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Δ¹³C VALUES OF SOIL ORGANIC CARBON AND THEIR RESPONSES TO C_3 AND C_4 PLANTS SHIFT IN MENGZI KARST GRABEN BASIN, SW CHINA

ODZIV VREDNOSTI Δ¹³C V ORGANSKEM OGLJIKU PRSTI NA SPREMEMBO SESTOJA RASTLIN C_3 IN C_4: PRIMER OBMOČJA MENGZI, JUGOZAHODNA KITAJSKA

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Abstract UDC 631.417.1:581.5(510-14)

Hui Yang, Tongbin Zhu, Farzaneh Garousi, Qiang Li & Jianhua Cao: δ¹³C values of soil organic carbon and their responses to C_3 and C_4 plants shift in Mengzi karst graben basin, SW China

Understanding the controlling factors of soil organic carbon isotope ($\delta^{13}C_{SOC}$) change and the vegetation succession process is crucial to guide ecological restoration and agricultural cultivation in karst rocky desertification region. However, the information about the combination of C_3 and C_4 plant distribution and rocky desertification remains unknown. Soils from different landforms, including basin, slope, and plateau, were sampled to investigate the spatial variance of the $\delta^{13}C_{SOC}$ distribution characteristics. The contribution of C_3 and C_4 plant species for $\delta^{13}C_{SOC}$ under the different rocky desertification grades (LRD: light rocky desertification; MRD: moderate rocky desertification; and SRD: severe rocky desertification) in Mengzi karst graben basin of Southwest (SW) China was also discussed. The $\delta^{13}C_{SOC}$ value decreased with the increase of altitude from basin, slope to plateau. At the same landform, different rocky desertification grades had no significant effect on the $\delta^{13}C_{SOC}$ in slope and plateau. Nevertheless, there were significant differences of $\delta^{13}C_{SOC}$ between LRD and SRD in basin. The C_4 plants account for more than 70% in the basin and slope, while C_3 plants account for more than 70% in the plateau. This may be due to the long-term cultivation of corn in the historical period in the basin and slope. However, the plateau area is not suitable for the growth of C_4 plants such as corn due to cold climate. In addition, in the same landform, with the aggravation of rocky desertification, the proportion of C_4 plants for $\delta^{13}C_{SOC}$ increased with the proportion of C_3 plants decreased. With the aggravation of rocky desertification, the composition of vegetation species changed from arbor (C_3 plants) to small shrubs and herbs (C_4 plants).

Key words: stable carbon isotope, rocky desertification, C_3 and C_4 plants, karst graben basin.

Izvleček UDK 631.417.1:581.5(510-14)

Hui Yang, Tongbin Zhu, Farzaneh Garousi, Qiang Li & Jianhua Cao: Odziv vrednosti δ¹³C v organskem ogljiku prsti na spremembo sestoja rastlin C_3 in C_4: primer območja Mengzi, jugozahodna Kitajska

Razumevanje povezave med spremembami izotopa v organskem ogljiku v tleh ($\delta^{13}C_{SOC}$) in procesi ekološke sukcesije je pomembno pri restavraciji in kultivaciji kraških degradiranih območij. O povezavi med porazdelitvijo sestoja rastlin C_3 in C_4 ter skalno dezertifikacijo na kraških območjih vemo le malo. Prostorsko spremenljivost $\delta^{13}C_{SOC}$ smo določali na različnih površinskih oblikah; v kotlini, na pobočjih in na kraški planoti na območju Mengzi v provinci Junan na jugovzhodu Kitajske. V vseh reliefnih oblikah smo obravnavali prispevek rastlinskih vrst C_3 in C_4 k vrednosti $\delta^{13}C_{SOC}$. Posebno pozornost smo posvetili tudi različnim stopnjam dezertifikacije (LRD: majhna; MRD: zmerna; in SRD: visoka). V splošnem vrednost $\delta^{13}C_{SOC}$ pada z naraščanjem nadmorske višine. Na planoti in pobočjih stopnja dezertifikacije ne vpliva pomembno na $\delta^{13}C_{SOC}$, v kotlini pa je značilna razlika med območji z nizko stopnjo dezertifikacije in območji z visoko stopnjo dezertifikacije. Sestoji rastlin C_4 tvorijo več kot 70 % rastlinja v kotlini in na pobočjih, sestoji rastlin C_3 pa 70 % rastlinja na planoti. Razlika je verjetno posledica pridelave koruze v kotlini in na pobočjih, saj planota zaradi hladne klime ni primerna za sajenje rastlin C_4, kot je koruza. Sočasno z napredovanjem dezertifikacije upada delež rastlin C_4 (npr. dreves) in narašča delež rastlin C_3 (grmičevje in zeli).

Ključne besede: stabilni ogljikov izotop, skalna dezertifikacija, rastline C_3 in C_4, kraška kotlina.

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INTRODUCTION

Soil organic carbon (SOC) mainly comes from the organic residues of terrestrial plants, especially decomposition and metabolites of the roots, stems and leaves of higher plants (Bai *et al*. 2006). Soil organic carbon has a carbon isotopic composition comparable to that of the source plant material prior to humification (Schwartz *et al*. 1986), and every change in vegetation between C_3 and C_4 types could thus lead to a corresponding change in the ^{13}C value of the SOC ($\delta^{13}C_{SOC}$) (Schwartz *et al*. 1986). Three photosynthetic pathways exist among terrestrial plants: C_3, C_4, and *crassulacean acid metabolism* (CAM) photosynthesis (Ehleringer & Cerling 2002). Plants with C_3, C_4 and CAM photosynthesis have unique $\delta^{13}C$ values which are not altered significantly during decomposition and soil organic matter formation (Boutton *et al.* 1998). Plants with C_3 photosynthesis have $\delta^{13}C$ values ranging from approximately -32 to -22‰ (mean ca. -27‰), while those with C_4 photosynthesis have $\delta^{13}C$ values ranging from approximately -17 to -9‰ (mean ca. -13‰). Plants with obligate CAM have $\delta^{13}C$ values similar to C_4 plants; however, those with facultative CAM may range from -30 to -10‰. It depends on the relative amount of carbon fixed by CAM vs. C_3 photosynthesis (Griffiths, 1992; Boutton *et al.* 1998). Consequently, $\delta^{13}C_{SOC}$ values reflect the relative contribution of plant species with C_3, C_4 and CAM photosynthetic. It also reveals the pathways to community net primary productivity, the vegetation change, the organic matter turnover. From the perspective of earth critical zone (ECZ), $\delta^{13}C_{SOC}$ avail to the understanding of earth-atmosphere-biosphere interactions (Boutton *et al.* 1998). Therefore, the composition of $\delta^{13}C_{SOC}$ is consistent with that of plants which form the source of organic matter (Bai *et al.* 2006). The stable carbon isotope ratio of SOC can be used to reconstruct the

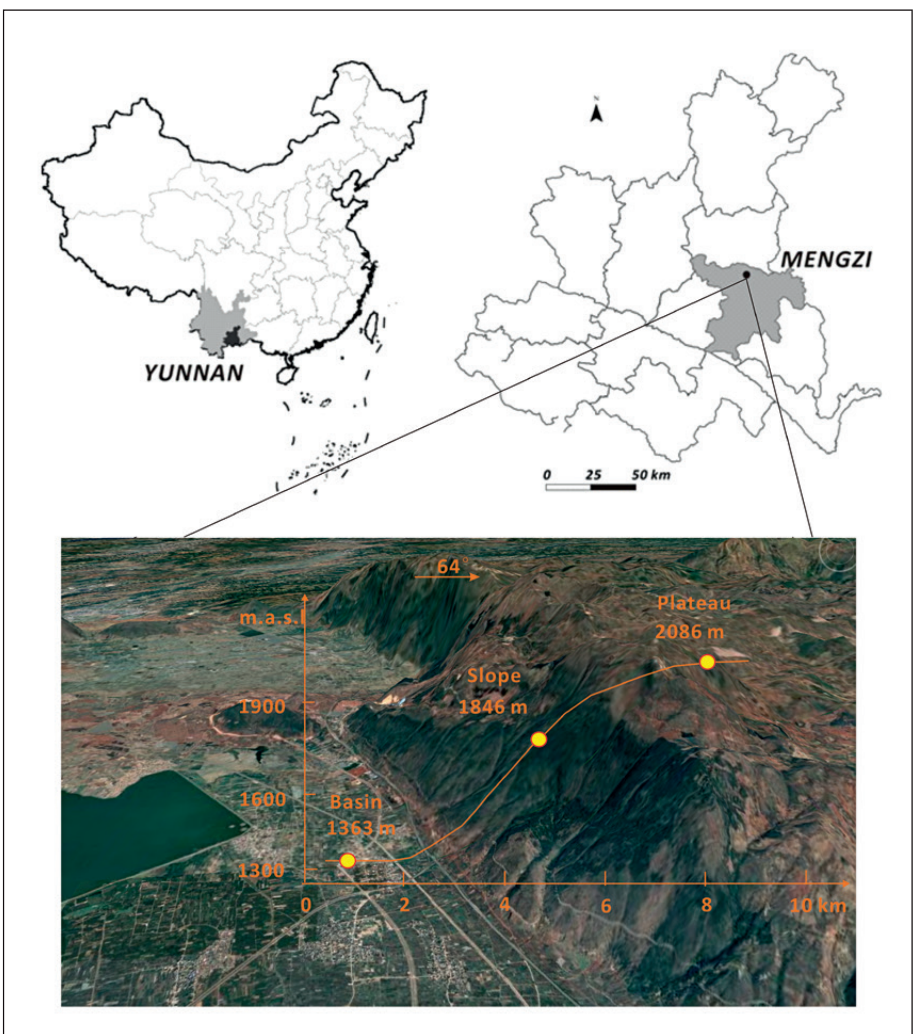

Fig. 1: Location of sampling sites in Mengzi county, Yunnan province.

vegetation dynamic process on the ecological and geological time scales. Studies on isotopic natural abundance have often been used to describe the dynamics of SOC (Balesdent *et al.* 1987; Desjardins *et al.* 1994; Ehleringer *et al.* 2000) or even to reconstruct vegetation changes over time (Boutton *et al.* 1998; Biedenbender *et al.* 2004; Xin *et al.* 2016).

The basin-mountain topography in the karst graben basin of Eastern Yunnan varies dramatically. The complex karst geo-environment factors (such as double-layer hydrogeological structure, the simultaneous droughts and floods, and the different maturity soil), and the adverse vegetation site conditions (such as the thin soil with lack of nutrients) induce serious rocky desertification (Cao *et al.* 2016). For the vegetation restoration of rocky desertification, the plant community structure, the species diversity, the vegetation evolution and its driving mechanism are the basic scientific points that aroused wide concern globally (Zhang *et al*. 2015; Wen *et al*. 2015; Wu *et al*. 2016; Wen *et al*. 2018). Nevertheless, few studies have been graded the combination of C_3 and C_4 plant distribution in rocky desertification area. In this paper, the carbon isotopic composition of SOC and its utilization in reconstructing vegetation are focused to provide theoretical basis for selecting suitable species during vegetation restoration in rocky desertification area of graben basin.

STUDY AREA

The study site was located in Mengzi County, Yunnan Province of SW China (Fig. 1). It is characterized with the typical karst topography of mountains and basins. Large elevation differentiation and steep slopes in karst mountainous areas where the rocky desertification usually generated results in the special gradient effects of the water, energy, and the elements, as well as the climate, biology mass, and soil that important to vegetation (Li

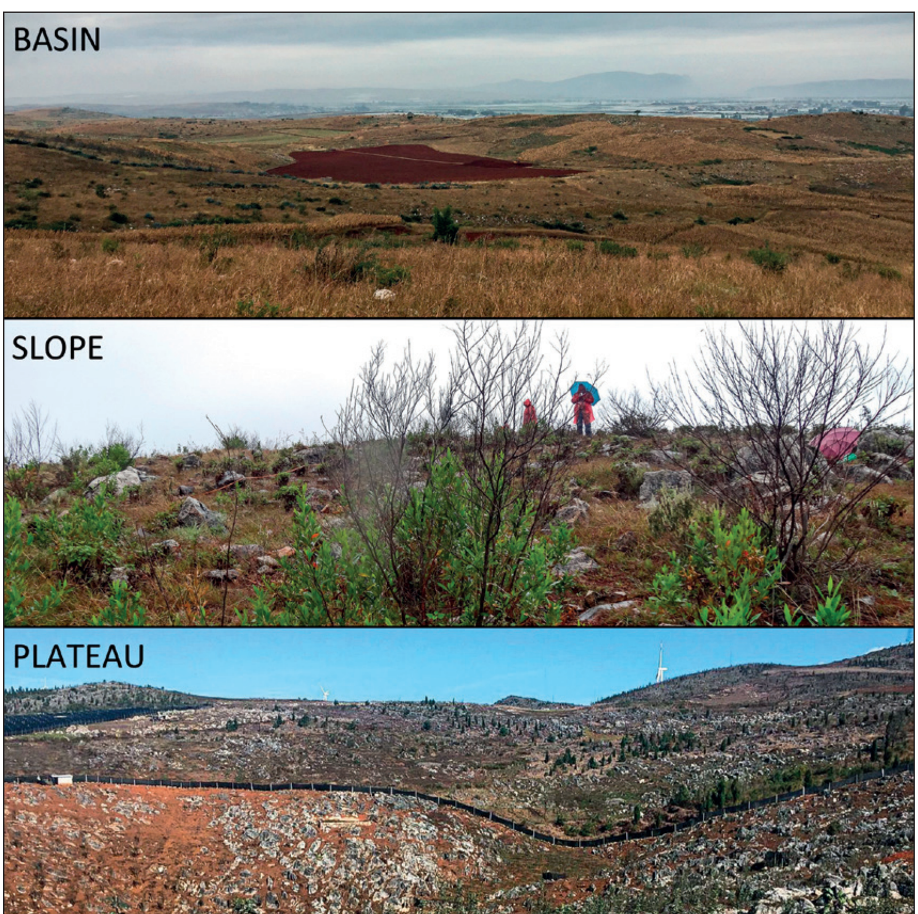

Fig. 2: Different examples of rocky desertification in basin, slope and plateau, where soil has been sampled (Photo: H. Yang).

2016). Soil samples were collected along the basin, slope, and plateau (Figs. 1 & 2). The annual average temperature of the basin, slope and plateau is 19.0, 15.6 and 13.7 °C, respectively, and the annual rainfall of the basin, slope and plateau is 663, 575, and 1027 mm, respectively (Wang *et al*. 2019).

SOIL SAMPLING

Soil samples were collected from different landforms, including basin (103°23’47”E, 23°28’22”N; elevation 1363 m a.s.l.), slope (103°26’13”E, 23°27’43”N; elevation 1846 m a.s.l.) and plateau (103°27’09”E, 23°27’08”N, elevation 2086 m a.s.l.) (Fig. 2). The higher organic layer (topsoil) of 0–15cm was sampled. Different rocky desertification grades were selected in each landform: light, moderate and severe rocky desertification (hereby abbreviated as LRD, MRD and SRD). The classification method of rocky desertification was referred to Jiang *et al.* (2014). The details of the sampling sites, including the vegetation and rocky desertification, are shown in the reference Yang *et al*. (2019).

We totally gathered 51 soil samples. They represented the plots of the LRD, MRD, and SRD in every landform position. The sampling sites were beyond 100 m of distance in LRD, MRD, and SRD. At each site, 5 plots (1 m × 1 m) were randomly chosen at 20 m intervals. Subsamples were collected after removing of covering litter and homogeneously mixed into one sample on behaves of one site. Fresh soil was primary treated by stones and roots removal and then sieve to 2 mm. After that, they are air-dried for chemical analysis in laboratory. Three repeats were done for each sample during chemical analysis.

METHODS

Isotopic $^{13}C/^{12}C$ concentration was determined in a Flash 1112A advantage auto analyzer coupled to a Delta V Advantage Isotope Ratio Mass Spectrometer (Thermo Scientific, USA). The results of the isotopic analysis were expressed in units of δ (‰), determined in accordance with the international Pee Dee Belemnite (PDB) standard (Zhang *et al*. 2014) as in Eq. (1):

$$\delta^{13}C = \frac{R_{sample} - R_{PDB}}{R_{PDB}} \times 10^3‰ \qquad (1)$$

where $\delta^{13}C$ is the isotopic composition, R_{sample} is the isotopic ratio of $^{13}C/^{12}C$ of selected sample, and R_{PDB} is the ratio of the international PDB standard. If the composition of organic matter in soil is known, the relative biomass of C_3 and C_4 plants in the surface vegetation can be estimated according to the following isotope mass balance equation (Boutton *et al.* 1998):

$$C_3(\%) = \frac{\delta^{13}C_{SOM} - \delta^{13}C_4}{\delta^{13}C_3 - \delta^{13}C_4} \times 100 \qquad (2)$$

$$C_4(\%) = 100\% - C_3(\%) \qquad (3)$$

where $\delta^{13}C_{SOM}$ is the carbon isotope composition of soil organic matter; $\delta^{13}C_3$ and $\delta^{13}C_4$ are the average carbon isotope of C_3 and C_4 plants, generally -27‰ and -13‰ respectively (Boutton *et al.* 1998); $C_3(\%)$ and $C_4(\%)$ are the relative biomass of C_3 and C_4 plants respectively.

RESULTS

ISOTOPE VALUES OF SOC

The $\delta^{13}C_{SOC}$ values in karst basin, slope and plateau are shown in Fig. 3. The isotopic composition of carbon pools varied greatly in the sampling area. Overall, the values of $\delta^{13}C$ varied from -22.5‰ to -13.0‰, averaging -18.6‰. Furthermore, the range differed strongly between types of landform. With the increase of altitude, the $\delta^{13}C_{SOC}$ becomes smaller. The values of $\delta^{13}C_{SOC}$ varied from -22.5‰ to -18.3‰, averaging -20.7‰ in plateau. The $\delta^{13}C_{SOC}$ values in basin ranged from -18.2‰ to -13.0‰, averaging -16.0‰, while $\delta^{13}C_{SOC}$ values in slope ranged from -17.9‰ to -14.5‰, averaging -16.0‰. There is no significant difference between $\delta^{13}C_{SOC}$ in basin and slope, while there is significant difference between $\delta^{13}C_{SOC}$ in basin and plateau.

In general, with the aggravation of rocky desertification at the same landform, $\delta^{13}C_{SOC}$ value gradually increased (Tab. 1). Under the same rocky desertification grade, the isotope values gradually decreased with the increase of altitude, while the $\delta^{13}C_{SOC}$ value of soil organic carbon in plateau is significantly different from other two locations.

VEGETATION CHANGES OF $\Delta^{13}C_{SOC}$

The relative biomass of C_3 and C_4 plants is shown in Fig. 4. As can be seen from Fig. 4, C_4 plants, as evident from $\delta^{13}C$‰, are dominant in basin and slope, while C_3 plants are more abundant at the plateau. Under the same degree of rocky desertification, C_3 plants increased with the increase of altitude while C_4 plants decreased. At the same landform, the proportion of C_3 plants decreased with increase of rocky desertification in basin and at slope.

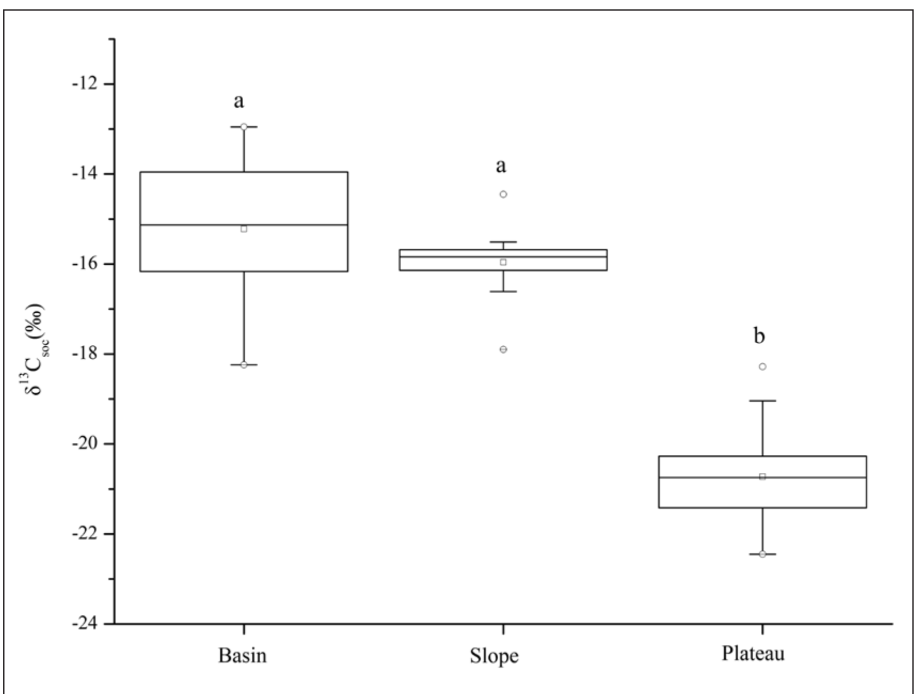

Fig. 3: Isotopic values ($\delta^{13}C$) in basin, slope and plateau position.

Tab. 1: Isotopic value of three rock desertification types ($\delta^{13}C_{SOC}$ ‰).

	Basin	Slope	Plateau
LRD	-16.5±2.3 aA	-16.7±1.0 aA	-20.9±0.9 aB
MRD	-15.4±0.9 abA	-16.1±0.4 aA	-21.1±0.7 aB
SRD	-13.5±0.5 bA	-15.2±0.6 aB	-20.4±0.9 aC

Note: LRD, MRD and SRD represent the light, moderate and severe rocky desertification, respectively. Identical lowercase letters in the landform at the 0.05 level; Identical capital letters in the same row indicate no significant differences in the $\delta^{13}C_{SOC}$ values under different landforms with the same grade of rocky desertification.

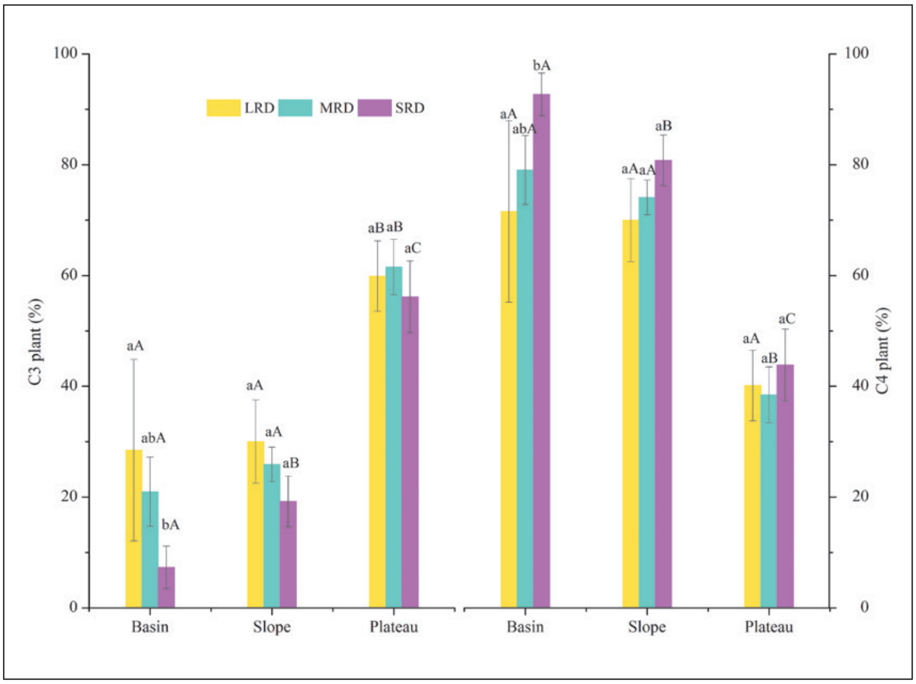

Fig. 4: The relative biomass of C_3 and C_4 plants.

THE RELATIONSHIP BETWEEN $\Delta^{13}C_{SOC}$ AND ENVIRONMENTAL VARIABLES

The response of $\delta^{13}C_{SOC}$ to the environmental variables (temperature, precipitation and altitude) was shown in Fig. 5a,b,c. In this study, statistical analysis results showed that there was a significant negative correlation between the annual average precipitation and $\delta^{13}C_{SOC}$ value (R^2=0.90), while there was a positive correlation between the annual average temperature and $\delta^{13}C$ value (R^2=0.72), and a negative correlation between elevation and $\delta^{13}C_{SOC}$ value (R^2=0.70). The effects of environmental variables on $\delta^{13}C_{SOC}$ of SOC could not be separated, and each response function of $\delta^{13}C_{SOC}$ to an environmental variable included direct and indirect effects.

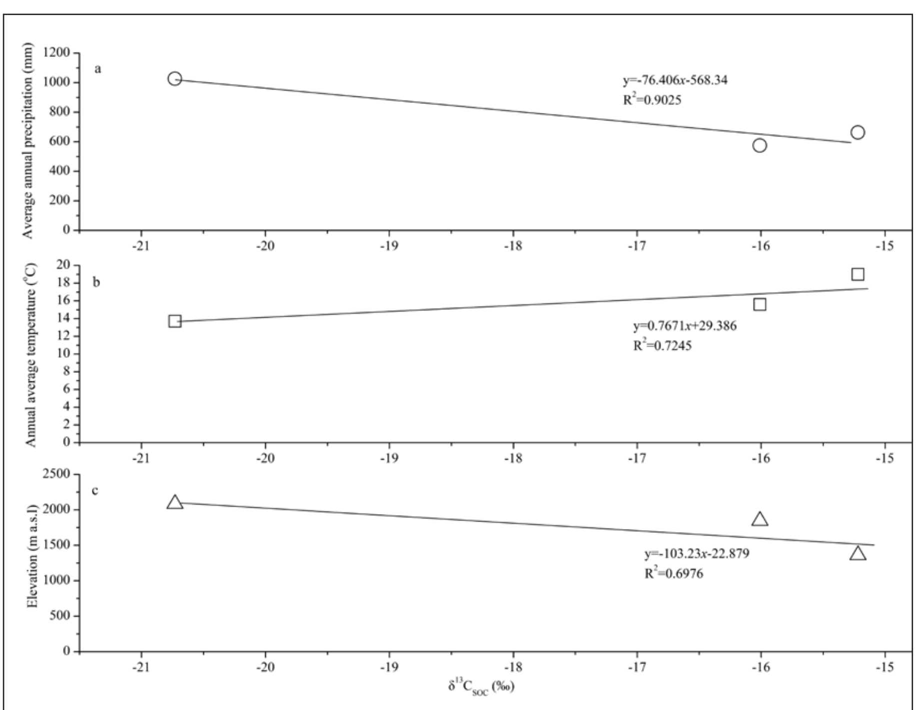

Fig. 5: The correlation between $\delta^{13}C$ and precipitation (a), temperature (b) and elevation (c).

DISCUSSION

SPATIAL PATTERN OF $Δ^{13}C_{SOC}$ AND ANALYSIS OF INFLUENCING FACTORS

It has been widely accepted that the stable isotope value of SOC is mainly controlled by vegetation type and biomass. There are also evidences that the topography, temperature, and precipitation can affect the stable isotope value of SOC (Wu *et al*. 1995; Bai *et al*. 2006; Li *et al*. 2009; Wen *et al*. 2018). Several studies reported variations of $δ^{13}C_4$ along environmental gradients, e.g., a decrease in $δ^{13}C_4$ with increasing precipitation (Schulze *et al*. 1996), or, in contrast, an increase of $δ^{13}C_4$ with increasing soil water content (Chen *et al*. 2002). In this study, our results also confirm that $δ^{13}C_{SOC}$ decreases with the increase of precipitation. Furthermore, both of altitude and temperature are important factors that affect the stable isotope value of soil organic carbon. The absence of any relationship to climatic gradients in our data set may thus be caused by compensating effects (Auerswald *et al*. 2009).

VEGETATION CHANGES

Most of the soil organic matter comes from the overlying vegetation, and its carbon isotope value inherits the isotopic characteristics of the overlying vegetation (Liu & Huang 2008). Therefore, the carbon isotope of soil organic matter can well reflect the carbon isotope composition of the overlying vegetation during the pedogenesis process (Zhang *et al*. 2015). The vegetation composition of Mengzi graben basin was a mixture of C_3 and C_4 plants, and its evolution responds to the change of rocky desertification degree. The present data indicated that with the deterioration of rocky desertification, the proportion of C_4 plants increased, while that of C_3 plants increased. From the ecological point of view, forest succession is a dynamic process, where, some trees replace other trees, and one forest community replaces another forest community. Obviously, the continuous accumulation of $δ^{13}C$ of soil organic carbon is closely related to the succession process of regional forest communities, as well as the restoration and reconstruction process of degraded forest ecosystems (Huang *et al*. 2015). Previous studies showed that the destruction of native vegetation by human beings will lead to the increase of C_4 plants, such as herbaceous plants (Boutton 1980). In this study, the ecological environment and species composition of different rocky desertification grades are different. The grade of LRD is dominated by shrubs and herbs, with a small number of trees; the MRD community is seriously degraded, and the community structure is characterized by sparse shrubs and grasses; in the SRD sample plot, a large number of rocks are exposed, the soil is shallow and the vegetation is sparse. Only a small number of tree seedlings and dwarf shrubs are scattered in the rocky crevices, and the areas with soil are mostly covered by herbaceous plants (Yang *et al*. 2019).

In addition, the proportion of C_3 plants in vegetation tends to increase with the increase of altitude, while C_4 plants in vegetation tend to decrease with the increase of altitude in this study. Studies have shown that the proportion of C_4 plants in vegetation tends to decrease with the increase of altitude, mainly occupying low-altitude areas, while C_3 plants dominate high-altitude areas, and the transition zone between them occurs at about 1500–3000m (Li *et al.* 2009). When the altitude exceeds 2000–3000 m, the number of C_4 plants in the plant population gradually decreases or even disappears (Boutton 1980; Rundel 1980; Cavagnaro 1988).

Temperature, precipitation and atmospheric CO_2 content were considered as important factors to control carbon isotope and vegetation composition of terrestrial plants (Wang *et al.* 2014). Previous studies have confirmed that the temperature of plant growth season is more closely related to the occurrence of C_4 plants, and C_4 photosynthetic pathway rarely occurs in areas where the average temperature of growth season is lower than 16 °C (Long 1983). According to the research of Sage *et al.* (1999) on the distribution of C_4 plants around the world, the key climate factor controlling the occurrence of C_4 plants was the temperature in the growing season. The researchers also speculated that there was a temperature threshold for C_4 plant growth (Long 1983; Sage *et al.* 1999).

CONCLUSION

In the present study, we quantified the spatial variance of the $δ^{13}C_{SOC}$ characteristics and the contribution of C_3 and C_4 plant species reflected by $δ^{13}C_{SOC}$ values under different rocky desertification grades from different landforms (basin, slope and plateau) in Mengzi karst graben basin of Southwest China. The $δ^{13}C_{SOC}$ value decreased with the increase of altitude, specifically from basin, slope and plateau. Meanwhile, at the same landform, different rocky desertification grades had no significant effect on the $\delta^{13}C_{SOC}$ in slope and plateau, while there were significant differences of $\delta^{13}C_{SOC}$ between LRD and SRD in basin. The C_4 plants account for more than 70% in the basin and slope, while C_3 plants account for more than 70% in the plateau. This may be related to the long-term cultivation of corn in the historical period in the basin and slope. However, the plateau area is not suitable for the growth of C_4 plants such as corn due to cold climate. In addition, in the same landform, with the aggravation of rocky desertification, the proportion of C_4 plants increased, while that of C_3 plants decreased. This may be related to the increase of herbaceous plants with the aggravation of rocky desertification. Although the present study focuses on $\delta^{13}C_{SOC}$ characteristics and specifically its effects on the proportion of C_3 and C_4 plants in few soil samples and not on the high number of soil samples, more studies should investigate the potential influence of bedrock lithology on C_3 and C_4 plants under vertical climate condition in karst graben basin. This result provides expanded guidance on the practice of ecological restoration and agricultural cultivation in karst rocky desertification regions. For example, when conducting ecological restoration of rocky desertification in karst graben basins, we should consider not only the impacts of altitude and vertical climate, but also the distribution characteristics of C_3 and C_4 plants. Selecting suitable species according to local conditions are of great significance for the promotion of ecological restoration in rocky desertification areas.

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