Science China Earth Sciences, Volume 62, November 2019, pp. 1756-1763
DOI: 10.1007/s11430-018-9328-3

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

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Abstract: The study of critical zone (CZ) of the Earth links the composition and function of aboveground vegetation with the characteristics of the rock layers, providing a new way to study how the special rock and soil conditions in the karst region affect the aboveground vegetation. Based on the survey results of rocks, soils and vegetation in the dolomite and limestone distribution areas in the Karst area of central Guizhou, it is found that the cover of woody plants increases linearly with the number of cracks with a width of more than 1 mm, while the cover of herbaceous plants shows an opposite trend ($p<0.01$). The dolomite distribution area is characterized by undeveloped crevice, 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 the trees, which leads to diversified species composition and complicated structure of aboveground vegetation. Based on the MODIS remote sensing data for the period 2001-2010, the normalized differentiated vegetation index (NDVI) and annual net primary productivity (NPP) results for each phase of the 16-day interval further indicate that the NDVI of the limestone distribution area is significantly higher than the dolomite distribution area, but the average annual NPP is the opposite. The results of this paper indicate that in the karst CZ, lithology determines the structure and distribution of the soil, which further determines the cover of woody plants 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 in 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 the karst CZ, and propose vegetation restoration measures suitable for different lithologies.
Key words: vegetation composition, vegetation productivity, dolomite, limestone, karst CZ

1. Introduction

China is an important distribution area of karst in the world. The area of karst distribution is 3.631 million km^2, of which the exposed carbonate bedrock is about 1.3 million km^2, and more than 40% is distributed in one of 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 consequent rapid expansion of rocky desertification has seriously affected the regional sustainable development. 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 them and ground environmental factors can be analyzed (Yue et al., 2010a, b). However, the complex underground structure of the karst distribution area may affect the surface vegetation by affecting 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 rate of surface soil to vegetation in the karst area of Southwest China is only 21%, and the contribution rate of topographic features is only 13.2%, indicating that it is difficult to explain the pattern of vegetation based on these two factors. There should be impact from the 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 further study of the mechanism of rock impact on surface vegetation.

The Earth's CZ refers to a heterogeneous near-surface environment, a natural habitat regulated by rock-soil-water-air-vegetation-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 has a large expansion 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 CZ in 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 CZ of the Earth. The karst CZ of this study refers to the area dominated by karst landforms.

The key areas of karst have serious soil erosion and 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, the developed rock joints cause the underground soil to be intermittently distributed (Yang et al., 2008). There is a big difference in the growth process for different plant species and even 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 CZ is limestone, followed by dolomite (Ma, 2002). The main difference between the two is the difference in Ca/Mg ratio. The limestone dominated by calcium carbonate is more likely to dissolve and form cracks, causing moisture and soil to enter the ground through cracks. The dolomite is mainly composed of magnesium carbonate, which is harder than limestone and is not easy to be 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 easy to infiltrate. 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 the difference of crevice structure 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 systematically studied the types of plant communities and their species composition 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 $\delta^{13}C$ value of leaves for dominant species in the karst area, it has been found that the $\delta^{13}C$ value is more negative, with narrower distribution range and lower variation for the leaves in the yellow soil area than that in the black lime soil area (Du et al., 2014). Correlation analysis showed that the main influencing factors of $\delta^{13}C$ value of plant leaves in yellow soil area were soil thickness and slope, and black lime soil area was soil water content, indicating that the effect of rock on plant $\delta^{13}C$ value was achieved by regulating soil moisture (Du et al., 2014). 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 such as pioneer species, sub-pioneer species, sub-climax species and climax species according to their drought tolerance. Among them, the pioneering species and the sub-pioneer species are more resistant to drought than the sub-climax species and the climax species (Yu et al., 2010). For 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 CZ of Karst in the central Guizhou Province, and made full use of the bedrock profile formed by aboveground vegetation. 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 the central Yunnan, with complex lithology and 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'-106°02'E, 26°25'-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 is seriously leaked, 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 surrounding areas in the core area of the CZ of the Karst. During the field investigation, the construction excavation site was 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 m a.s.l.. A total of 18 plots were excavated, and the length of each plot was over 10 m (Fig. 1). Longitude, latitude, altitude, slope, aspect, profile direction, lithology and other information are recorded at each survey site. In order to explain the influence of human disturbance, vegetation surveys were carried out in places with less disturbances such as Tianlong Mountain (26°14.8´N, 105°45.8´E), and 8 plots under 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 soil and roots in the cracks were recorded along the profile. The thickness of the surface soil layer was recorded at each location, and 10 values were averaged for each plot. 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 uses the 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 pre-processing, the field sampling area was centered and expanded to neighbor areas, and all the limestone and dolomite pixels were selected separately, and the LAI data and the annual NPP data of each pixel are extracted. The area of the selected limestone area is 5986 km^2, and the area of the dolomite area is 6051 km^2. For the dolomite and limestone areas, the 10-year mean of each phase NDVI and the 10-year mean of NPP were calculated separately.

2.4 Data Analysis

First, quantify the multi-degree data of each species recorded in the field, and then calculate the relative abundance (RA), relative cover (RC) and relative height (RH) for each species recorded in the plot, and finally calculate important value (IV) of each species in the plot.

RA = abundance of a species / total abundance of all species within a plot (1)

RC = cover of a species / total cover of all species within the plot (2)

RH = height of a species / total height of all species within the plot (3)

IV = (relative abundance + relative cover + relative height) / 3 (4)

The IV was calculated for each woody and herbaceous species. The species with high IV are recognized as the dominant species of the community.

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

3. Results

3.1 Differences in vegetation composition under different lithologies

Field survey results show that the development of crevices under different lithologies is quite different. In the dolomite-based areas, the number of crevices with a width of >1 cm along the exposed rock section are usually less than 1 per 10 m distance, while the number of cracks in the limestone-based area is usually more than 5 per 10 m distance. A total of 304 plant species were recorded in the study area. The distance from the urban area generally reflects the degree of human interference. With the increase of human disturbance, species diversity is gradually reduced. The average plant species richness of plots in Tianlong Mountain is 40 species/100m^2, Zhaojiatian is 28.5 species/100 m^2, and Shawan is 26.7 species/100 m^2. It is 25.5 species / 100 m^2, while Puding has only 21.2 species / 100 m^2. At the same time, the composition of the community may change. The dominant vegetation types of Tianlong Mountain are *Platycaya strobilacea*-forest and *Machilus pingii*-forest. There are few thorny plants under the forest, and the dominant species of herbaceous layer are not obvious. The dominant species of arbor layer at Zhaojiatian, Shawan, Xiushui and Puding are *Coriaria nepalensis*, *Itea yunnanensis*, *Rosa cymosa*, and *Viburnum foetidum* var. *ceanothoides*, *Rhamnus heterophylla*, and so on. The proportion of thorny plants such as *Itea yunnanensis*, *Rosa cymosa* and *Rhamnus heterophylla* increased significantly with the decrease of distance from the urban area, also reflected the impact of human activities. The dominant species of the herb layer is mainly *Cymbopogon goeringii* and *Themeda triandra* var. *japonica*.

Although human activities may reduce species diversity and change species composition of plant communities, the cover of woody plants and herbaceous plants in human-disturbed plots such as Zhaojiatian, Shawan, Xiushui, and Puding did not show any correlation with human activities. 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 degree of crevice development ($p<0.01$; Figure 2).

3.2 Differences in vegetation activities and productivity under different lithologies

The averaged NDVI value of each of the 23 phases for the period 2001-2010 between limestone and dolomite distributions shows that the NDVI of the limestone distribution area is significantly higher than that of the dolomite distribution area for about 3/4 phases (17 phases) within a year (p<0.01). Insignificant months mainly occur in January, February, May and August. However, comparing the multi-year NPP data of the dolomite and limestone distributions, it is found that the average NPP of the limestone distribution area for the period 2001-2010 is significantly lower than that of the dolomite area (Fig. 3).

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

4. Discussion

The results of this paper show that both the species composition and cover reflected by field surveys and the vegetation activities and productivity reflected by remote sensing data are closely related to rock types. The limestone area is more suitable for the growth of deep-rooted trees, while the dolomite area is more suitable for the growth of shallow root herbaceous plants. Although the NDVI in the limestone area is higher than that in the dolomite area, its vegetation productivity is lower than that of dolomite, which is consistent with the general characteristics of low biomass but high productivity compared with forests (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 are distributed in the deep soil and the roots of the herbaceous plants are distributed in the shallow soil (Schrenk 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. The rock gap provides 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 a lot of rock cracks in the limestone area, and the surface soil is easily washed along these cracks into the underground crevice network, and the soil erosion enhanced. Despite this, the water reaching the deep cracks is difficult to evaporate and is easily absorbed by the 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 rock-soil-vegetation-air continuum in dolomite and limestone distribution areas are proposed (Fig. 4). In this study, the observation of the crack of the rock profile shows that the roots of the trees can reach more than 1 m along the crack, which greatly exceeds the depth of concern for the soil moisture research in the past. As the depth of the crack increases, 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 et al. 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 soil of the dolomite distribution area, the water is easily evaporated and lacks the water connection with the deep rock. 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 aboveground vegetation. Deep root depth means that plants can feed carbon energy into weathering layers and even 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, accelerate the decomposition of soil organic matter while meeting the nutrient requirements of plants, and closely link 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 the key areas of karst, which are threatened by rocky desertification. Global deep-rooted plants (more than 5% of roots distributed over a depth of more than 2 m) are mainly distributed in drought-stressed areas (Schrenk 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 limited water and nutrients of the shallow layer. Planting plantations in the karst CZ for ecological restoration needs to focus on the limestone distribution areas with developed crevices. Planting herbs for ecological restoration needs to focus on the dolomite distribution area, so as to make full use of 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 the plant, nor the role of soil nutrients. But it is certain that the moist deep soil can preserve the water through the interaction with the rock interface, which provides a way for further quantitative research on the utilization of water in the soil and rock storage. The relationship between rock crevices, soil distribution and volume, vegetation species composition and productivity can provide a basis for accurately quantifying the resilience and sustainability of CZ (Richter and Billings, 2015). Due to differences in 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 explores the close relationship between the lithology of the karst CZ and the composition and productivity of aboveground vegetation through the vegetation survey and remote sensing image analysis of the CZ in the Karst area. The dolomite rocks lack large cracks, and there are large gaps in the limestone rocks. The cover ratio of woody/herbal species in the aboveground vegetation shows positive correlation with the wide crack (width >1 cm) in the rock. The NDVI results obtained based on MODIS remote sensing data further indicate that the NDVI values of the limestone distribution areas are higher than the dolomite distribution areas, but the vegetation productivity is lower than that of the dolomite distribution areas, which is consistent with the general characteristics of forest land 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.

Acknowledgement

This paper is granted by the China-UK Earth CZ Project "The Formation Mechanism of Ecosystem Services and Land Use Optimization in Karst CZ" from the National Natural Science Foundation of China (NSFC, grant No. 41571130044), NSFC Distinguished Young Scholar Funding (grant No. 41325002), 111 Plan (B14001), and Peking University Undergraduate Talents Training Program. We also thank the Puding

Karst Ecosystem Research Station of the Chinese Academy of Sciences for providing assistance in the field survey.

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Figure captions

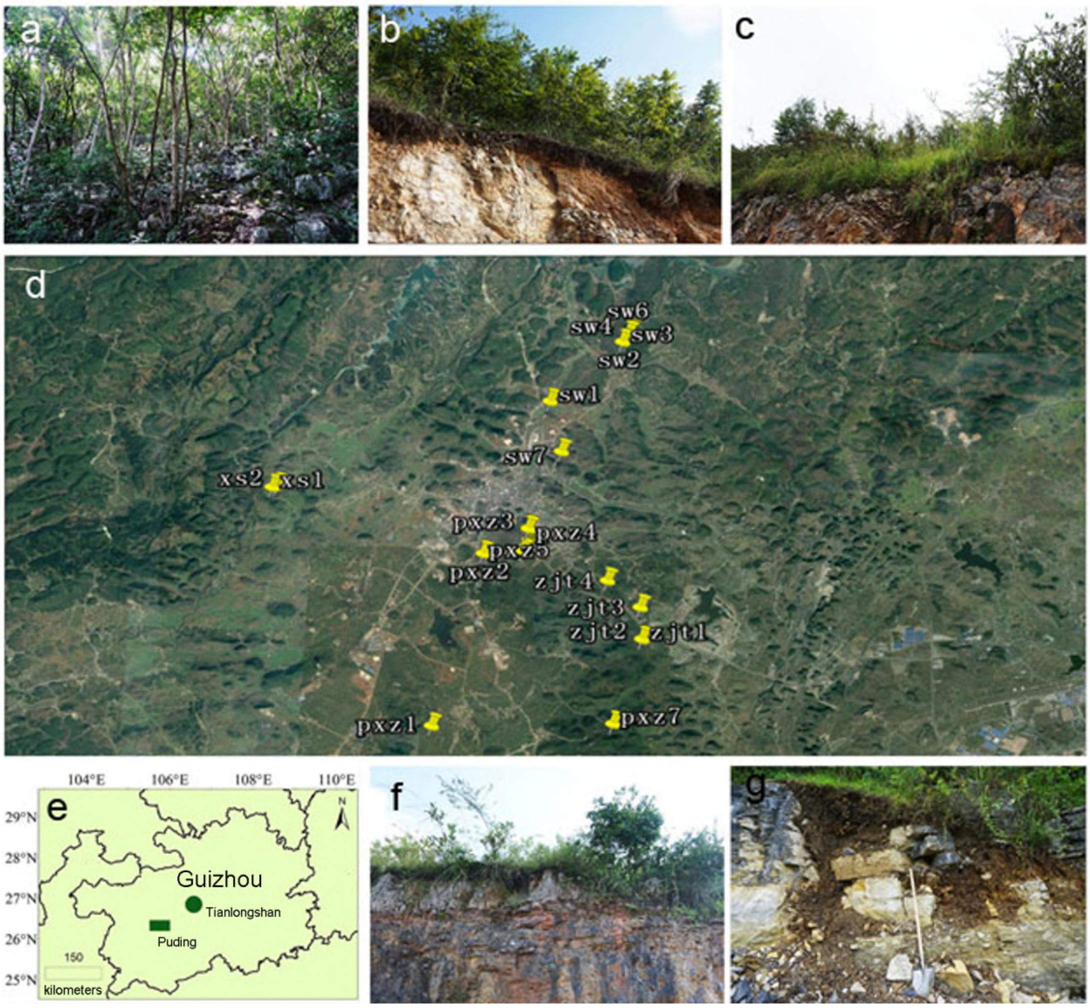
Figure 1 Location and some sample photos (taken by Dai Jingyu in the summer of 2016). a, b, c respectively represent the forest vegetation on the limestone with high crevice density, the shrub vegetation on the limestone, and the grassland vegetation on the dolomite with low crevice, respectively, taken at sw1 and sw2 plots in the Tianlong Mountain, respectively. d represents the position of the section in the study area (Puding County and surrounding sampling area), pxz, sx, sw, zjt represent Puding (New Administrative Center), Xiushui, Shawan, 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 density, respectively (photo taken in the pxz4 and zjt2 plots, respectively).

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%.

Figure 3 Comparison of vegetation NDVI under different lithological conditions in the study area. Black squares indicate limestone areas, open circles indicate dolomite areas, and * indicates significant differences ($p < 0.01$). The upper right panel shows the comparison of plant growth (average of net primary productivity for multi-years) in 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. The figure above shows that the difference in the subsurface crevices of dolomite (left) and limestone (right) leads to different soil distributions, which further affects the composition and cover of aboveground vegetation. The following picture shows the corresponding field photos (Dolomite on the left and limestone on the right)

Figure 1


a
b
c
d
sw6
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sw2
sw1
sw7
xs2
xs1
pxz3
pxz4
pxz5
pxz2
zjt4
zjt3
zjt2
zjt1
pxz1
pxz7
104°E
106°E
108°E
110°E
29°N
28°N
27°N
26°N
25°N
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N
Guizhou
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150
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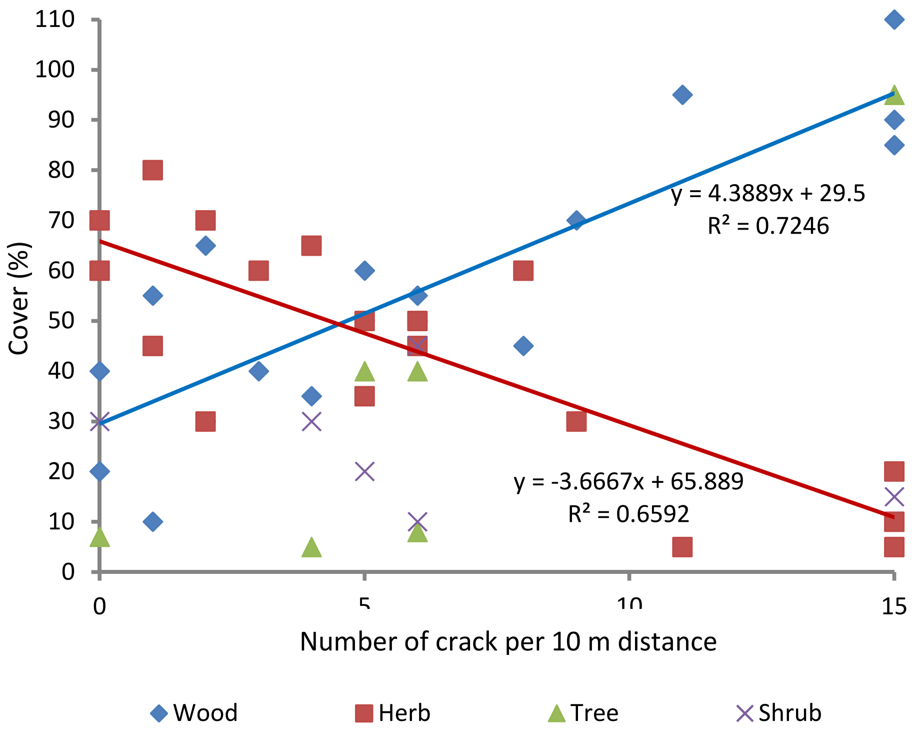
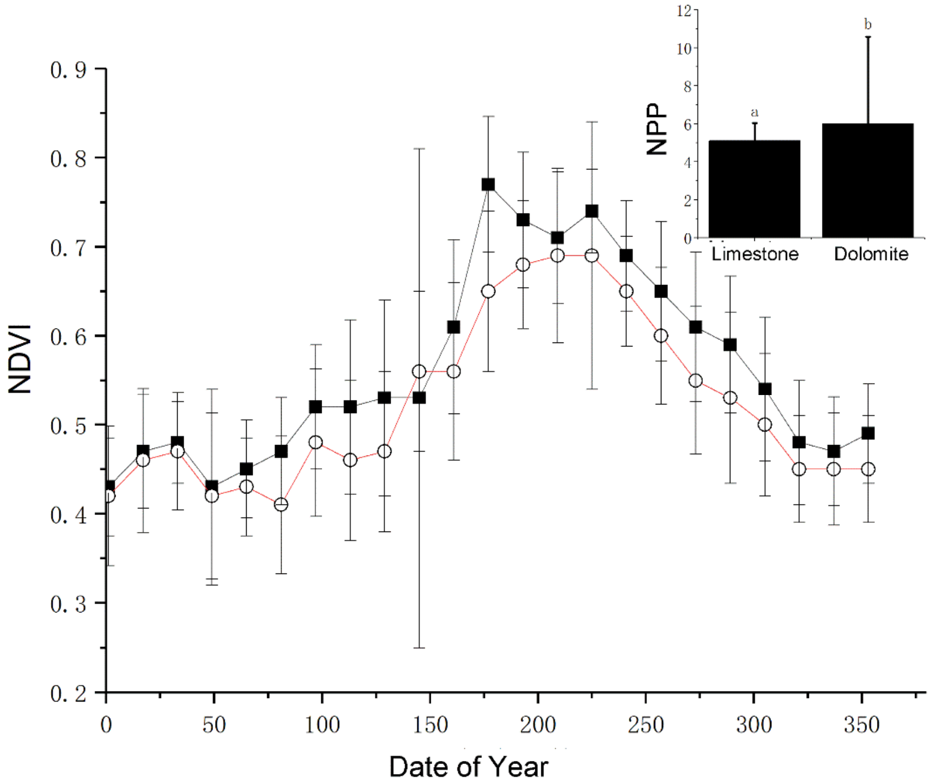
Figure 2



110
100
90
80
70
60
50
40
30
20
10
0
Cover (%)
0
5
10
15
Number of crack per 10 m distance
y = 4.3889x + 29.5
R² = 0.7246
y = -3.6667x + 65.889
R² = 0.6592
Wood
Herb
Tree
Shrub

Figure 3



NDVI
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0
50
100
150
200
250
300
350
Date of Year
NPP
12
10
8
6
4
2
0
a
b
Limestone
Dolomite

Figure 4