Bedrock type mediates the response of vegetation growth to seasonal precipitation in the karst zone of subtropical China

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Abstract: Low water conservation ability of carbonate limits vegetation growth in karst landscape has been commonly recognized, but how bedrock mediates the effect of precipitation on vegetation growth remains unclear. We studied the spatio-temporal differences of vegetation growth in Guizhou Province of China by dividing the study region into three types of lithological region based on stream sediment geochemical data. The differences of precipitation-vegetation growth relationship among them were assessed. The results show that in months with low precipitation (0–150 mm), lower vegetation growth occurs in regions where the bedrock has higher calcium (Ca) content, whereas in months with high precipitation (150–250 mm), significant differences are not observed in the vegetation growth among various lithological regions. Extremely high amount of precipitation (>250 mm) can even benefit vegetation growth on the karst landscape. Our findings highlight that there is a threshold of precipitation amount for limiting vegetation growth in the karst landscape, which should be taken into account when studying responses of vegetation growth to climate change in the karst landscape.

Keywords: carbonate rock, karst, intermittent drought, enhanced vegetation index, temporal and spatial distribution of precipitation

1. Introduction

Restricted vegetation growth in karst region has been commonly attributed to the low water conservation ability of the regolith (Hamp et al., 2014; Morford et al., 2011; Neff et al., 2006; Wang et al., 2010), although surface climate and soil conditions have been considered the main cause of the spatial variations in vegetation growth (Fridley et al., 2011; Guay et al., 2014; Lobell et al., 2015; Medlyn et al., 2016). Despite the recognition of bedrock on vegetation growth, how bedrock mediates the effect of precipitation on regional vegetation growth, however, remains unclear.

The main challenges of evaluating the mediation of bedrock lie on spatial heterogeneity of bedrock distribution and the high costs involved in quantifying chemical and physical constituents of bedrock samples, which limits high-precision rock sampling within large areas. Stream sediments are products of re-precipitation after rock weathering; such sediments are mechanically transported by or dissolved in and then transported by surface runoff or groundwater into stream systems (Cheng and Agterberg, 2009). Extensive research demonstrates that the contents of stream sediments are close to the average element contents of rocks in the upstream catchment basin (Albanese et al., 2007; Vital and Stattegger, 2000). Recent research has found significant chemical element similarities between stream sediments and rocks on a large scale, which provides an excellent tool for analysing the effects of bedrock-mediated available water on vegetation (Kirkwood et al., 2016).

Vegetation in carbonate zones might be easily affected by drought during low precipitation seasons, whereas vegetation in non-carbonate zones can use water contained in deep soil layers during drought episodes, thus have greater resilience to drought episodes. Under sufficient precipitation, the difference in vegetation productivity between carbonate and non-carbonate zones is expected to disappear. In this study, we hypothesized that vegetation growth patterns differed among bedrock types. In other words, vegetation growth is slower in carbonate zones during periods with lower precipitation than in non-carbonate zones; as precipitation increases, such differences may not exist.

Regions underlain by carbonate rocks in Guizhou Province situated in subtropical China account for 66% of its total area. A relatively large variety of lithological types with complex compositions occurs in Guizhou. In addition, karst landforms have developed in most regions. Due to their low water conservation ability, karst ecosystems are extremely vulnerable and prone to rocky desertification characterized by reduced vegetation cover and severe erosion of soil (Zhan et al., 2013). Field observations have found that regions with high rock $CaCO_3$ content in Guizhou have developed large

numbers of cracks and undergone more significant rocky desertification (Sun et al., 2002). However, how lithology is linked to drought that affects vegetation growth remains unclear. The main objective of this study is to investigate the indirect effects of lithology–associated drought that affect vegetation growth in Guizhou Province based on remote sensing, climate and stream sediment data, and to answer the following two questions:

(1) Does lithology affect vegetation growth by regulating the relationship between precipitation and vegetation?

(2) Is vegetation growth more sensitive to droughts in regions with more carbonate rocks and more severe soil erosions?

2. Study area

Situated in subtropical China (24°30'–29°13'N, 103°1'–109°30E), Guizhou Province encompasses an area of 176,167 km^2, of which 66% has carbonate bedrock and the remaining approximately 34% (mainly distributed in the south, southwest and north) has clastic and igneous rock substrates. The study area has a subtropical humid monsoon climate with annual average temperatures of 11–20 °C and annual precipitation of 730–2,300 mm. Significant seasonal changes in precipitation occur, and 75% of the annual precipitation occurs in summer and fall (June-October, based on meteorological station data statistics for the period 2001–2010).

3. Data sources and methods

The precipitation data used in this study originated from monthly data collected at 78 meteorological stations for the period 2001–2010 and downloaded from the National Meteorological Information Center of China (http://data.cma.cn/user/toLogin.html). The enhanced vegetation index (EVI) can reflect the growth conditions of vegetation and is often used to monitor vegetation growth. The EVI data used in this study originated from Moderate Resolution Imaging Spectroradiometer (MODIS) sensor data (resolution: 500 m; time interval: 16 days) (https://ladsweb.modaps.eosdis.nasa.gov/) for the period 2001–2010.

The geochemical distribution data for stream sediments used in this study originated from the *Geochemical Atlas of Guizhou Province* (Feng, 2009). This atlas was prepared using loaded regional geochemical survey data for Guizhou Province at a 1:200,000 scale. The whole Guizhou Province was

95 divided into 1 km^2 sampling units. At least one sampling point was set in each sampling unit, mainly in
96 the middle of secondary stream systems and at the mouths of primary stream systems. A total of
97 464,004 stream sediment or diluvial soil samples were collected. During the atlas preparation process,
98 the concentrations of each chemical element were divided into 12 levels statistically.
99
100 **3.2 Data analysis**
101 The monthly precipitation recorded at the meteorological stations was interpolated using the
102 kriging interpolation method. Precipitation in regions with various levels of calcium (Ca) concentration
103 was calculated using regional analysis. Thus, precipitation time-series data was obtained. The EVI data
104 was corrected, and unclear images removed. The EVI for each month was calculated. Similarly,
105 precipitation time-series data for regions with various levels of Ca concentration were also calculated
106 by regional analysis.
107 Because the extent and erosion rate of carbonate rocks are determined by the fractions of calcite
108 and dolomite, geochemical differences in Ca can reflect the differences in bedrock. To simplify the
109 analysis, the EVI time-series data for different regions were subjected to cluster analysis. Because the
110 complexity of time series affects the estimate of the difference between separate time series, a
111 complexity-invariant dissimilarity (CID) measure (see equation below) was used to calculate the
112 distance between any two EVI time series (Serrà and Arcos, 2014).
113

114 $$CE(X_T) = \sqrt{\sum_{t=1}^{T-1}(X_t - X_{t+1})^2}$$

115 $$CF(X_T, Y_T) = \frac{\max\{CE(X_T), CE(Y_T)\}}{\min\{CE(X_T), CE(Y_T)\}}$$

116 $$d_{CID}(X_T, Y_T) = CF(X_T, Y_T).d(X_T, Y_T)$$

117 where X_T and Y_T represent time series X and Y, respectively; $CE(X_T)$ is the variability of time
118 series X; $CF(X_T, Y_T)$ is a complexity correction factor; and $d_{CID}(X_T,Y_T)$ is the distance between time
119 series X and Y.
120 To analyse the differences in the EVI between rocks with various levels of Ca in different months,
121 a multi-sample *t*-test was performed (Cressie and Whitford, 2010). Prior to the *t*-test, the normal

distribution of each set of data was determined. Data that failed to conform to a normal distribution were transformed using log-transformation. Calculations involving the EVI were performed using ArcGIS. The *t*-test and cluster and discriminant analysis were conducted using the "TSdist" package for the R statistical software (Mori et al., 2016).

4. Results

4.1 Division of lithological regions and their characteristics of plant growth

Based on the calculation results for the CID measure, grids with 12 levels of Ca content were clustered into three types (Fig. 1): I. regions with stream sediments having Ca contents lower than 25.6%; II. regions with stream sediments having Ca contents greater than 25.6% but lower than 50.7%; and III. the remaining regions with a Ca content greater than 50.7%. A clustering score of 8.65 (full score: 10) indicates that the discriminant analysis based on the CID measure reflects the difference between clusters relatively well.

The clustering results were validated using the lithology distribution map. The results show that 100% of the Type I regions contain clastic and igneous rocks with no rocky desertification (vegetation degradation in the karst region), that 85% of the Type II regions contain limestone or dolomite (of which 65% have undergone rocky desertification), and that 90% of the Type III regions contain limestone (of which 25% have undergone severe rocky desertification). These validation results demonstrate that geochemical distribution data for stream sediments can satisfactorily reflect the difference in bedrock and soil erosion situations.

The temporal change of EVI among three lithological regions were similar (Fig. 2): all of three lithological regions show lower EVI in spring (Jan-Mar) and winter (Oct-Dec), and the peak exhibit in Aug. The EVI of type I lithological region significantly higher than type II and III in each month, but the difference change across time, the greatest difference of EVI among three lithological zone were more pronounced in spring and winter, whereas the differences were lower during summer (Jun-Aug).

4.2 Characteristics of precipitation in different lithological regions

Precipitation in Guizhou exhibits relatively significant temporal heterogeneity (Fig. 3). The statistical precipitation data for the period 2001–2010 show that 61% of the precipitation was concentrated between May and August of each year, with only 17% of the precipitation occurring

between January and April, and 21% occurring between September and December. In addition, the highest precipitation occurred in June, whereas the lowest precipitation occurred in December. There is no significant difference in annual precipitation amount among Types I, II and III lithological regions. The significant difference in monthly precipitation amount only exhibited in June, July and August, when the precipitation in Type I lithological regions was significantly higher than those in Types II and III lithological regions ($p < 0.01$).

4.3 Relationship between vegetation growth pattern and precipitation in different lithological regions

The relationship between vegetation growth patterns and precipitation varied between different lithological regions (Fig. 4). An analysis of the EVIs corresponding to various levels of precipitation showed that in months with precipitation less than 150 mm, the EVIs for Type I lithological regions were significantly higher than those of Types II and III lithological regions (type I -type II: $p < 0.01$;); in months with precipitation greater than 150 mm but less than 250 mm, significant differences were not observed in the EVIs among the three types of lithological regions; and in months with a precipitation greater than 250 mm, the EVIs for Type I lithological regions were again higher than those for Types II and III.

5. Discussion

The analysis of the relationship between vegetation growth patterns and precipitation in regions with different types of bedrock shows that the properties of bedrock alter the relationship between vegetation and precipitation. In regions where the bedrock contains relatively high amounts of Ca, vegetation growth is more sensitive to drought stress. The insignificant difference in vegetation growth among regions with different lithologies during periods with high precipitation demonstrates that there is a threshold of precipitation amount for the mediation of bedrock on the precipitation-determined vegetation growth.

The solubility of bedrock is related to its composition. Because the dissolution of carbonate rocks is caused by the hydrolysis of calcium carbonate ($CaCO_3$) (Ford and Williams, 2011; Estrada-Medina et al., 2013), rocks with higher carbonate content, including both calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) present higher dissolution rates. Laboratory simulations have shown that the dissolution

rates of carbonates are several tens to hundreds of thousands of times those of silicates (Dreybrodt, 1990). Due to their high solubility (Bakalowicz, 2005; Zhang et al., 2012), carbonate rocks develop large numbers of cracks on their surface as a result of precipitation-induced water erosion, which significantly increases the infiltration of water, and therefore, limits the growth of aboveground vegetation through prolonged drought period (Liu et al., 2019). As a result, the regions where the bedrock with high Ca content commonly exhibit low water storage capacity (Karasuyama et al., 2011). Therefore, under low precipitation period, vegetation growth could be limited by drought stress. In contrary, water storage of regolith can help vegetation to resist drought in a region with low Ca concentration bedrock.

It is noteworthy that under high precipitation condition, the vegetation growth in Type I bedrock regions was significantly superior to those in Types II and III regions, which might be due to the regolith layer in regions with carbonate rocks has low water storage capacity. In addition, vegetation coverage in these regions is low. As a result, precipitation can easily cause floods or mudflows, thereby affecting vegetation growth (Xu et al., 2008). Another possibility is that vegetation in regions with carbonate rocks has low tolerance to floods (Rong and Xiong, 2007). Because regions with carbonate rocks are prone to droughts, a number of types of vegetation have developed an aerial root structure (Liu et al., 2011). Heavy precipitation renders the root systems of these types of vegetation unable to respire normally, thereby damaging or destroying them and consequently affecting vegetation growth. This finding reflects the vulnerability of ecosystems in regions with carbonate rocks. Due to severe soil erosion, vegetation in regions with carbonate rocks is more easily affected by extreme weather conditions than in other regions.

We do not intend to deny that bedrock can affect vegetation growth in a number of other ways. For example, the soil composition strongly relies on bedrock (Xiang et al., 2011). Some important nutrient elements (e.g., phosphorus, iron, and magnesium) are mainly originated from the weathering of rocks. In addition, the physical and chemical properties of soil are affected by bedrock. For example, the clay component of a soil primarily comes from the weathering of silicon and magnesium compounds in rocks (Williamson et al., 2004). However, the availability of soil nutrients is greatly associated with available water in the soil, and the percentage of clay component also contributes to soil water availability.

5. Conclusions

In this study, the determination and classification of changes in the chemical elements in stream sediments shows that these changes reflect the difference in bedrock very well and suggests that stream sediments can be used as a basis for distinguishing bedrock types, which could provide a useful tool for studying the mediation of bedrock on vegetation growth on a large scale. The effects of bedrock are found to be significant in karst regions, even on a regional scale (approximately 170,000 km^2), based on remote sensing images and stream sediment data. The bedrock-mediated available water can regulate the relationship between precipitation and vegetation growth on a large scale. There is a threshold of less than150 mm monthly precipitation amount for limiting vegetation growth in the karst landscape in the subtropical region of China. As regions with carbonate bedrock cover 15% of the Earth's surface, this kind of threshold should be taken into account when studying responses of vegetation growth to climate change in the karst landscape.

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Fig. 1 Division of lithological regions based on stream sediment and their temporal changes in the EVI. Within the red borders are Type III bedrock regions, where the bedrock has relatively high Ca content (consists mainly of limestone and dolomite) and karst landforms are well developed; within the blue borders are Type II bedrock regions, where the main bedrock types are dolomite and sandstone-shale; the remaining area is Type I bedrock, where the main bedrock types are clastic and igneous rocks. The grey levels from black to white represent EVI from 0 to 1.

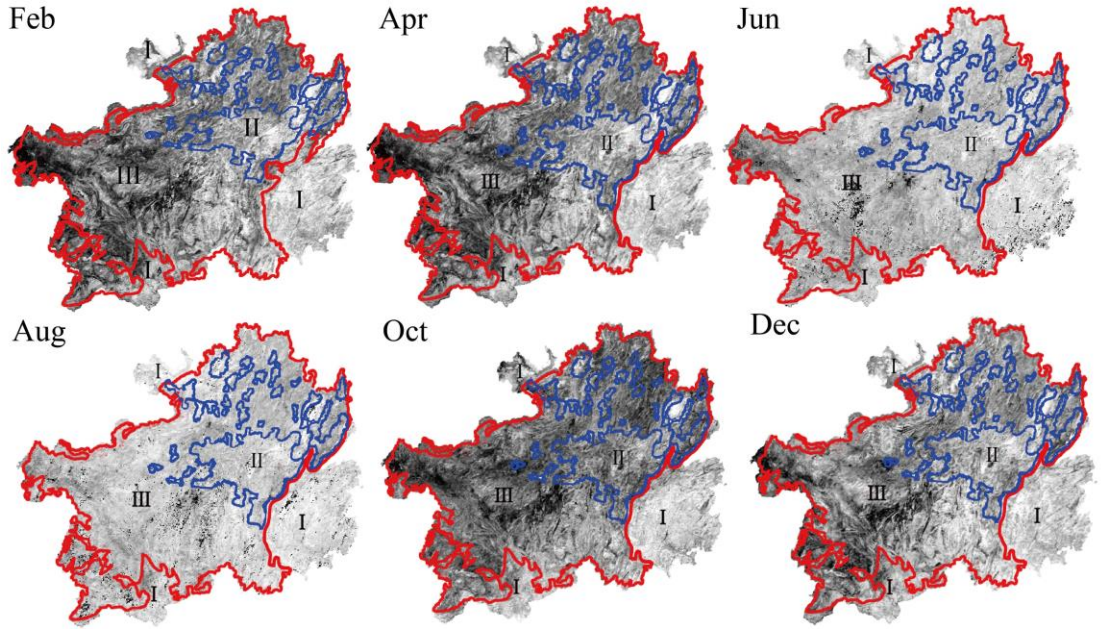

Fig.2 Vegetation growth patterns in different lithological regions of Guizhou Province. The curves show the changes in the EVI for different lithological regions, with the curves of different types representing the different lithological regions.

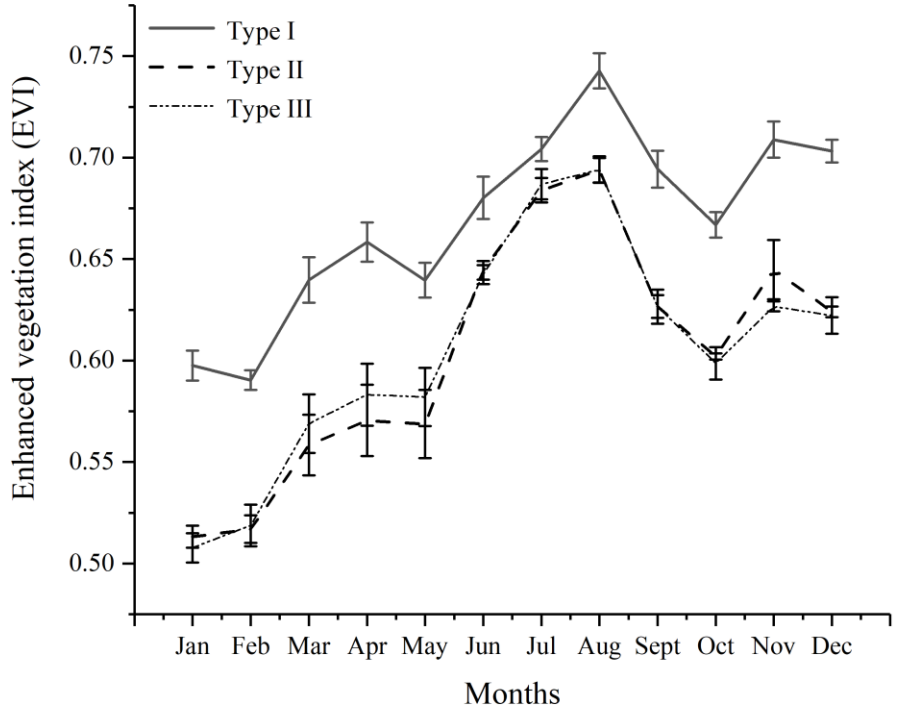

Fig.3 Temporal distribution of precipitation in different lithological regions. The dots show precipitation conditions in Type I lithological regions; the triangles show precipitation conditions in Type II lithological regions; the squares show precipitation conditions in the Type III lithological regions. The histogram in the upper right corner shows the difference in annual precipitation between lithological regions.

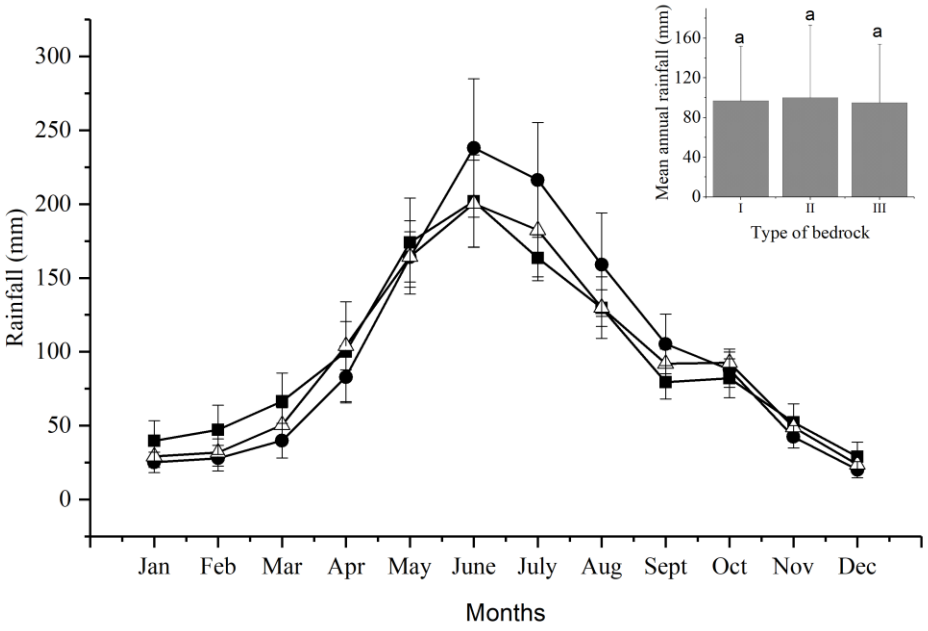

Fig. 4 Relation between bedrock type and vegetation growth (EVI) under various precipitation conditions. The value at the upper right corner of each histogram is the monthly precipitation.