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Rock crevices determine woody and herbaceous plant cover in the karst critical zone

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Abstract The study of the critical zones (CZs) of the Earth link the composition and function of aboveground vegetation with the characteristics of the rock layers, providing a new way to study how the unique rock and soil conditions in karst regions affect the aboveground vegetation. Based on survey results of the rocks, soils and vegetation in the dolomite and limestone distribution areas in the karst area of central Guizhou, it was found that woody plant cover increases linearly with the number of cracks with a width of more than 1 mm, while the cover of herbaceous plants shows the opposite trend (p<0.01). The dolomite distribution area is characterized by undeveloped crevices, and the thickness of the soil layer is generally less than 20 cm, which is suitable for the distribution of herbaceous plants with shallow roots. Due to the development of crevices in the limestone distribution area, the soil is deeply distributed through the crevices for the deep roots of trees, which leads to a diversified species composition and a complicated structure in the aboveground vegetation. Based on moderate resolution imaging spectroradiometer (MODIS) remote sensing data from 2001 to 2010, the normalized differentiated vegetation index (NDVI) and annual net primary productivity (NPP) results for each phase of a 16-day interval further indicate that the NDVI of the limestone distribution area is significantly higher than that in the dolomite distribution area, but the average annual NPP is the opposite. The results of this paper indicate that in karst CZs, the lithology determines the structure and distribution of the soil, which further determines the cover of woody and herbaceous plants in the aboveground vegetation. Although the amount of soil in the limestone area may be less than that in the dolomite area, the developed crevice structure is more suitable for the growth of trees with deep roots, and the vegetation activity is strong. At present, the treatment of rocky desertification in karst regions needs to fully consider the rock-soil-vegetation-air interactions in karst CZs and propose vegetation restoration measures suitable for different lithologies.

Keywords Vegetation composition, Vegetation productivity, Dolomite, Limestone, Karst critical zone

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1. Introduction

China is an important karst distribution area in the world. The area of karst distribution is 3.631 million km^2, of which the exposed carbonate bedrock is approximately 1.3 million km^2, and more than 40% is distributed in the southwestern regions centered on the Guizhou Plateau (Jiang et al., 2014; Sweeting, 2012). Increasing soil erosion caused by degraded vegetation has enhanced the conflict between people and land in the karst region of southwest China, and the con-

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sequent rapid expansion of rocky desertification has seriously affected sustainable development in the region. Exploring the vegetation composition and cover of the karst distribution area is the basis for vegetation restoration in this region (Tong et al., 2018).

The complex lithofacies and their intricate distribution in the karst distribution area strongly affect the vegetation characteristics and their distribution. Based on remote sensing data, vegetation characteristics can be obtained at regional scales, and then the relationship between these characteristics and ground environmental factors can be analyzed (Yue et al., 2010a, 2010b). However, the complex underground structure of the karst distribution area may affect the surface vegetation by affecting the soil distribution and water conditions, and it is difficult to explore the influence of underground structure on vegetation composition and productivity by means of remote sensing. Previous studies have shown that the contribution of surface soil to vegetation in the karst area of southwest China is only 21%, and the contribution of topographic features is only 13.2%, indicating that it is difficult to explain the pattern of vegetation based on these two factors. There could be an impact from rock that needs further exploration (Du et al., 2015). A recent report from North America showed that rocks can store 27% of precipitation (Rempe and Dietrich, 2018), providing new clues for the further study of the mechanism of rock impacts on surface vegetation.

The critical zone (CZ) of the Earth refers to the heterogeneous near-surface environment, which is a natural habitat regulated by a rock-soil-water-vegetation-air-interaction that provides resources to support life systems (National Research Council, 2001). The CZ of the Earth extends vertically from the canopy to the bedrock and expands greatly in the horizontal direction (National Research Council, 2001; Brantley et al., 2007). Soil is an intermediate link between rocks and plants. The formation mechanism of vegetation composition and productivity in karst areas needs to be based on the rock-soil-plant-air continuum in the study of the CZ of the Earth. However, research on this aspect is still rare (Guo and Lin, 2016). The central Guizhou area is a representative area of karst development in China, and it is an ideal place for research based on the CZ of the Earth. The karst CZ of this study refers to the area dominated by karst landforms.

Key karst areas have serious soil erosion and an uneven soil distribution. According to previous studies, the thickness of the soil layer in this area is often less than 30 cm (Yin et al., 2013), which makes the vegetation growth rate slow. At the same time, developed rock joints cause the underground soil to be intermittently distributed (Yang et al., 2008). There are large differences in the growth processes of different plant species and even in different individuals of the same species (Zhu, 1997). However, previous studies have neglected the effects of rock differences within the karst CZ on soil and vegetation. According to the regional geological map, the most widely distributed karst CZs are limestone, followed by dolomite (Ma, 2002). The main difference between the two is the difference in the Ca/Mg ratio. Limestone dominated by calcium carbonate is more likely to dissolve and form cracks, causing moisture and soil to enter the ground through the cracks. Dolomite is mainly composed of magnesium carbonate, which is harder than limestone and is not easily dissolved. It is characterized by dense but narrow cracks in the weathered surface of dolomite, often forming a thin soil layer on the rock surface, and water is not easily infiltrated. Based on the different characteristics of dolomite and limestone, this paper proposes the following scientific hypothesis: limestone and dolomite may affect the composition and productivity of surface vegetation through differences in the crevice structures in the karst CZ.

The karst CZ in central Guizhou is an ideal place to study the influence of the underground structure of the karst CZ on the surface vegetation. Previous works have systematically studied the types of plant communities and their species compositions in this and adjacent regions (Huang et al., 1988; Song et al., 2010; Liu et al., 2011). In local-scale studies, the effects of soil moisture on aboveground vegetation have been noted. By measuring the δ^{13}C value of leaves of the dominant species in the karst area, it has been found that the δ^{13}C value is more negative, with a narrower distribution range and a lower variation in the leaves in the yellow soil area than in the black lime soil area (Du et al., 2009). A correlation analysis showed that the main influencing factors on the δ^{13}C value of plant leaves in the yellow soil area were soil thickness and slope, and the main factor in the black lime soil area was soil water content, indicating that the effect of rock on the plant δ^{13}C values was achieved by regulating the soil moisture (Du et al., 2009). Another study explored the relationship between plant community species composition and soil moisture and divided the main tree species in this region into different species, including pioneer species, subpioneer species, subclimax species and climax species, according to their drought tolerances. Among them, the pioneering species and the subpioneer species were more resistant to drought than the subclimax species and the climax species (Yu et al., 2002). Regarding the relationship between lithology, soil and plant community composition and productivity at different spatial scales, there is still a lack of research due to the difficulty of observation.

We selected the widely distributed limestone and dolomite in the karst CZ in central Guizhou Province and used the bedrock profile formed by the aboveground vegetation. The vegetation productivity data under different lithological conditions were calculated from remote sensing images. On this basis, the effects of rock crevices on vegetation composition and productivity in the karst CZ were analyzed.

2. Research areas and research methods

2.1 The karst CZ

Triassic limestones and dolomites are widely distributed in central Yunnan, with a complex lithology that is often mixed with other rocks, such as sandstone, shale and mudstone (Ma, 2002). The two types of rocks, dolomite and limestone, are either distributed separately or mixed, resulting in different Ca/Mg ratios at different locations and different degrees of crevice development (Bucker and Grapes, 2011).

We chose the area centered on Puding as the core research area (105°25′E–106°02′E, 26°25′N–26°33′N). The study area belongs to the subtropical monsoon humid climate, with an annual average temperature of 15.1°C, an average annual precipitation of 1378.2 mm, and abundant rainfall. The karst landforms in the study area are very typical, with a wide distribution and complete types. Due to the development of karst, the river water in the limestone area seriously leaks, forming more than 20 underground rivers. The study area is located in the watershed of the Yangtze River system and the Pearl River system, with the Yangtze River system in the north and the Pearl River system in the south (Compilation Committee of the Local Chronicle of Puding County, 1999).

2.2 Field survey methods

Field surveys were conducted in Puding and the surrounding areas in the core area of the karst CZ. During the field investigation, construction excavation sites were selected and concentrated in Puding (105°43.5′E, 26°14.5′N), Shawan (105°45.1′E, 26°19.9′N), Zhaojiatian (105°46.7′E, 26°16.1′N) and Xiushui (105°40.9′E, 26°18.4′N), with an altitude range of 1210–1240 masl (meter above sea level). A total of 18 plots were excavated, and the length of each plot was over 10 m (Figure 1). Longitude, latitude, altitude, slope, aspect, profile direction, lithology and other information were recorded at each survey site. To explain the influence of human disturbance, vegetation surveys were carried out in places with less disturbance, such as Tianlong Mountain (26°14.8′N, 105°45.8′E), and 8 plots with different slope directions and topographic conditions were recorded.

The number of cracks >1 mm in width, the width of each crack, and the distribution of the soil and roots in the cracks were recorded along the profile. The thickness of the surface

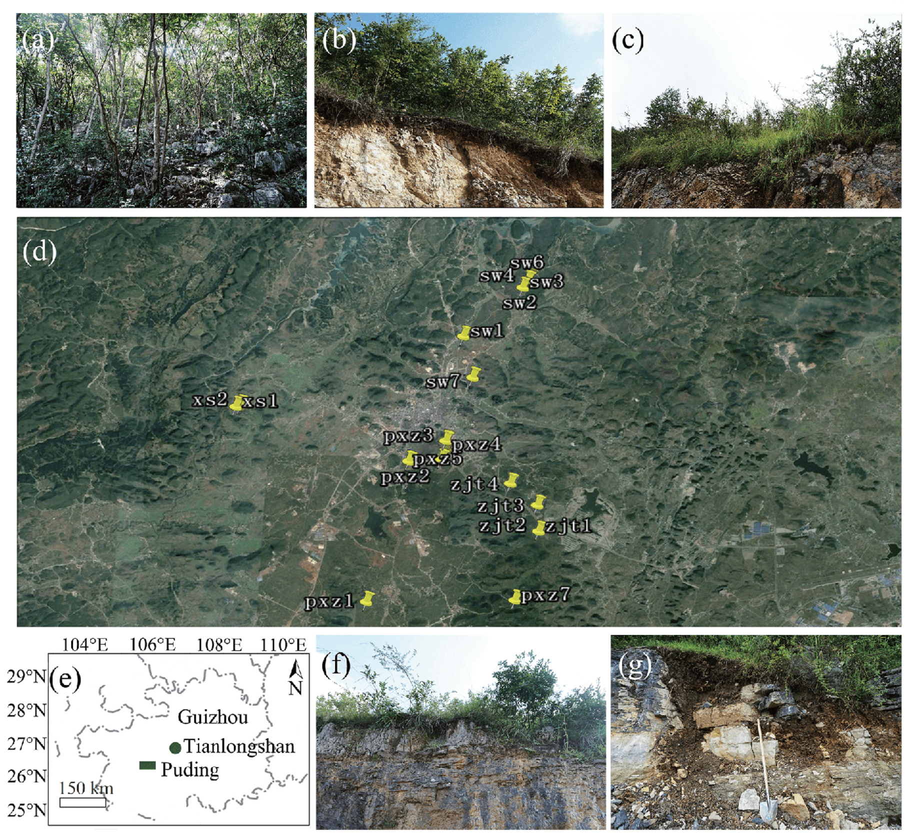

Figure 1 Location and sample photos (taken by Dai Jingyu in the summer of 2016). (a)–(c) Represent the forest vegetation on the limestone with a high crevice density, the shrub vegetation on the limestone, and the grassland vegetation on the dolomite with a low crevice density, respectively, taken on Tianlong Mountain, at the sw1 and sw2 plots, respectively; (d) represents the position of the section in the study area (Puding County and the surrounding sampling area): pxz, sx, sw, and zjt represent Puding (New Administrative Center), Xiushui, Shawan, and Zhaojiatian, respectively; (e) indicates the location of the study area and the Tianlong Mountain plot; (f) and (g) represent the soil profiles with low and high crevice densities, respectively (photos taken at the pxz4 and zjt2 plots, respectively).

soil layer was recorded at each location, and 10 values were averaged for each plot.

A vegetation survey was carried out above each rock section. The plot area was 10 m×10 m. The plant species appearing in the plot and the abundance, cover and height of each species were recorded.

2.3 Remote sensing data and its processing

This paper used MODIS data of the study area from 2001 to 2010 with a spatial resolution of 500 m and a time resolution of 16 d (23 phases per year). According to the regional geological map, this area is mainly limestone and dolomite. In the data preprocessing, the field sampling area was centered and expanded to the neighboring areas, all the limestone and dolomite pixels were selected separately, and the LAI data and the annual NPP data of each pixel were extracted. The area of the selected limestone area was 5986 km^2, and the area of the selected dolomite area was 6051 km^2. For the dolomite and limestone areas, the 10-year mean of each NDVI phase and the 10-year NPP mean were calculated separately.

2.4 Data analysis

First, the data of each species recorded in the field were quantified, the relative abundance (RA), relative cover (RC) and relative height (RH) for each species recorded in the plots were calculated, and finally, the important value (IV) of each species in the plots was calculated.

$$\text{RA}=\text{abundance of a species/total abundance of all species within a plot,} \quad (1)$$

$$\text{RC}=\text{cover of a species/total cover of all species within a plot,} \quad (2)$$

$$\text{RH}=\text{height of a species/total height of all species within a plot,} \quad (3)$$

$$\text{IV}=\text{(relative abundance+relative cover+relative height)/3.} \quad (4)$$

The IV was calculated for each woody and herbaceous species. The species with high IVs were recognized as the dominant species in the community.

For the NDVI and NPP values extracted from the remote sensing data, the difference in the NDVI in the different lithology areas was determined by a *t*-test, and the difference in NPP was determined by a *K-S* nonparametric test. The normal distribution of each set of data was tested prior to the *t*-tests.

3. Results

3.1 Differences in vegetation composition under different lithologies

The field survey results showed that the development of crevices under different lithologies was quite different. In the dolomite-based areas, the number of crevices with a width of >1 cm along the exposed rock section was usually less than 1 per 10-m distance, while the number of cracks in the limestone-based area was usually more than 5 per 10-m distance.

A total of 304 plant species were recorded in the study area. The distance from an urban area generally reflects the degree of human interference. With the increase in human disturbance, species diversity is gradually reduced. The average plant species richness of the plots in Tianlong Mountain was 40 species/100 m^2, Zhaojiatian was 28.5 species/100 m^2, and Shawan was 26.7 species/100 m^2. The average plant species richness in Xiushui was 25.5 species/100 m^2, while Puding had only 21.2 species/100 m^2. At the same time, the composition of the community may change. The dominant vegetation types in Tianlong Mountain were *Platycarya strobilacea* forest and *Machilus pingii* forest. There were few thorny plants under the forest, and the dominant species in the herbaceous layer was not clear. The dominant species in the arbor layer at Zhaojiatian, Shawan, Xiushui and Puding were *Coriaria nepalensis*, *Itea yunnanensis*, *Rosa cymosa*, *Viburnum foetidum* var. *ceanothoides*, and *Rhamnus heterophylla*. The proportion of thorny plants, such as *Itea yunnanensis*, *Rosa cymosa* and *Rhamnus heterophylla,* increased significantly with the decrease in distance from the urban area, which also reflected the impact of human activities. The dominant species in the herb layer was mainly *Cymbopogon goeringii* and *Themeda triandra* var. *japonica*.

Although human activities may reduce species diversity and change the species composition of plant communities, the cover of woody plants and herbaceous plants in the human-disturbed plots in Zhaojiatian, Shawan, Xiushui, and Puding did not show any correlation with human activities. The linear fitting of the woody and herbaceous cover of 18 plots in four plots with the development of rock crevices showed that the cover of woody plants in each plot was proportional to the degree of crevice development, while the cover of the herbaceous layer was inversely proportional to the degree of crevice development ($p<0.01$; Figure 2).

3.2 Differences in vegetation activities and productivity under different lithologies

The average NDVI value of each of the 23 phases from 2001–2010 between the limestone and dolomite distributions showed that the NDVI of the limestone distribution area was significantly higher than that of the dolomite distribution area for approximately 3/4 of the phases (17 phases) within a year ($p<0.01$). Insignificant months mainly occurred in January, February, May and August. However, comparing the multiyear NPP data of the dolomite and limestone distributions, the average NPP of the limestone distribution area

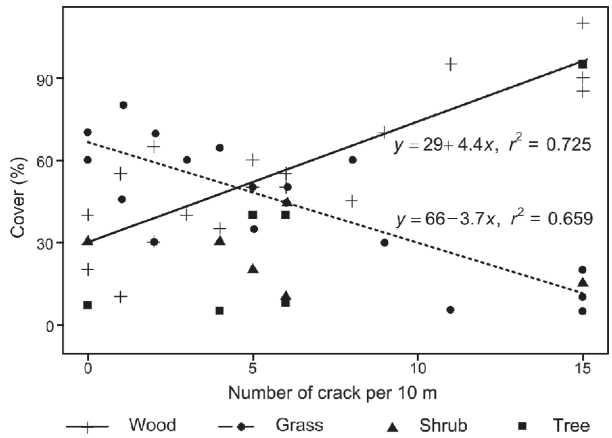

Figure 2 Relationship between vegetation characteristics and crevice density in the study area. The woody plant cover in the figure is the sum of the tree cover and the shrub cover, and its value is >100%.

from 2001 to 2010 was significantly lower than that of the dolomite area (Figure 3).

The NDVI characterizes vegetation activity while NPP characterizes productivity levels. The results of the vegetation activities and productivity under different lithologies corresponded well with the corresponding vegetation composition and cover results. In the limestone-based areas, the woody plants had high cover and strong vegetation activities, but the productivity level was low. In the dolomite-based areas, the herbaceous plants had high cover and weak vegetation activities, but the productivity level was high.

4. Discussion

The results of this paper show that both the species composition and cover reflected by the field surveys and the vegetation activities and productivity reflected by the remote sensing data were closely related to rock type. The limestone area was more suitable for the growth of deep-rooted trees, while the dolomite area was more suitable for the growth of shallow-root herbaceous plants. Although the NDVI in the limestone area was higher than that in the dolomite area, its vegetation productivity was lower than that of the dolomite area, which is consistent with the general characteristics of low biomass but high productivity of grasslands (Schultz et al., 1995). This result further demonstrates that the rock type-related soil distribution in the subsurface has an important impact on the aboveground vegetation, especially the distribution of woody plants and herbaceous plants, thus verifying the hypothesis proposed above.

The results of this paper further confirm the two-layer model of plant root distribution, that is, the roots of the trees were distributed in deep soil and the roots of the herbaceous plants were distributed in shallow soil (Schenk and Jackson, 2005). Deep-rooted trees may only grow in areas with thick soil layers or underground crevice networks to obtain sufficient water and nutrients for long-term stability, while thin soil areas can only sustain short-lived herbaceous plants. Rock gaps provide physical space for the roots of woody plants. The roots of deep-rooted woody plants can pass through soil or crevices to obtain deep groundwater to ensure normal plant growth (Canadell et al., 1996; Richter and Billings, 2015). There are many rock cracks in the limestone area, the surface soil is easily washed along these cracks into the underground crevice network, and soil erosion is enhanced. Despite this, the water reaching the deep cracks is difficult to evaporate and is easily absorbed by deep root trees.

The results of this study indicate that soil depth rather than soil volume determines the composition and productivity of aboveground vegetation, and different models of the rock-soil-vegetation-air continuum in dolomite and limestone distribution areas are proposed (Figure 4). In this study, observations of the cracks in the rock profile show that the roots of the trees can reach more than 1 m along the crack, which greatly exceeds the depth of concern for soil moisture research in the past. As the depth of a crack increases, the water and nutrient reserves increase by several orders of magnitude, and the retention time of water and nutrients in underground reservoirs is also lengthened (Richter and Billings, 2015). The underground crevices in the limestone distribution zone also promote the water connection between the deep rock and the aboveground vegetation. The bedrock may control the aboveground vegetation from the bottom up (Rempe and Dietrich, 2014, 2018; Hahm et al., 2014). Unlike the limestone distribution area, the dolomite distribution area has less soil leaching through the crevices. If the surface soil loss is not considered, the soil area per unit area of the dolomite distribution area is larger than that of the limestone distribution area, but the soil layer of the former is shallow, rarely exceeding 20 cm, and is not suitable for the growth of trees with deep roots. In the shallow soils of the dolomite distribution area, the water is easily evaporated and lacks the water connection with the deep rocks. Therefore, the vegetation cover of the dolomite distribution area is mainly herbaceous, and the NDVI value is low.

The results also suggest that the interaction between plant roots and rock layers is critical to the aboveground vegetation. A deep root depth means that plants can feed carbon energy into the weathering layers and even the rock crevices, further promoting soil weathering (Roering et al., 2010). Ectomycorrhiza can penetrate the micropores of the weathering layer at a depth of 4 m to promote water nutrient cycling within the system (Bornyasz et al., 2005). Plant roots, microbes, soil, and rock are often intertwined in the soil, making underground water and nutrient processes more complex (Richter and Yaalon, 2012). The rhizosphere effect of plants can activate organic nutrients and accelerate the

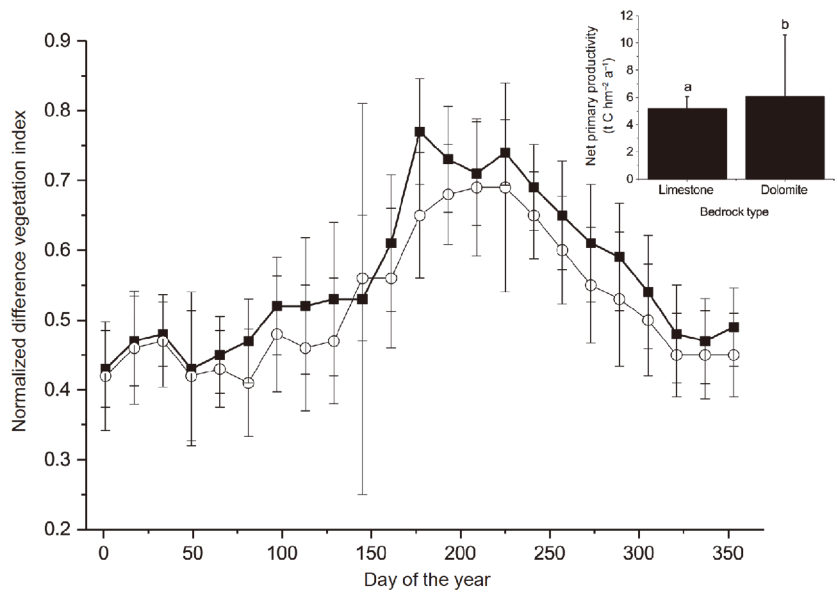

Figure 3 Comparison of the vegetation NDVI under different lithological conditions in the study area. Black squares indicate limestone areas, open circles indicate dolomite areas. The upper right panel shows the comparison of plant growth (average of net primary productivity for multi-years) in the dolomite and limestone regions, and a and b indicate whether there is a difference.

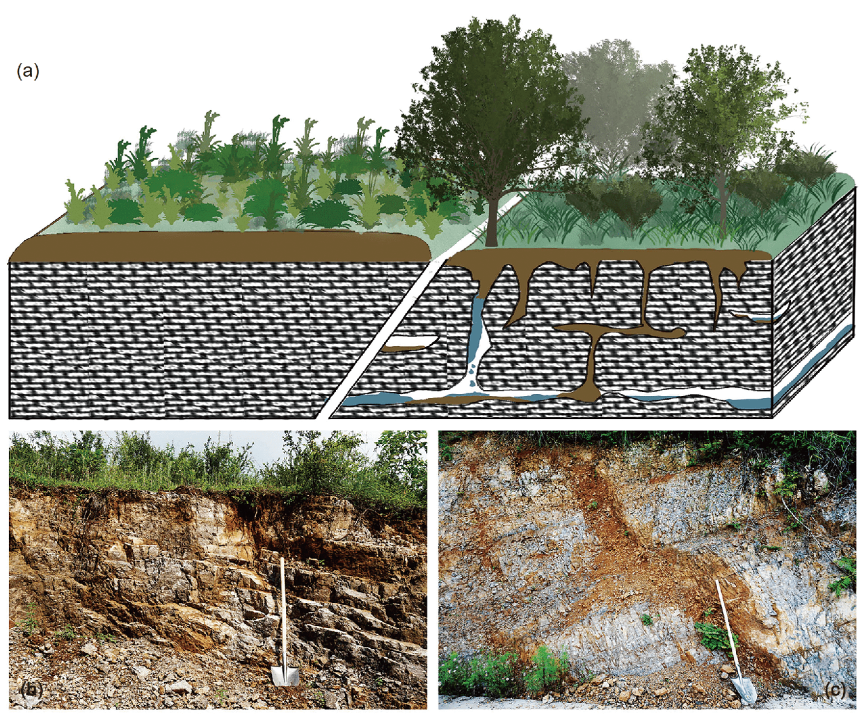

Figure 4 Schematic diagram of the rock-soil-vegetation-air system in the study area. (a) Shows that the difference in the subsurface crevices of the dolomite (b) and limestone (c) lead to different soil distributions, which further affects the composition and cover of the aboveground vegetation. The following picture shows the corresponding field photos: (b) dolomite; (c) limestone.

decomposition of soil organic matter while meeting the nutrient requirements of plants and the closely linked roots, microorganisms and soil (Kuzyakov and Xu, 2013).

The results of this study are of great significance for vegetation improvement and land-use optimization in key karst areas, which are threatened by rocky desertification. Globally, deep-rooted plants (more than 5% of the roots distributed over a depth of more than 2 m) are mainly distributed in drought-stressed areas (Schenk and Jackson, 2005), while the depth of agricultural tillage layers generally does not exceed 0.5 m. If tall trees are destroyed for planting relatively small crops, it means that plants can only use the limited water and nutrients in the shallow layer. Planting plantations in karst CZs for ecological restoration must focus on limestone distribution areas with developed crevices. Planting herbs for ecological restoration needs to focus on dolomite distribution areas to make full use of the water and heat resources, improve ecosystem productivity, and enhance its stability (Loreau and Hector, 2001).

It is still not possible to determine the amount of water that the rock layer itself provides to the roots of plants or the role of soil nutrients. However, it is certain that moist deep soil can preserve water through the interaction with the rock interface, which provides a way for further quantitative research on the utilization of water in soil and rock storage. The relationships among rock crevices, soil distribution and volume, and vegetation species composition and productivity can provide a basis for accurately quantifying the resilience and sustainability of CZs (Richter and Billings, 2015). Due to differences in the vegetation types and lithologic structures, the lower boundaries of water and nutrients in different CZs are highly variable (Roering et al., 2010; Holbrook et al., 2014). How to clearly define the water and nutrient dynamics on the vertical gradient of CZs is still a challenge (Lin, 2010).

5. Conclusions

This study explored the close relationship between the lithology of the karst CZ and the composition and productivity of aboveground vegetation through a vegetation survey and remote sensing image analysis of the karst CZ area. The dolomite rocks lacked large cracks, and there were large gaps in the limestone rocks. The cover ratio of the woody/herbal species in the aboveground vegetation showed a positive correlation with the wide cracks (width >1 cm) in the rocks. The NDVI results obtained based on the MODIS remote sensing data further indicated that the NDVI values of the limestone distribution areas were higher than those in the dolomite distribution areas, but the vegetation productivity was lower than that of the dolomite distribution areas, which is consistent with the general characteristics of forestland and grassland. The results of this study show that in the karst CZ, lithology determines the structure and distribution of the soil, which further determines the composition of the aboveground vegetation. Although the amount of soil in the limestone distribution area may be small, the developed crevice structure is more suitable for the growth of trees with deep roots, and the vegetation productivity is high. The current control of rocky desertification in karst areas needs to fully consider the rock-soil-vegetation-air interactions in the CZs of the Earth and consider measures for vegetation restoration based on lithology.

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