced soil formation and soil erosion rates, inevitably forming a large number of bedrock outcrops with soil patches under the background of global climate change and increasing human activities⁴. These bedrock outcrops increase the degree of surface fragmentation, which significantly changes the hydrological cycle and soil erosion processes at a small scale. This is an important reason for the high heterogeneity of habitats and poor sustainability of ecological restoration⁵. There is no doubt that vegetation plays a positive role in the process of soil erosion in general^{6–8}, as a result, it become the best choice for ecological restoration in karst areas. However, the intensity of soil erosion is stronger in areas with strong heterogeneity in vegetation distribution patterns^{9,10}. We believe that this situation also exists in karst rocky desertification areas, where the bedrock is extensively exposed. However, it is unclear whether exposed bedrock produces greater soil erosion or whether vegetation conserves the soil.

In areas experiencing serious rocky desertification¹¹, bedrock outcrops have a significant impact on the rainfall–runoff generation process. On one hand, the presence of the outcrops increases the area of impervious

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surface and promotes the convergence of rainfall runoff on the rock surface, which, in turn, increases surface runoff production¹². In contrast, outcrops reduce the surface erodible area and enhance the ability to intercept surface runoff^{13,14}. Therefore, it is particularly important to understand the erosion of soils around bedrock outcrops during the natural ecological restoration of karst areas. Regardless of whether vegetation restoration has been achieved in areas with bedrock outcrops, the impervious rock surface intercepts rainfall and throughfall to form rock surface flows (RSFs) from the bedrock outcrops. The process of the RSF flowing to the soil around the outcrops is called the "funnel effect" of the outcrops¹⁵. It has also been noted that outcrops redistribute rainfall, where exposed bedrock outcrops can transport half of the intercepted rainwater to the surrounding soil through runoff. Additionally, the amount of water received by the surrounding soil from the RSF was equal to that received from rainfall when the bedrock exposure rate reached 70%¹⁶, which had a significant effect on the sparse soil around the outcrops. However, the extent to which the scouring scale of the RSF affects the soils around outcrops remains unknown.

Soil erosion causes the soil texture to become coarser, and soil structure and properties deteriorate by changing the soil's sand, silt and clay contents^{17,18}. Previous studies shows that most silt is transported as primary particles, whereas clay and sand are eroded as aggregates^{6,7,19,20}. The soil particle size distribution parameter can reflect the erosion results of rainfall runoff²¹, which has also become one of the means to analyse the sediment sorting results by soil erosion. Hence, understanding the relationship between the parameters of soil particle size distribution and the processes of erosion and deposition would be beneficial for establishing an erosion model in karst areas^{22–24}. With global warming, the frequency of extreme rainfall and drought in southwest China has increased significantly, and the process of rocky desertification control is slow and faces serious challenges of instability and susceptibility to secondary rocky desertification²⁵. Therefore, it is urgent to reveal the erosion effect of the RSF on the soil around outcrops in rocky desertification areas, especially in ecological restoration areas that lack attention, to provide guidance for the effective use and regulation of the RSF and the adjustment of rocky desertification control plans.

Once natural ecological restoration is implemented, the time for ecological restoration can be considered as the duration of the effect of RSF on the soil around bedrock outcrops. However, there is a problem that has been puzzling us all along is whether ecological restoration plays a greater role in maintaining soil particles or whether RSF plays a greater role in scouring soil particles. This study is an initial attempt to confirm the sorting effect of RSF on soil particles around bedrock outcrops. Therefore, a series of soils around bedrock outcrops exposed to sloping farmland (without RSF), abandoned land (1-year RSF), and shrub–grassland (5-year RSF) were examined in a natural ecological restoration area of rocky desertification. The goals of this study were to 1) determine the differences in the soil particle size distribution in horizontal distance from outcrops and vertical depth along rock–soil interface and 2) reveal the sorting effects of the RSF on the soil particles around outcrops and its influencing factors. These results further explain the mechanism of soil erosion and leakage loss in karst areas, which is important for ensuring the sustainability of ecological restoration in karst rocky desertification areas.

Materials and methods

Site description

The study area is located in Ganhe Village (106° 13' 6" ~ 106° 38' 48" N, 25° 38' 48" ~ 26° 17' 30" E), Changshun County (a typical rocky desertification county), Guizhou Province, China (Fig. 1a). A humid mid-subtropical monsoon climate prevails in the study area. The relative humidity in this region is approximately 80%. The average annual temperature ranges from 13.5 to 18.5 °C. The average annual rainfall varies between 1250 and 1400 mm, with most of the annual rainfall occurring from April to September. Changshun County is dominated by limestone. The main soil types are limestone and loamy. The karst area in Changshun County is 1448 km², including 1220 km² of rocky desertified land with a typical karst landscape. Changshun County is one of the key counties for controlling rocky desertification in Guizhou Province; hence, ecological restoration has always been a key measure for controlling rocky desertification in this region²⁶.

Methods

Experimental design and sample collection

Several sites with exposed bedrock undergoing ecological restoration were selected in the study area, including abandoned land, shrub–grassland, and sloping farmland (Fig. 1b). After farming the sloping farmland (SF) in April 2021, there were no other farming activities; thus, the area was regarded as a control. In April 2020, the abandoned land (AL) was not disturbed by farming activities (ploughing) and recovered naturally. Shrub–grassland (SG) was restored naturally in early 2016. There was no human disturbance at these sites during natural restoration. To highlight the significance of the influence of the RSF on the soil particles around the outcrops, outcrops with a concave surface, in which soils were scoured by the RSF with a concentrated flow path, were selected. All rock surfaces were consistent in terms of roughness and size. Height, dip angle, and other outcrop indicators were also measured (Table 1).

Soil samples around the selected outcrops were collected in May 2021. In the absence of human disturbance (tillage, trampling, etc.), the time required for ecological restoration was consistent with the duration of the RSF. At this moment, the soils around the outcrops exposed in the SF were slightly affected by the RSF, the soils around the outcrops exposed in the AL were affected by the RSF for approximately one year, and the soils around the outcrops exposed in the SG were affected by the RSF for five years. Before collecting the soil samples, weeds, litter, etc. on the soil surface around the outcrops were removed. According to the flow path of the RSF created by rainwater collecting on the rock surface, soil sampling was performed at the most concave site of the rock–soil interface to ensure that the soil samples were representative of the influence of the RSF on the soils around the outcrops. Two factors were considered in the sampling process. First, the RSF flowed into the soil

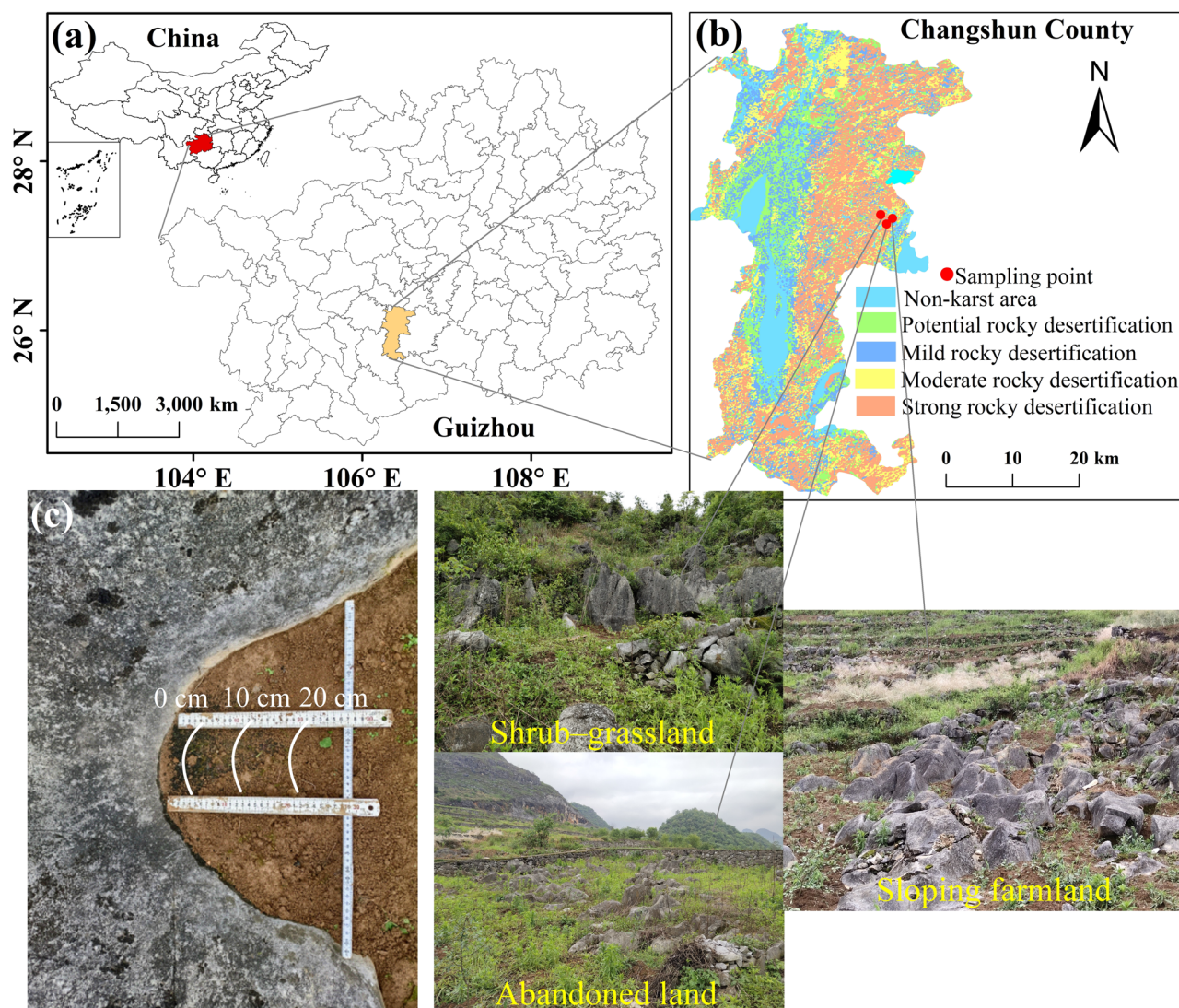


Figure 1. Location of the study area (a); sampling selected location (b); schematic diagram of soil sampling locations around outcrops (c).

Sampling plots	SF	AL	SG
Geographical coordinates	26° 1' 31" N, 106° 29' 58" E	26° 1' 30" N, 106° 30' 0" E	26° 1' 30" N, 106° 29' 59" E
Altitude (m)	1002	1003	1005
Slope position	Middle slope		
Rock exposure rate (%)	35%	45%	30%
Catchment area of outcrops (cm ²)	6872	4289	708
Height of outcrops (cm)	106	70	114
Inclination angle of rock surface (°)	49.5	42	77
Length of rock soil contact within a range of 50 cm (cm)	83	60	51
Duration of the RSF	Little	1 a	5 a
Time for ecological restoration	Little	1 a	5 a
Vegetation	<i>Zea mays</i> L. (height of 15 cm)	<i>Gnaphalium affine</i> D. Don. (height of 25 cm); <i>Sonchus wightianus</i> DC. (height of 40 cm)	<i>Bidens pilosa</i> L. (height of 60 cm); <i>Zanthoxylum bungeanum</i> Maxim. (height of 150 cm); <i>Erigeron annuus</i> (L.) Pers. (height of 60 cm); <i>Miscanthus sinensis</i> Anderss. (height of 120 cm)

Table 1. Basic information of outcrops exposed in the study area. The RSF is the rock surface flow from outcrops. The same as below. SF sloping farmland, AL abandoned land, SG shrub-grassland.

in two directions along the rock surface (including the exposed and unexposed parts): horizontal and vertical. Second, the preferential flow at the rock–soil interface formed the RSF, which significantly affected the soil closely adhering to the rock–soil interface²⁷. Based on that, soil samples with a width of 2 cm were collected at horizontal distances of 0, 10 and 20 cm from the exposed rock surface (Fig. 1c), and those at vertical depths of 0–10 cm and 10–20 cm were collected in layers. The soil samples were dried naturally and sieved through a soil sieve with an aperture of 1 mm for particle analysis.

Detection of soil particles

The particle size distribution of the soil samples was analysed using the laser diffraction method (Baxter laser particle size analyser)²¹. Organic matter and carbonate were removed before the implementation of this method. Each soil sample was tested three times to obtain average values. The analysis results included particle sizes corresponding to 5%, 16%, 25%, 50%, 75%, 84% and 95% of the volume fraction of soil particles. At the same time, according to the Soviet Soil Texture Classification Standard, clay particles are <0.001 mm, silt particles are 0.001–0.05 mm, and sand particles are 0.05–1 mm in diameter.

Calculation of soil particle size parameters

Soil particle size parameters were calculated using the Folk and Ward formula²⁸. First, the particle sizes corresponding to 5%, 16%, 25%, 50%, 75%, 84% and 95% volume fractions of soil particles were converted using the logarithmic conversion method.

$$\Phi = -\log_2 \xi \quad (1)$$

where ξ is the particle size (μm), and Φ_5 , Φ_{16} , Φ_{25} , Φ_{50} , Φ_{75} , Φ_{84} and Φ_{95} are log-transformed values for soil particle volume fractions of 5%, 16%, 25%, 50%, 75%, 84% and 95% particle sizes, respectively.

Then, the mean particle size (M_z), standard deviation (σ), skewness (SK), and kurtosis (KG) of the soil particle size were calculated by the following equations²⁹.

M_z is the concentrated particle size of soil particle size distribution (PSD):

$$M_z = \frac{\Phi_{16} + \Phi_{50} + \Phi_{84}}{3} \quad (2)$$

σ is the degree of dispersion of the PSD:

$$\sigma = \frac{\Phi_{84} - \Phi_{16}}{4} - \frac{\Phi_{95} - \Phi_5}{6.6} \quad (3)$$

SK is the symmetry of coarse and fine distributions of soil particles:

$$SK = \frac{\Phi_{16} + \Phi_{84} - 2\Phi_{50}}{2(\Phi_{84} - \Phi_{16})} + \frac{\Phi_5 + \Phi_{95} - 2\Phi_{50}}{2(\Phi_{95} - \Phi_5)} \quad (4)$$

KG is the degree of concentration of the PSD:

$$KG = \frac{\Phi_{95} - \Phi_5}{2.44(\Phi_{75} - \Phi_{25})} \quad (5)$$

The fractal dimension is an important indicator of soil texture. The volumetric fractal dimensions of the soil particles (D) were calculated using the following equation³⁰:

$$\frac{V(r < R_i)}{V_t} = \left(\frac{R_i}{R_{\max}} \right)^{3-D} \quad (6)$$

where $V(r < R_i)$ is the volume of soil particles with particle sizes less than R_i (%); V_t is the total volume of soil (%); R_i is the average value of the measured soil particle size (μm); R_{\max} is the maximum particle size in the soil (μm); and D is the fractal dimension of the soil particles.

Data processing and statistical analysis

A multivariate analysis of variance (MANOVA) was used to test for significant differences in the factors affecting PSD around the outcrops. Principal component analysis (PCA) was used to determine the relationships between the PSD parameters and factors affecting PSD.

Results

Influence range of the RSF on the soil around outcrops

Difference in the PSD in horizontal distance from outcrops

Figure 2 shows the soil particle size distribution in terms of horizontal distance from the outcrops under the influence of the RSF. There was a slight difference in the particle size distribution of the soils along the horizontal distance from the outcrops. M_z , SK and KG decreased with increasing horizontal distance from the outcrops. They were significantly ($p < 0.05$) different at 0 cm from 10 and 20 cm in the horizontal distance from the outcrops, but were insignificant ($p > 0.05$) at 10 and 20 cm. The σ of the soil at the rock–soil interface differed significantly ($p < 0.05$) from those at 10 and 20 cm in horizontal distance from outcrops, where those at 10 and 20 cm were not significantly different ($p > 0.05$). The sand content decreased as the horizontal distance from outcrops increased,

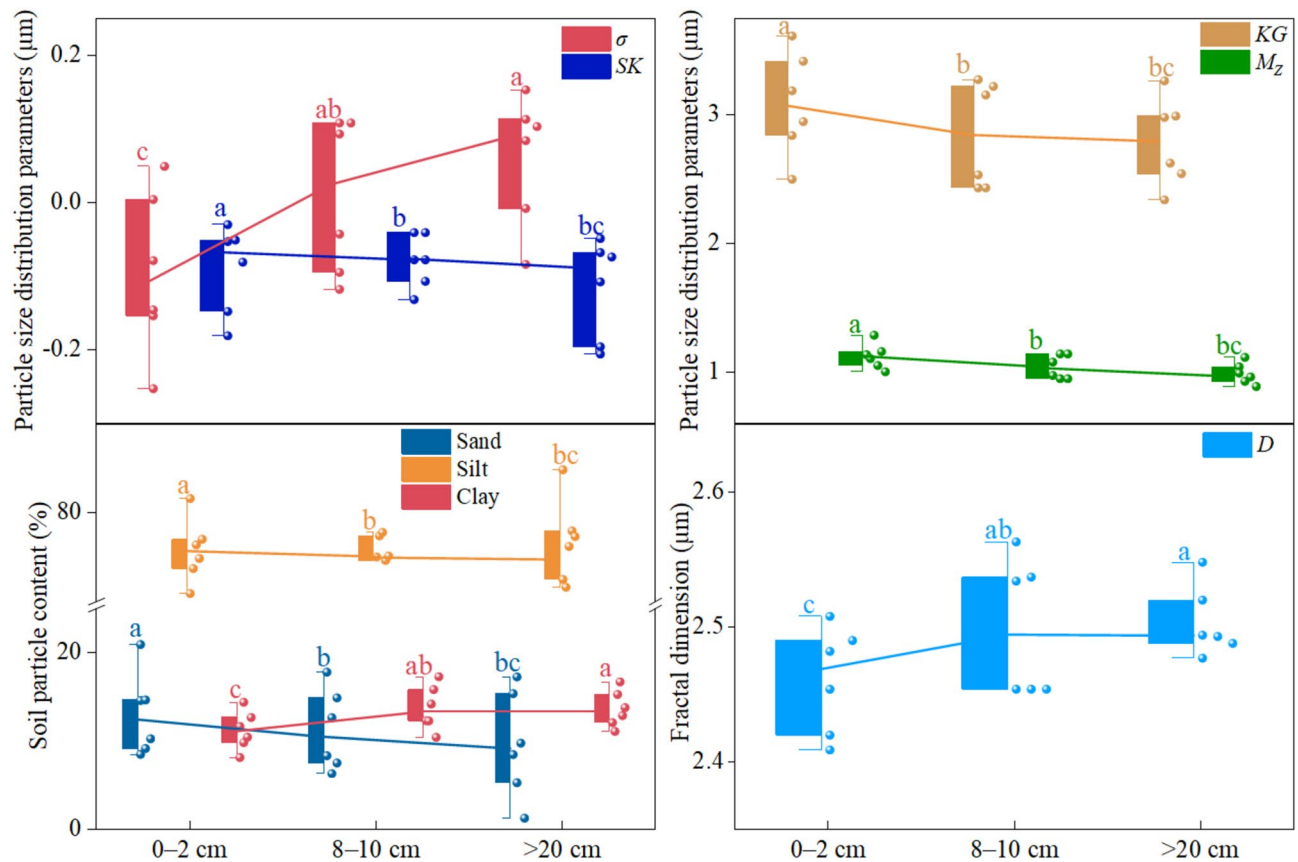


Figure 2. Soil particle size distribution in horizontal distance from outcrops under the influence of RSF. Note σ standard deviation, SK skewness, M_z mean particle size, D fractal dimension and KG kurtosis. The same column marked with different lowercase letters indicates significant differences between groups ($p < 0.05$), and the same letter indicates that the difference between groups was not significant ($p > 0.05$). The same as below.

where the sand content at 0 cm was significantly different ($p < 0.05$) from that at 10 and 20 cm in horizontal distance from outcrops. However, the silt and clay contents increased with increasing horizontal distance from the outcrops, in which the clay content at 0 cm was significantly different ($p < 0.05$) from that at 10 and 20 cm. The D of the soil at the rock–soil interface was significantly ($p < 0.05$) lower than that at 10 and 20 cm, whereas there was no significant difference ($p > 0.05$) between 10 and 20 cm in the horizontal distance from the outcrops. This indicates that the D of the soil closely adhering to the rock–soil interface was smaller, whereas that away from the outcrop was larger.

Difference in PSD in vertical depth along rock–soil interface

The M_z , SK , and sand contents at 0–10-cm soil depth were considerably higher than those at 10–20-cm depth. However, the σ , KG , silt and clay contents at the 10–20-cm soil depth were greater than those at the 0–10-cm soil depth. The M_z and sand contents were significantly different ($p < 0.05$) among soil depths, whereas D and SK did not vary significantly. The average soil particle sizes were substantially larger at the 0–10-cm soil depths of SF, AL and SG than those at the 10–20-cm soil depth. The SK of the 0–10-cm soil layer was greater than that of the 10–20-cm soil layer. The KG and σ of the 10–20-cm soil depth were significantly ($p < 0.05$) higher than those of the 0–10-cm soil depth. With increasing soil depth, the sand content increased, whereas the silt and clay contents decreased. The D of soils closely adhering to the rock–soil interface at the 10–20-cm soil depth was higher than that at the 0–10-cm soil depth (Fig. 3). This indicates that the content of coarse particles (sand) in the 0–10-cm soil layer was high, with a more concentrated and uniform distribution, whereas the fine particles (silt and clay) in the 10–20-cm soil layer were high, with a more dispersed distribution.

Accumulative effects of the RSF on the soil around outcrops

Figure 4 shows the soil particle size distribution influenced by the duration of the RSF or the duration of ecological restoration. AL with a 1-year duration of RSF showed the largest M_z values. Moreover, the smallest σ value was also found in the AL. These results indicate that the effects of RSF were greater than those of ecological restoration. However, the SG with a 5-year duration of RSF presented the smallest M_z and greatest σ values, indicating that soil particles were more concentrated in the areas with smaller particle sizes, and was more discrete in the content of each particle size. The effects of ecological restoration were greater in AL than those in

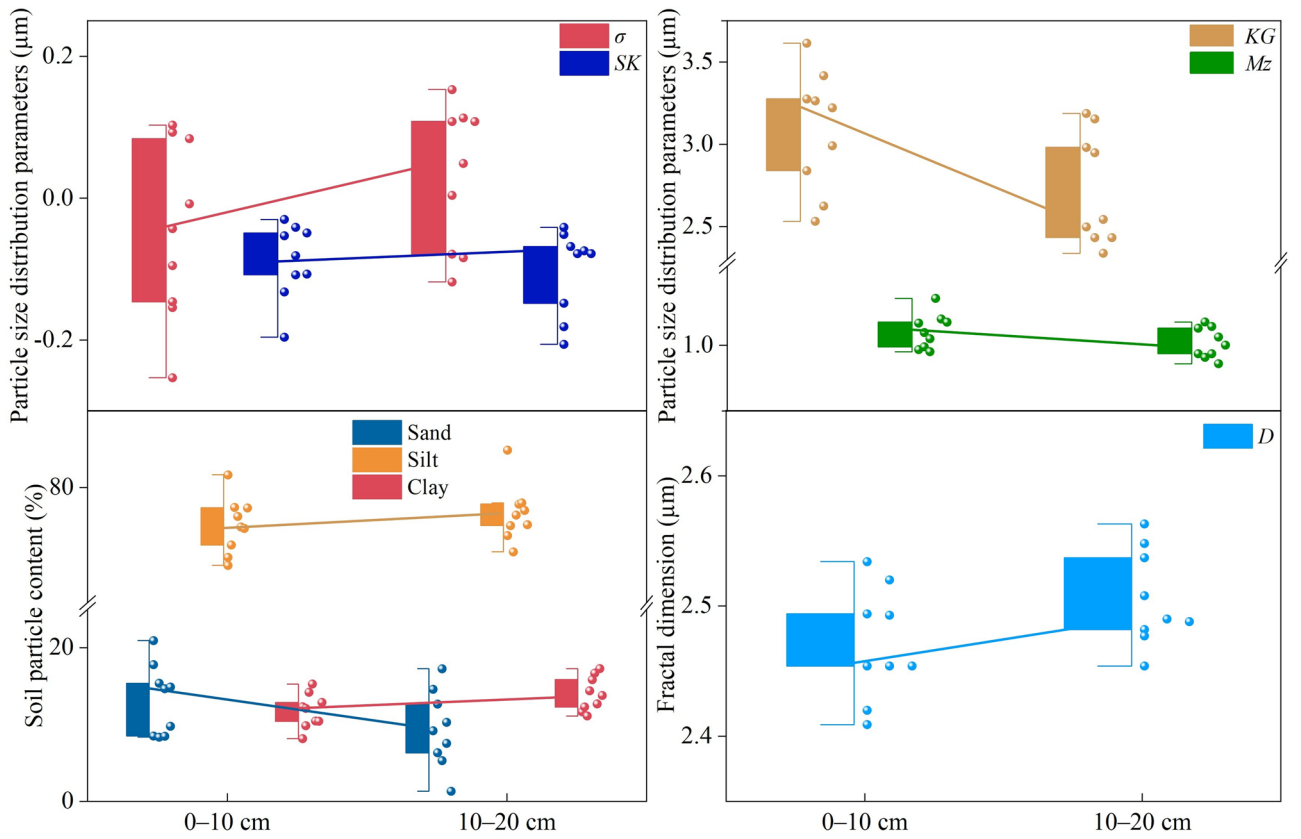


Figure 3. Soil particle size distribution in the soil depths along the rock–soil interface under the influence of the RSF.

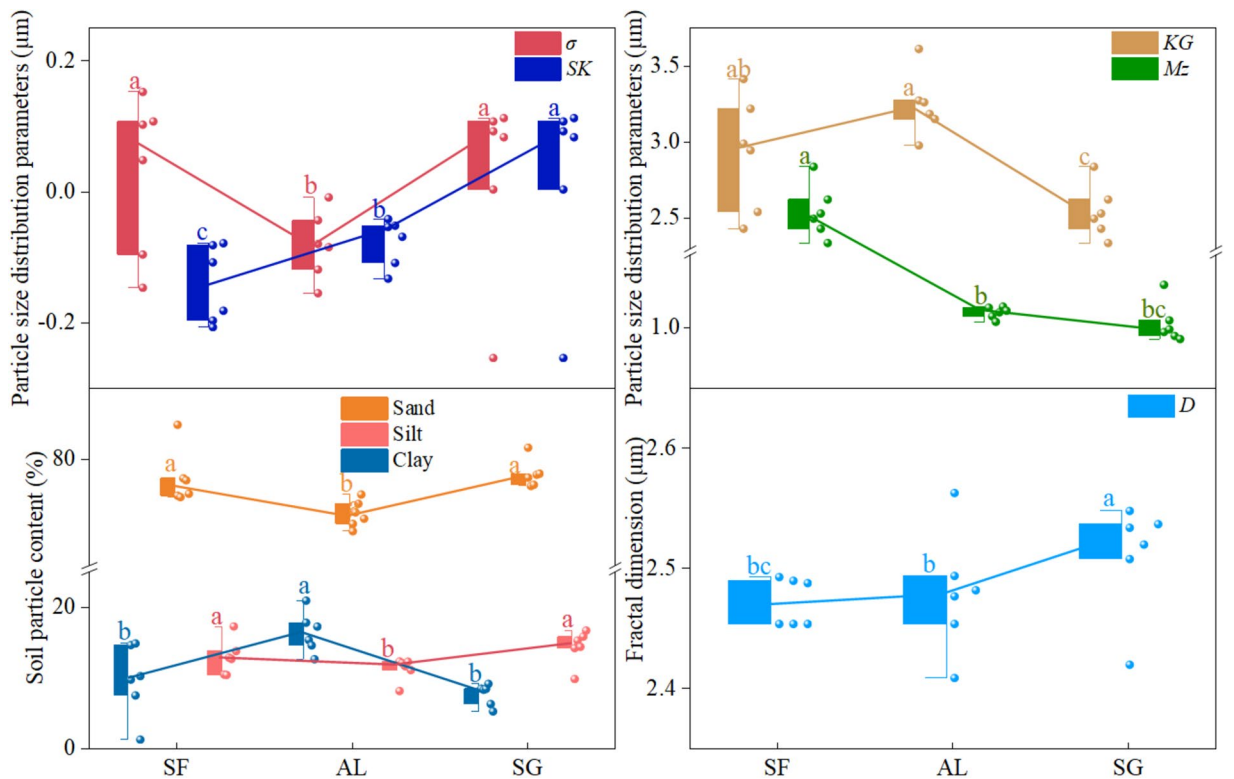


Figure 4. Soil particle size distribution influenced by the duration of the RSF (or the ecological restoration period). Note SF sloping farmland, AL abandoned land, SG shrub–grassland.

RSF. *SK* and *KG* showed that the particle size distribution of the soil in both *AL* and *SG* was skewed to the left. The distribution curve of the *AL* was narrow and convex, whereas that of the *SG* was wide and flat.

The silt and clay contents of the soil around the outcrops followed the same order: $SG > SF > AL$; however, the sand content was $AL > SF > SG$. Silt was the dominant particle type in the soil around outcrops. The sand content in *SF* and *AL* was significantly ($p < 0.05$) higher than the clay content, but the opposite was true for *SG*. In addition, the sand content in *SG* with a 5-year ecological restoration period was lower than that of *SF*, but both the silt and clay contents were higher than those of *SF*. Compared with *SF* without ecological restoration, *SG* showed an increase in the content of fine particles (silt and clay) and a decrease in the content of coarse particles (sand) under the effect of the 5-year ecological restoration period. Similarly, *AL* presented a decrease in the content of fine particles and an increase in the content of coarse particles under the effect of a 1-year duration of RSF. The same results were also found for the *D* of *AL*, *SF* and *SG*.

MANOVA and PCA for the soil around outcrops

The results of the MANOVA of the factors affecting the soil particle size distribution parameters are shown in Table 2. The duration of the RSF (or the ecological restoration duration), vertical soil depth, and horizontal distance from the outcrops had extremely significant effects on the soil particle size distribution parameters ($p < 0.01$); however, the interactions among these factors indicated significant differences ($p < 0.05$). The interaction between soil depth and horizontal distance from the outcrops was not significant for sand or silt content ($p > 0.05$). Notably, the interactions between the duration RSF and soil depth had an extremely significant effect on the soil particle size distribution parameters, except for clay content ($p < 0.01$). However, the interactions between the duration of the RSF and horizontal distance from the outcrops had a significant effect on all soil particle size distribution parameters ($p < 0.01$).

The PCA results for the factors and soil particle size distribution parameters are presented in Fig. 5. The total contribution rates of PC1 and PC2 reached 90.8%, indicating that these PSD parameters represent an important contributor to the factors affecting PSD. The contribution rate of PC1 was 72.8%, and the main influencing factors were the duration of RSF (*SF* and *AL*), distance from the rock surface (0–2 and > 20 cm), and soil depth (0–10 and 10–20 cm), and the soil depth had the most significant influence. The contribution rate of PC2 was 18%, and

Factor	M_z	σ	<i>SK</i>	<i>KG</i>	Sand	Silt	Clay
DT	0	0	0	0	0	0	0
SD	0	0	0	0	0	0	0
HD	0	0	0	0	0	0	0
DT × SD	0	0	0	0	0	0	0.167
DT × HD	0	0	0	0	0	0	0
SD × HD	0.023	0	0	0	0.192	0.175	0
DT × SD × HD	0	0.042	0.081	0.023	0	0	0

Table 2. MANOVA on the factors affecting the soil particle size distribution parameters. Values indicate statistical significance ($p < 0.05$). *DT* duration of the RSF (or ecological restoration duration), *SD* soil depth, *HD* horizontal distance from the outcrops.

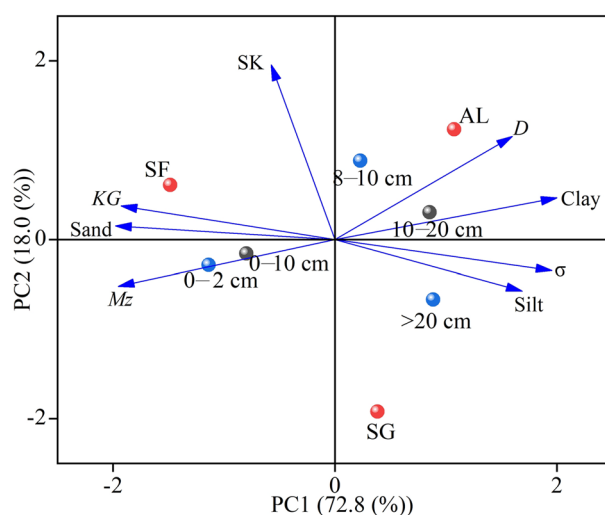


Figure 5. PCA between the factors and soil particle size distribution parameters.

the main influencing factors were the duration of the RSF (AL, SG and SF) and distance from the rock surface (10 cm), among which the duration of the RSF (or ecological restoration duration) was the most significant.

Discussions

Relationship between the RSF scouring and ecological restoration

In the absence of human disturbance, the time required for ecological restoration was consistent with the duration of RSF. In this study, we found that the content of fine particles increased and that of coarse particles decreased in the SG with a 5-year duration of RSF compared with the SF without RSF. Previous studies have indicated that the fine particle (silt and clay) content increases in shrub–grassland³⁰, which is consistent with the results of this study. The reason for this trend is that the growth and development of roots in the soil and litter on the surface help prevent fine particles from eroding via runoff⁷. We also found that the content of fine particles decreased and that of coarse particles increased in AL with a 1-year duration of RSF compared with SF. This was inconsistent with previous results showing that the content of coarse particles on land where crops were planted were greater than those of other land-use types³⁰. More importantly, the soils around the outcrops exposed in AL were eroded by the RSF from the outcrops. During the erosion process, fine particles are selectively removed by rainfall runoff³¹, and less soil erosion occurs on land with grassland vegetation³². In this study, the content of fine particles in the SG increased under the effect of the 5-year ecological restoration period, but that in the AL was significantly reduced under the influence of the 1-year ecological restoration period. This indicates that the influence of RSF scouring on the soil was greater than that of ecological restoration in the short term (1 year). Meanwhile, it can also be observed from D from the different times of ecological restoration and duration of RSF, that is, $SG > SF > AL$. This demonstrates that a long-term (5 years) ecological restoration has a more significant impact on the soil around bedrock outcrops. Therefore, the sorting influence of RSF on the soil should be considered when there is conducting ecological restoration, especially in the early stages, and corresponding measures should be formulated to reduce their negative impact on the soil around bedrock outcrops.

Reasons for the difference in soil particle distribution between soil depths

In this study, we found that there were more sand particles at the 0–10-cm soil depth, and M_z was larger, whereas there were more silt and clay particles at the 10–20-cm soil depth. Rainfall reduces the content of fine particles (clay particles) and increases the content of coarse particles (sand particles) at the 0–10-cm soil depth due to the splashing effect of raindrops^{33,34}. Meanwhile, the soil particles in the 0–10-cm soil depth were dispersed by the impact of raindrops during rainfall, and the smaller clay particles were continuously transported by runoff³⁵, so the content of fine particles in the 0–10-cm soil depth was low and the average particle size of the soil particles was large.

The restoration of vegetation can improve soil infiltration, especially for the surface soil⁸. Meanwhile, soil particle size is significantly and positively correlated with soil pore size, and D is significantly and negatively correlated with soil infiltration capacity³⁶. Therefore, for surface soil with coarser texture, the 0–10-cm soil depth had larger pores and a stronger soil infiltration capacity. This is because that fine particles in the 0–10 cm soil layer gradually migrated downwards with rainfall to the lower soil layer (10–20 cm) and accumulated, resulting in a higher content of silt and clay particles at the 10–20-cm soil depth³⁷. The surface soil gradually migrated downward and the surface area of the outcrops continued to increase, resulting in a gradual increase in soil erosion/leakage³⁸. This study found that soil depth had the most significant influence on the PSD parameters. Therefore, the change in the PSD with soil depth had no significant relationship with the RSF. Previous studies have shown that there is no significant difference in the distribution of soil particle size along the soil depth for different vegetation types³⁹, which is consistent with the findings of this study.

Horizontal influence range of RSF on soil erosion around outcrops

The variety of landscapes in Southwest China's karst region is a result of the substantial amount of bedrock exposed at the surface, and the mosaic distribution of outcrops and soils plays an important role in this⁴⁰. Currently, there is no consensus regarding the influence of vegetation on eroded sediment particles. Previous studies have shown that vegetation has little effect on eroded sediment particles⁶, but other studies have shown that vegetation reduces the transportation of sand particles¹⁹. In this study, it was found that the M_z , sand content, and KG of soil particles around the outcrops gradually decreased with increasing distance, while the σ , silt and clay content gradually increased with increasing distance. This is because the exposed bedrock also increases the impervious surface area and promotes the convergence of rainfall runoff in the soil patches around the outcrops^{41,42}, which, in turn, affects the distribution of soil particles over long distances. Therefore, the contents of silt and clay particles in the soil in the horizontal direction gradually increased with distance, which led to a gradual decrease in M_z and KG in the soil around the outcrops with increasing distance.

At the same time, there were significant differences in PSD at horizontal distances of 0, 10 and 20 cm from the outcrop, but insignificant differences at 10 and 20 cm. This is because part of the rainwater formed an RSF along the outcrop surface and continued to preferentially enter the soil along the outcrop surface during rainfall^{43,44}, resulting in the most significant impact on the soil particles in the 0-cm area close to the outcrop surface under the influence of the RSF. It has been noted that a decrease in the clay content of the soil is an important indicator of soil erosion, and the D value is proportional to the clay content in soil⁴⁵, which is consistent with the findings of this study.

According to our study, the soil particle D at 0 cm was much lower than those at 10 and 20 cm, but there was no discernible difference in the fractal dimensions at 10 and 20 cm. The change in soil texture from coarse to fine or loose to dense can be represented by the D value from small to large⁴⁶, which shows that the soil texture at 0 cm was coarse and loose, but there was no discernible difference between 10 and 20 cm. The RSF impacts the

soil near outcrops, and lateral runoff is generated between the outcrop surface and the soil to strip and transport fine particles (silt and clay particles) in the soil immediately adjacent to the outcrop surface^{47,48}. The above results show that surface flow from outcrops has a limited range of influence on the surrounding soil, causing a more pronounced scouring effect on soil particles at 0 cm, whereas the scouring effect on soil particles at distances (10 and 20 cm) from the surface of the outcrops is less pronounced. Vegetation coverage is effective for reducing soil erosion⁴⁹. However, in karst areas where the outcrop is exposed over a large area and the rock–soil interface is widely distributed, the mechanism of vegetation restoration hindering the loss of soil particles near the rock–soil interface needs to be further explored.

In karstic rocky desertification areas, the shape of the exposed bedrock is diverse, and there are significant differences in the soil, climate, and outcrop type within each region. In our study, SF without RSF, AL with RSF for one year, and SG with RSF for five years were selected from typical rocky desertification plots with similar environmental conditions. To highlight the significance of the erosion effect of the surface flow over the exposed rock on the soil around the outcrops, the soil around the concave outcrops was selected, and the soils around the outcrops with longer flow durations and other characteristics were not considered. It is necessary to strengthen research on the factors influencing soil particle size distribution around other exposed outcrops. This study obtained an understanding in the effect of RSF on the sorting of soil particles around the bedrock outcrops based on changes in soil particle distribution, and discovered that this sorting effect will be weakened after a certain period of ecological restoration. This is the first evidence to discover that the RSF derived from bedrock outcrops can cause soil erosion around the bedrock outcrops. However, the main limitation of this study is the lack of validation of observational data on the RSF and soil erosion associated. It is crucial to discern their contributions to establishments in the connections of surface and underground leakage loss of soil in karst areas in future studies.

Conclusions

The soil particles sorting around bedrock outcrops, especially the soil close to the rock–soil interface, were related to erosion caused by the RSF in the early stages of ecological restoration, but this sorting effect will be weakened after a certain period of ecological restoration. The RSF had a limited effect on the particle size distribution of the soils, only having a significant scouring effect on the soils at the rock–soil interface within a horizontal distance of 2 cm from the outcrops. The RSF had no clear scouring effect on the soil far from the outcrop at horizontal distances (10 and 20 cm). There were significant differences in PSD at horizontal distances of 0, 10 and 20 cm from the outcrop, but insignificant differences at 10 and 20 cm. Compared with SF, the fine particle content in the soils around the outcrops presented a significant decrease in AL with 1 year of RSF but a significant increase in SG with 5 year of RSF. Within a short period after natural recovery, the RSF had a reduced effect on the fine particles of the soil around the outcrops; however, this did not occur after a long period.

Data availability

All data generated or analyzed during this study are included within the manuscript.

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J.Z.: Conceptualization, Methodology, Experiment, Data curation, Formal analysis, Roles/Writing—original draft, Writing—review & editing. X.P.: Conceptualization, Methodology, Supervision, Project administration, Validation. Q.D., D.Y., L.C., T.L.: Conceptualization, Methodology, Visualization, Resources.

Competing interests

The authors declare no competing interests.

Additional information

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