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Soil types determine vegetation communities along a toposequence in a dolomite peak-cluster depression catchment

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Abstract
Aim A further understanding of relationship between soil and vegetation is a prerequisite for accelerating vegetation restoration in karst area. Remarkable achievements have been made at regional and individual plant scales, but research on the relationship between soil and vegetation is insufficient at the hillslope catena scale in karst area.
Methods Soils and vegetation were investigated along a toposequence of the dolomite peak-cluster depression catchment. Redundancy analysis (RDA) and structural equation modelling (SEM) were used to analysis topography, soil, and vegetation relationships.
Results The dolomite rocks displayed an evenly progressive karstification process. This led to an undeveloped underground karstic network that was unable to transport soil materials into ground. Soil materials accumulated at different topographic positions and formed continuous catena. Soil types showed a gradual transition in the form of: Entisol--Inceptisol--Semi-alfisol--Alfisol. The vegetation communities also corresponded to the change of different soil types along the slope, showing a gradual transition of herbs--herbs and shrubs--shrubs and trees--herbs and trees. RDA analysis displayed that the fine soil mass ratio was an important influencing factor for vegetation. SEM demonstrated that slope gradient directly

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impacted on soil nutrient stocks and indirectly affected vegetation diversity.
Conclusions A continuous soil catena pattern was developed along the toposequence. Parameters for nutrient stocks might be more suitable for assessing soil productivity and guiding vegetation restoration in karst regions than nutrient content parameters. Slope gradient, fine soil mass ratio and nutrient stocks were important factors affecting plant diversity in karst areas.

Keywords dolomite · soil catena · nutrient stocks · vegetation patterns · soil-epikarst system

Introduction

Toposequence is a spatial object that maintains flow connectivity from the top of the mountain to the foot. Catenary is usually developed along a toposequence because of the degree of transport and deposition of soil particulate in the soil profile at different topographic positions (Schlichting 1970; Brunner et al. 2004; Lozano-García and Parras-Alcántara 2014).

Upper-slope erosion and accompanying lower-slope sedimentation result in gradual thickening of the soil layers and regolith from the upper-slopes to the depressions (Birkeland and Burke 1988; Applegarth and Dahms 2001). Regular changes of regolith thickness and soil profile morphological characteristics along a topography are represented as the primary conceptual model for the soil catenary (Sommer and Schlichting 1997; Applegarth and Dahms 2001; Lozano-García and Parras-Alcántara 2014). The catena indicates spatial patterns of soil-vegetation combination that on a specific landform. However, soil and vegetation characteristics can vary significantly along a toposequence due to different environment factors such as parent materials, climate, topography and human activities (Boling et al. 2008; Podwojewski et al. 2011).

Karst peak-cluster depression is a special geomorphic unit which is characterized by a depression surrounded by slopes (Fig. 1). It achieves a change from cliff to depression in a short horizontal distance, showing a rapidly changing topographic character. Potential energy decreases sharply from the top slope to the depression, leading to a remarkably potential gradient between the slope part and the depression part. Spatially, soils and vegetations in this unique peak-cluster depression system have the topographic and hydrological conditions to form a catenary pattern. However, for the karst landscape, knowledge on the soil-vegetation relationships has mostly focused on regional or plant individual scales. Related studies at catchment or catenary scales are relatively rare due to the ubiquitous extremely high heterogeneity at these scales. For instance, for karst regional scale, Jiang et al. (2020) found that bedrock geochemistry determines the karstic vegetation productivity via influencing the regolith water-retention capacities. In individual plant scale, karstic site-specific characteristics such as bedrock outcrops extent and soil thickness were the main controlling environmental factors to determine plant community composition (Liu et al. 2019). Thin soils were dominated by shallow-rooted plants preferring surface soil water, while continuous carbonate rock outcrops were usually dominated by deep-rooted plants preferring rock crevices water (Nie et al. 2011; Ding et al. 2021). Considering that hillslopes and catchments are usual as basic management units for implementing ecological restoration in severely degraded karst ecosystems (Jiang et al. 2014), there is a strong demand to conduct works for fulfilling the knowledge gap in the catenary scale.

Moreover, systematic studies involving soil-forming processes through the implementation of complete topographic-scale profile excavations in peak-cluster depressions region have rarely been reported. Researchers usually regard that the high Ca and Mg content of carbonate rocks and unique karstification processes hinder the losses of salt-based components in the soil profile, thus leading to weak desilicification and allitization (Huang 2017). There are four sub-categories of calcareous soils: black; brown; yellow; and, red calcareous soil. Typically they are shallow, not obviously stratified, clayey, and abruptly contact the underlying rock. Based on the PRC's second national soil survey, these results were conducted at cultivated soils on gentle slopes. However, soil resources of mountainous areas were not comprehensively studied. A in depth understandings of the soil-vegetation relationship and the key controlling factors in the catenary scale are the basic prerequisites for the rational use of scarce soil resources in karst catchments.

Soil parent material, distinct hillslope hydrological processes, and topography, impacts on the catena

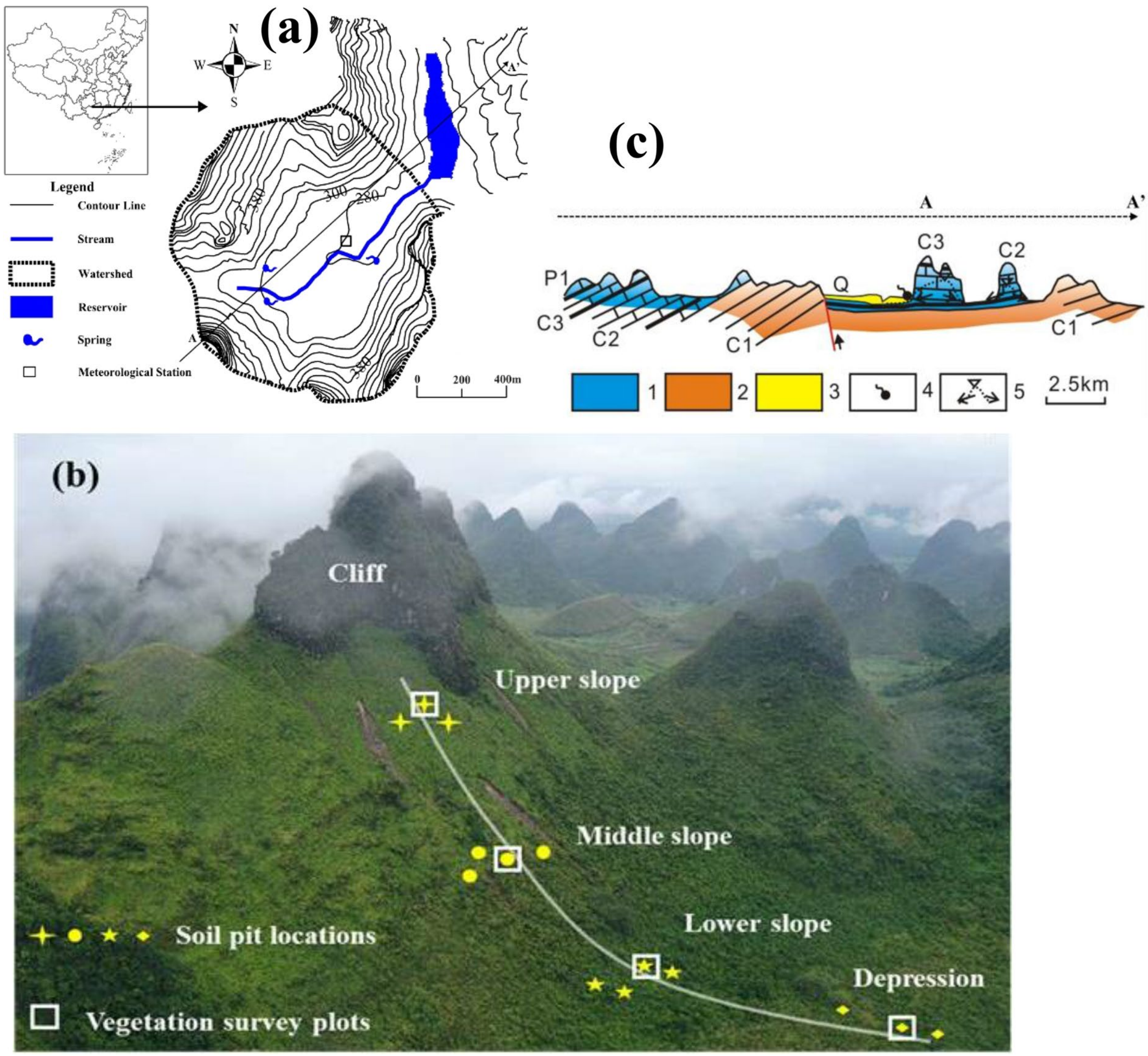


Fig. 1 Location and geohydrologic background of the study area

formation in many ways in karst areas. Three factors are as follows: 1) The Southwestern China karst area is low in acid-insoluble and insufficient sources of soil-forming materials in carbonate rocks. 2) Carbonate bedrock slopes are characterized by well-developed underground drainage systems which often start at or near the surface. They facilitate rapid surface flow recharging into the underground (Williams 1983; Feng et al. 2016). At hillslope scale, overland flow rarely occurs in karst areas compared to non-karstic areas (primarily silicate rocks) (Wang et al. 2021). Will this weaken the differential sorting and redistribution of soil particles across the slope? 3) In karst catchment, there is no clear transition between slopes and depressions. So far, it remains on whether karst slopes were able to form a soil catenary pattern similar to non-karst areas.

Therefore, the objective of this study is to verify the following hypotheses: (a) dolomite slope still presents a typical soil catena pattern; (b) vegetation communities and soil types are spatially associated in this dolomitic peak-cluster depression catchment.

Materials and methods

Study area

This study was conducted in a typical karst catchment (24°43’58.9″~24°44’48.8″N, 108°18’56.9″~108°19’58.4″E) located in Mulian, Huanjiang County, Guangxi (Fig. 1). The area is 1.46 km^2 and an elevation of 272 to 647 m above sea level. It has a subtropical mountain monsoon climate, with an average annual rainfall of 1389 mm. The rainy period mainly lasts from May to October and accounts for 70% of the annual rainfall (Hu et al. 2015). Annual average temperature in this area is between 19.6-21.6°C. The lowest temperatures, about 3.4~8.7°C occurs in January -March. The highest, 23.0-26.7°C, in July-September. Slope soil is shallow. Gravel content is high. The soil thickens gradually from slope to depression. Since 1985, the government has carried out a "returning farmland-to-forest"project. The area is recovering to a natural state. The main trees are *Radermachera sinica*, *Celtis biondii*, *Rhus chinensis*, *Schefflera heptaphylla*. The shrubs are *Vitex negundo* and *Ligustrum lucidum*, *Pyracantha fortuneana*. The precominant herbs are mainly *Miscanthus floridulus*, *Bidens pilosa* and *Pteridium aquilinum*.

Mulian catchment is in the western wing of the Mulian anticline. Its aquifer is primarily constituted of middle and late Carboniferous dolomite with a strata orientation of 278°∠10°. It has an early Carboniferous sandstone aquifer which is relatively impermeable (Fig. 1). The underlying rocks are pure dolomite rocks. Borehole analysis suggests that karstification degree decreases as depth increases. Karstification is characterized by penetrating dissolution pores, micro-tensile dissolution fractures, and local dissolution fractures. Its highly weathered dolomite is lost its original rock structure mostly and deconstructed into dolomite sand. There is no obvious bubble reaction obtained after dropping dilute hydrochloric acid on it.

Methods

Collection of soil, rock, and vegetation samples

The four topographical positions along the toposequence in Mulian catchment: upper-, middle- and lower-slopes, and depression were chosen to examine soil, rock, and vegetation characteristics (Fig. 1). At each topographical position, a 20 m×20 m plot was established. The 400 m^2 large sample plot was divided into several subplots:10 m×10 m for the tree survey; 5 m×5 m for the shrub survey; and 1 m×1 m for the herb layer survey. Species type, height, diameter at breast height and plant number of trees, shrubs and herbs in each plot were recorded.

Due to the strong spatial heterogeneity in the karst area, a total of 14 soil pits were used: 3 for both upper-slope and depression positions, and 4 for both mid-slope and lower-slope positions (Table S1). Soil pits were excavated to the C horizon or the epikarst zone. The main topographic variables (e.g. altitude, slope gradient, gravel content, morphological characteristics) were recorded and described according to FAO-ISRIC-ISSS (2006) (Wrb 2006). Soil samples were taken for each soil genetic horizons of the pits. Traditional small metal cylinder with a volume of 100 cm^3 were unsuitable for solid cores from rocky soils of this karst catchment. Large PVC tubes with height 15 cm, inner diameter of 10 cm, and a volume 1178 cm^3 were fabricated and used as soil cylinders to obtain undisturbed soil samples.

A series of boreholes (with a diameter of 15 cm) were made in the upper-, middle-, lower-slopes and depressions in order to study near-surface hydrological processes in the slope-depression system. Borehole core profiles were photographed and described during the drilling process of the sampling of dolomite rocks from the middle-slope and the depression for analyzing chemical compositions.

Determination of vegetation diversity

The plant diversity index contains the Simpson index, the Shannon-Wiener index and the Pielou evenness index. Species richness is equal to the number of species occurring in the sample site, expressed as S.

$$\text{Simpson index (D)} = 1 - \sum_{i=1}^{s} p_i^2 \tag{1}$$

$$\text{Shannon} - \text{Wiener } (\text{H}') = -\sum_{i=1}^{s} p_i linp_i \tag{2}$$

$$\text{Evenness index (J)} = {H'}\Big/{lnS} \tag{3}$$

S is number of species occurring in the sample site. Pi is the ratio of the number of individuals of species i to the total number of individuals in the sample.

Determination of soil physical properties

Soil saturated hydraulic conductivity was determination: First by putting the soil cylinder samples into a sink. The liquid level of the sink was 2 cm below the upper end of the soil cylinder. Soaking for 12 hours was allowed for the soil to fully absorb water and saturated. Then constant-head method was used to measure soil saturation hydraulic conductivity.

$$K_S = \frac{10QL}{A\Delta HT} \times 60 \tag{4}$$

Where K_S (mm/h) is saturated hydraulic conductivity. Q-outflow (ml) is within t time. L (cm) is linear distance of the water flow path. A (cm^2) is the water flow cross-sectional area. ΔH (cm) is the total head difference between the beginning and end of the seepage path. T (min) is the outflow time (Yi et al. 2019).

Determination of the soil material composition: Due to the high gravel content of the study site, the soil material was divided into two fractions: (1) the diameter > 2 mm of debris as the gravel fraction; (2) the diameter < 2 mm of debris and soil as the fine soil fraction. The total mass of the soil material is equal to the mass of the cylinder after drying, expressed as M_T; its volume is the volume of the cylinder, expressed as V_T. The gravel was selected from the soil cylinders, dried and weighed to obtain the mass of the gravel. The weighed gravel was soaked in water for 12 h and the volume of gravel was calculated by applying the drainage method (Wang et al. 2017).

$$\rho_g = {m_g}\Big/{v_g} \tag{5}$$

$$v_f = V_T - v_g \tag{6}$$

$$MF = {m_f}\Big/{M_T} \times 100\% \tag{7}$$

$$MG = {m_g}\Big/{M_T} \times 100\% \tag{8}$$

$$VF = {v_f}\Big/{V_T} \times 100\% \tag{9}$$

$$VG = {v_g}\Big/{V_T} \times 100\% \tag{10}$$

ρ_g (g/cm^3) is gravel density. m_g (g) is gravel mass. v_g (g) is gravel volume. m_f (g) is fine soil mass. v_f (cm^3) is fine soil volume. M_T(g) is the total mass of the soil material. V_T(cm^3) is the total volume of the soil material. MF (%) is the fine soil mass ratio. MG (%) is gravel mass ratio. VF (%) is fine soil volume ratio. VG (%) is gravel volume ratio.

Soil bulk density (BD) and fine soil bulk density (δf) are indicated as the bulk density of the total soil material and the soil material excluding gravel component, respectively. They were calculated as follows.

$$BD = {M_T}\Big/{V_T} \tag{11}$$

$$\delta_f = {\left(M_T - m_g\right)}\Big/{\left(V_T - v_g\right)} \tag{12}$$

Calculating of pedon scale average nutrient content and nutrient stocks

There was a significant positive correlation between soil thickness and vegetation productivity. This correlation became more significant for the soil thickness in the 0-50 cm (Li and Duan 2014). Shallow soil nutrient stocks affect productivity, which is not only controlled by soil nutrient content. Soil nutrient content may not fully reflect actual soil productivity. This study compared average nutrient content with nutrient stocks within the pedon scale to explore the appropriate index for assessing shallow and high gravel soil productivity in peak-cluster depressions.

The soil nutrient content (N_c) parameters were measured including total nitrogen (TN), total phosphorus (TP), total potassium (TK) content, and soil organic matter content parameters according to the techniques report by Bao (2000).

This study used the calculation method of soil organic carbon stocks presented in the second edition of the "2011 Soil Investigation Laboratory Information Handbook" of the Natural Resources Conservation Service of the United States Department of Agriculture for soil nutrient stocks index (U.S. Department of Agriculture; Fei et al. 2015).

The soil cylinders did not have the same height. The height of soil cylinder was equal to the sum of the fine soil height and gravel height. According to the equal area of PVC tube bottom, so the ratio of gravel volume to fine soil volume is equal to the ratio of gravel height to fine soil height of soil cylinders. The height of gravel and fine soils were calculated for each soil layer, combination with the known thickness of the soil layer.

$$v_g / v_f = d_g / d_f \tag{13}$$

$$\mathrm{d_g} + \mathrm{d_f} = D \tag{14}$$

The following values were calculated from the gravel density and the fine soil bulk density.

$$V_1 = d_g \times 10^4 \tag{15}$$

$$V_2 = d_f \times 10^4 \tag{16}$$

$$m_1 = V_1 \times \rho_g \times 1000 \tag{17}$$

$$m_2 = V_2 \times \delta_f \times 1000 \tag{18}$$

$$m_t = m_1 + m_2 \tag{19}$$

$\mathrm{d_g}$ (cm) and $\mathrm{d_f}$ (cm) is the gravel height and fine soil height for each soil layer respectively. D (cm) is the soil layer thickness. V_1 (cm^3/m^2) and V_2 (cm^3/m^2) is gravel volume and fine soil volume of the soil layer per unit area. m_1 (kg/m^2) and m_2 (kg/m^2) is the mass of gravel and fine soil per unit area of soil. m_t is represents the total mass of soil per unit area.

In the calculation of the nutrient stocks per unit area of each soil layer, N_s is the nutrient stocks per unit area for each soil layer measured as kg/m^2. N_c is the each soil layer nutrient content measured as g/kg. The formula was as follows:

$$N_s = m_2 \times N_c \times 1000 \tag{20}$$

Pedon scale nutrient stocks was equal to the sum of gravel nutrient stocks and fine soil nutrient stocks for each soil layer, but the gravel nutrient content was extremely low (Table S2), resulting in the low nutrient stocks of gravel, and negligible. Therefore, the nutrient stocks of the pedon scale were equal to the sum of the nutrient stocks of fine soil in each soil layer. Specific values of nutrient content and nutrient stocks for each soil genetic horizons are in Table S3.

Data analysis

Excel 2019 was used to process data. One-way analysis of variance and Duncan method were used to analyze soil physical and chemical properties differences. The significance level was set at α=0.05. Origin 2021 drew related charts. Redundancy analysis (RDA) and structural equation modelling (SEM) were analyzed and constructed using Rstudio.

Results

Spatial variability of soil formation characteristics along the toposequence

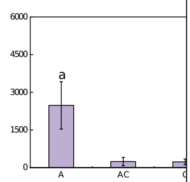
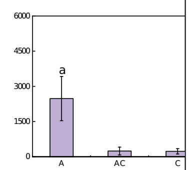
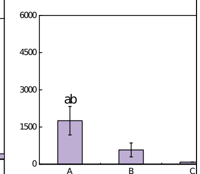
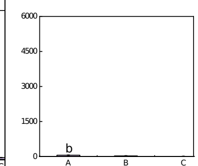
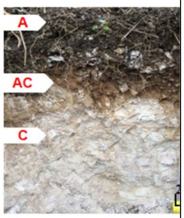
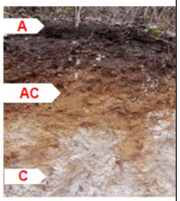
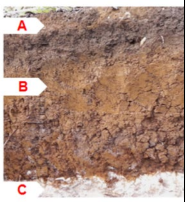
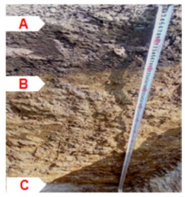
Soil formation conditions at different topographic positions

Peak-cluster depressions a unique landform resulting from the long-term karstification process. The hillside abruptly changes into a depression. The height difference between the peak-cluster top and the depression was about 377 m. The slope was about 400 m long. The depression was about 300 m wide. The slope length-to depression width was about 4:3. Slope and depression areas accounted for 64% and 27% in the catchment area, respectively.

Soil-forming material at different topographic positions show a sorting phenomenon from coarse to fine. Between the cliff and the depression, the large weakly-weathered rock mass changes to a moderately-weathered rock mass, then to strongly-weathered clastic rock ending in dolomitic sand layer (Table 1).

The average mass contents for CaO and MgO in drilling cores were about 31% and 21%, with acid-insoluble mass accounting for only 0.17%, suggesting a very pure dolomite rocks in this study

Table 1 Site characteristics, soil hydrological conditions, and soil-rock profile morphology at different topographic positions

	Upper-Slope	Middle-Slope	Lower-Slope	Depression
Slope gradient (°)	32.06±5.85a	23.00±2.48b	18.46±2.39b	4.40±0.53c
Gravel coverage (%)	45.69±18.20a	50.22±11.92a	16.88±7.56b	7.83±1.02b
Soil thickness (m)	0.56±0.15b	0.70±0.07b	0.76±0.12b	1.18±0.04a
pH	8.11±0.07a	8.12±0.13a	7.35±0.39b	6.89±0.15c
Soil saturated hydraulic conductivity (mm/h)				
Soil profiles photos				
Drill core photos				
Soil types (site drainage (	Entisol (well drained)	Inceptisol (well drained)	Semi-alfisol (moderate drained)	Alfisol (poorly drained)
The chemical composition of parent rock	n.a.	acid insolubles<0.16% CaO-30.91% MgO-21.54%	n.a.	acid insolubles<0.18% CaO-31.15% MgO-21.54%

Lowercase (a,b) represent the Anova results in same parameters (p<0.05).

n.a.: not analysed.

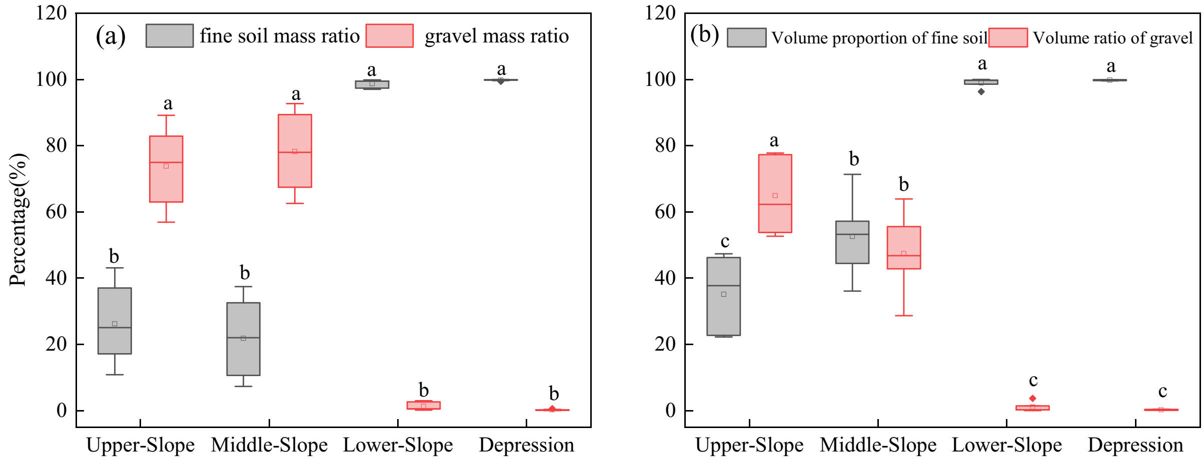


Fig. 2 Pedon scale mass ratio and volume ratio of gravel and fine soil for different topographic positions

catchment (Table 1). As the slope gradient decreases, the soil pH value of the soil gradually decreased (Table 1). pH at upper-slope and mid-slope inherited the high alkaline characteristics of the underlying weathered dolomite.

Soil profile morphological characteristics in different topographic positions

Soil profile for different topographic positions could be divided into three soil genetic horizons based on dissimilar properties. They were designated as A; AC or B; and C. The "A" layer is black surface layer. "AC or B" is a yellow illuvial horizon and "C" is a white dolomite strongly weathered layer (Table 1). There was a deep dolomite weathering layer in the study catchment. The degree of weathering decreases with depth (Table 1). Weathering was weakest on the upper-slope where the weathered layer was about 1.5 m. Strongly weathered layers of dolomite in other topographic positions range in thickness from 2.5 m to 10 m. The dolomite weathered layer was dominated by fine sand formed by overall dissolution. There were no large pores, cracks, karst conduits and other structures in the weathered layer. The boundary between soil and dolomite weathering layer was clear, with an extremely irregular wavy shape. No soil particles had migrated vertically through the rock weathering layer.

From the upper-slope to the depression, soil profiles property change was obvious. The upper-slope soil was weakly developed and well drained Entisol. Differentiation between the various soil layers was not obvious. Middle-slope soil was Inceptisol. A light yellow weakly illuvial horizon was observed under the black surface layer suggesting a weak eluvial and illuvial process. Lower-slope soil was moderate drained Semi-luvisol. The soil profile was moderately developed and a yellow-brown sedimentary layer was easily detected. Depression soil was Alfisol with an apparent illuvial horizon. The lower part of it was affected by lateral seepage and formed calcareous concretions and iron-manganese nodules.

Soil physico-chemical characteristics along the toposequence

Soil physical properties at different topographic positions

Upper- and middle-slope soil profiles were mainly composed of gravel. Average gravel mass and volume ratios on the upper- slope were 73% and 64% respectively (Fig. 2), while those on the middle-slope were 78% and 47% respectively. Lower-slope and depression soil profiles were mainly fine soil. Lower-slope gravel mass and volume ratios were 1.30% and 1.09%, respectively. Depression ratios were 0.21% and 0.24%. Gravel mass and gravel volume proportions decreased as slope gradient decreased. Fine soil mass and fine soil proportion volumes showed the opposite trend which were obvious slope colluvium characteristics (Fig. 2).

The average clay content varied 32% and 52% in the lower-slope and depression profiles (Fig. 3). Clay content on the lower-slope varied smoothly against depth (Table 2). The upper and middle slopes had higher sand content that increases with depth. The average profile sand content was between 68% and 81% (Fig. 3). This showed that lower-slope and depression belonged to the clay group. Saturated hydraulic conductivity decreased as the soil depth increased (Table 2). Depression saturated hydraulic conductivity was the lowest, with a maximum value of 61 mm/h (Table 1). Middle slope maximum saturated hydraulic reached 5095 mm/h. Dolomite slope land was Entisolic with high permeability and well drainage. Depression land soil was Alfisolic with low permeability and poorly drained.

Average nutrient content and nutrient stocks at different topographic positions

Changes in nutrient content along the studied slope were not obvious (Fig. 4). Soil nutrient stocks gradually increase at different topographic positions. This largely agreeed with the variations in soil thickness and apparent soil productivity along the slope. TN (2.07 kg/m^2), TP (1.19 kg/m^2), TK (9.68 kg/m^2), and organic matter (47.68 kg/m^2) nutrient stocks were significantly higher than those for the upper- and middle-slopes (Fig. 4). Soils of karst areas are commonly shallow and gravelly, thus pedon scale nutrient stocks may be more suitable than nutrient content to assess soil productivity.

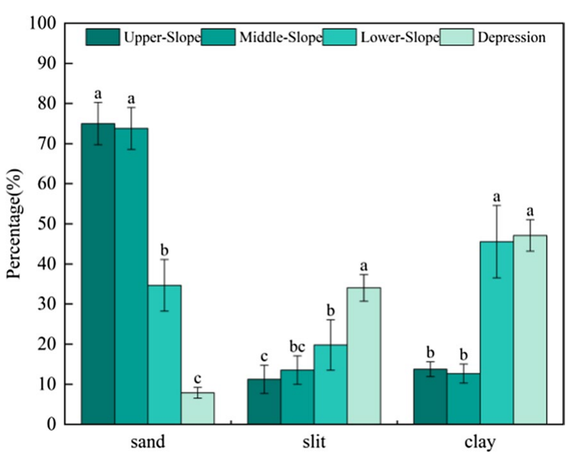


Fig. 3 Pedon scale grain size distribution of the fine soil fractions for different topographic positions

Nutrient accumulation in A-layer

The surface accumulation of soil nutrients was significant in Fig. 5. A layer nutrient was not accurately reflected soil fertility and productivity. Upper-slope A layer had the greatest nutrient accumulation. It ranged from 63%-85% (Fig. 5). Middle-slope A layer's nutrient accumulation ranged from 60%-76%. Lower-slope A layer's nutrient accumulation was between 33%-56% and for depressions it was 22%-26% (Fig. 5). A layer of depression nutrient accumulated relatively few. Along the slope, nutrient accumulation of A layer gradually lessens. From the characteristics of the black soil layer (Table 1) of the upper-slope soil profile, it could also be derived that A layer's nutrient accumulation on slope was significantly stronger than depression.

Fine soil volume in the upper-slope A layer was the greatest (53.64%, Fig. 6). The values for middle-, lower-, and depression were 40.96%, 45.10%, and 33.29% respectively. A layer' soil nutrient accumulation increased as the amount of fine soil volume increased except for lower-slopes.

Vegetation patterns responses to topographic change

Vegetation changes along the toposequence

At catenary scale, the upper-slope was dominated by herbs plants; the middle-slope was dominated by shrubs; the lower-slope and depressions were dominated by trees (Fig. 7). In terms of the key vegetation characteristics, middle-slope showed the highest of shrub species richness, Shannon-Wiener index, Simpson index and evenness index. Trees became dominant layer on the lower-slope. The biodiversity index of trees increased to the maximum on the lower-slope. In the depression, trees' species richness and Shannon-Wiener index were the greatest, but herbs' Simpson and evenness index were the greatest. It showed that the combination of trees and herbaceous plants made vegetation community more stable in the depressions.

Table 2 Physical properties of soil genetic horizons for different topographic positions

Topographic position (soil type)	pedon scale	Genetic horizon	Soil thickness (cm)	BD (g/cm^3)	δ_f (g/cm^3)	Sand (%)	Slit (%)	Clay (%)	m_1 (kg/m^2)	m_2 (kg/m^2)	m_t (kg/m^2)
Upper -Slope (Entisol)	U1	A	0-25	1.18	0.78	52.66	22.53	24.81	340.38	73.65	414.03
		C	25-59	1.46	1.21	85.13	7.99	6.87	482.67	155.24	637.90
	U2	A	0-17	1.34	1.22	59.74	17.39	22.87	193.19	98.28	291.47
		AC	17-42	1.51	1.24	76.22	7.95	15.83	501.10	70.44	571.54
		C	42-69	1.80	0.62	98.17	1.00	0.83	445.47	52.55	498.03
	U3	A	0-22	1.22	0.45	59.74	16.39	23.87	272.01	45.80	317.81
		AC	22-40	1.83	0.86	96.22	3.05	0.73	335.10	34.38	369.48
		C	>40	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Middle -Slope (Inceptisol)	M1	A	0-22	1.25	0.66	61.62	22.55	15.83	290.82	62.21	353.03
		AC	22-48	1.79	1.34	60.29	20.89	18.82	340.11	125.36	465.47
		C	48-71	1.43	0.34	92.72	7.00	0.28	299.11	34.89	334.00
	M2	A	0-25	1.11	0.58	56.19	19.99	23.82	173.96	103.95	277.91
		AC	25-51	1.36	0.57	61.73	18.40	19.88	267.90	84.65	352.55
		C	51-72	1.56	0.64	91.21	7.93	0.87	255.36	71.07	326.44
	M3	A	0-18	1.29	0.65	60.73	19.40	19.88	151.93	75.59	227.52
		AC	18-53	1.62	0.49	86.25	4.94	8.81	482.63	84.01	566.64
		C	53-75	1.75	0.19	97.22	1.95	0.83	257.06	20.25	277.31
	M4	A	0-40	1.14	0.17	63.72	17.40	18.88	416.34	38.82	455.16
		AC	40-60	1.13	0.45	81.12	9.00	9.88	206.00	49.54	255.54
		C	>60	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Lower -Slope (Semi-alfisol)	L1	A	0-20	1.05	1.04	32.31	25.88	41.80	1.17	200.52	201.69
		B	20-45	1.26	1.20	30.31	23.89	45.80	0.33	288.60	288.93
		C	45-80	1.46	1.45	57.64	32.54	9.83	0.01	505.08	505.08
	L2	A	0-25	1.04	1.03	32.23	29.94	37.82	2.98	254.16	257.14
		B	25-61	1.19	1.18	22.28	14.04	63.68	0.00	424.21	424.21
		C	>61	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	L3	A	0-15	1.09	1.08	44.31	20.02	35.67	0.14	162.03	162.16
		B	15-90	1.21	1.20	18.27	13.04	68.69	0.33	901.66	901.99
		C	>90	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	L4	A	0-15	1.05	1.05	44.39	17.99	37.62	0.13	157.14	157.27
		B	15-71	1.17	1.17	35.73	8.4	55.87	0.00	654.11	654.11
		C	>71	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

Table 2 (continued)

Topographic position (soil type)	pedon scale	Genetic horizon	Soil thickness (cm)	BD (g/cm^3)	δ_f (g/cm^3)	Sand (%)	Slit (%)	Clay (%)	m_1 (kg/m^2)	m_2 (kg/m^2)	m_t (kg/m^2)
Depression (Alfisol)	D1	A	0-20	1.25	1.25	27.65	32.32	40.03	0.47	249.53	250.00
		B	20-100	1.21	1.21	20.53	30.84	48.63	0.30	965.87	966.17
		C	100-120	1.13	1.33	19.37	30.54	50.09	0.00	265.83	265.83
	D2	A	0-25	1.28	1.28	26.87	32.01	41.12	1.15	317.80	318.95
		B	25-110	1.30	1.30	17.77	36.73	45.5	0.14	1100.54	1100.68
		C	110-120	1.34	1.44	15.34	38.24	46.42	0.00	143.92	143.92
	D3	A	0-28	1.32	1.32	21.03	31.62	47.35	0.55	368.95	369.49
		B	28-97	1.41	1.41	18.41	34.28	47.31	0.28	972.30	972.58
		C	97-113	1.38	1.38	17.38	34.43	48.19	0.05	220.73	220.78

BD is total soil bulk density. δ_f is fine soil bulk density. m_1 is gravel mass per unit area. m_2-fine soil mass per unit area. m_t is soil mass per unit area.

n.a.: not analysed.

Correlation among topographic, soil properties, and vegetation factors

Redundancy Analysis (RDA) (Fig. 8) showed that the fine soil mass ratio was the most important factor influencing the distribution of vegetation, with a contribution rate of 64.5%. Several index indicators such as gravel volume ratio, fine soil mass ratio, soil texture, gravel cover, pH and slope showed significant correlations with the vegetation diversity indices. The contribution of fine soil mass ratio and gravel volume ratio ranked first and third respectively. The greater proportion of gravel may directly affect the vegetation community type, which can also affect soil productivity. The contribution of organic matter stocks and total phosphorus stocks was 14.8% and 3.5% respectively. Conversely, there was no significant correlation between soil nutrient content and vegetation diversity indicators. It suggested that nutrient stocks index was more suitable for evaluating karst soil productivity than nutrient content index. Slope gradient ranked fifth in terms of its contribution. It was found that the lower the slope gradient, the higher the diversity and species richness for trees and herbaceous; while the lower diversity and species richness for shrubs.

Discussion

Dolomite-slope shallow soils form a continuous soil catena pattern

In non-karst areas, the weathering of rock is dominated by physical weathering, followed by chemical weathering. Weathering usually occurs at the surface, or close to the surface. Weathering affected physical and chemical characteristics deep bedrocks (Worthington et al. 2016; Beven et al. 2021). Carbonate rock is generally solvable; therefore karst-area chemical weathering processes are often stronger than physical weathering processes (Gilfillan et al. 2009; Ford and Williams 2015). The weakly acidic water continuously dissolves the deep carbonate bedrock. This has led to a range of thicknesses of 10-1000 m in the karst region for the strongly weathered layers (Hartmann et al. 2017). It also results in more and more robust spatial heterogeneity of the material structure. The drilling core profiles showed that dolomite weathered layer

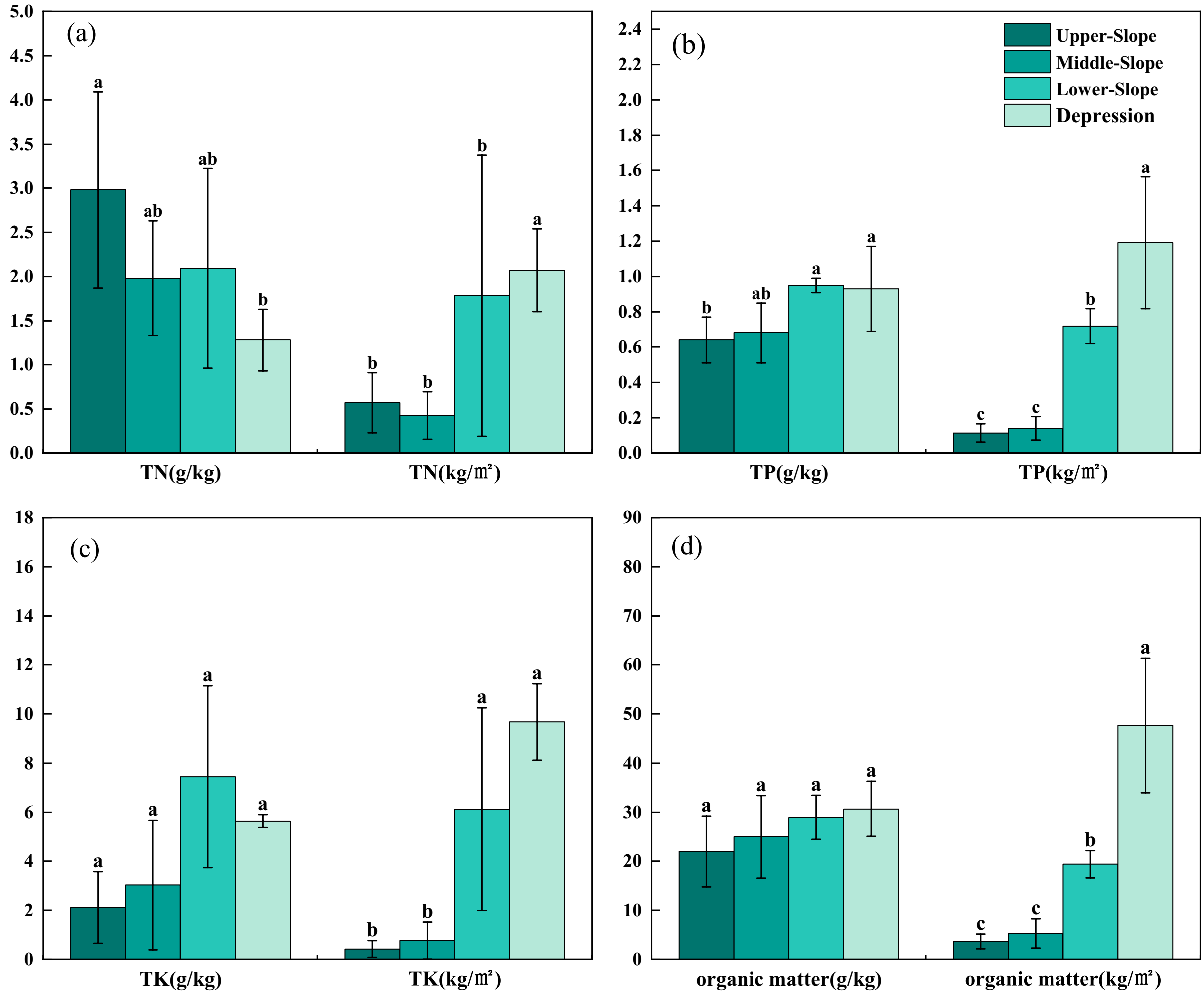


Fig. 4 Pedon scale average nutrient content and nutrient stocks for different topographic positions

thicknesses could beyond 50 m. Strongly-weathered and the weakly weathered layers alternated. This result provided direct evident to confirm that, in a karst area, the chemical dissolution in carbonate weathering process is dominated.

The dolomite showed an overall uniform weathering pattern. The rock outcrops in the hillslopes are relatively low, thus bare rocks are no barriers for the continuous soil distribution. Even where soil was shallow and the dolomite strongly weathered and the weathering layer was thick, the dolomitic weathering was characterized by diffuse and integral dissolution. As a result, karst fissures and conduits were not well developed.

Soil was mainly distributed on the surface. Vertical, water-driven migration into underground karst voids was not detected. This suggests that small pore structures predominate on strongly weathered dolomite. Water, but not soil particles, channels through small pores. This results in dolomite soil slopes having a soil catena pattern where soil gradually thickens and has continuous distribution along a slope.

Compared with soil catena developed in non-karst areas, those developed on dolomite slopes have a short average distance between adjacent soil types, while the number of soil types differs less to non-karst areas. Brunner et al. (2004) studied a Ugandan soil catena, which consisted of granites, gneisses and schists of the Precambrian age. The soil catena

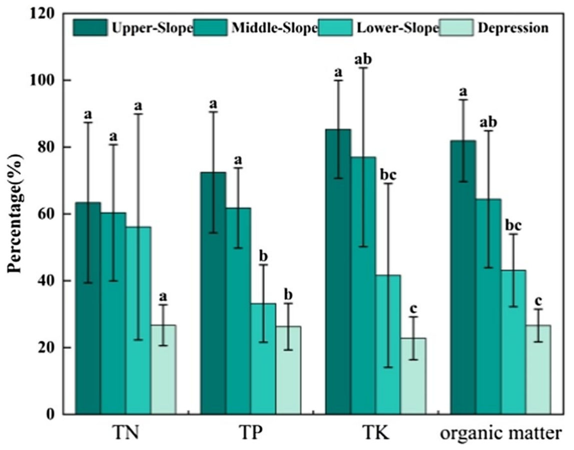


Fig. 5 The ratio of A-horizon's nutrient stock to pedon scale nutrient stocks

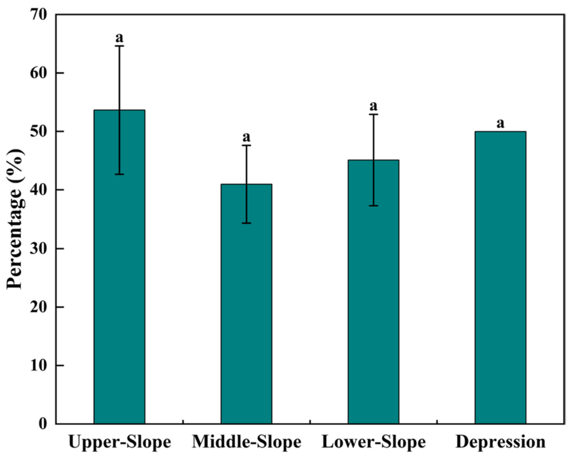


Fig. 6 The ratio of A-horizon's fine soil volume to pedon scale fine soil volume

there was composed of seven primary soil types. The average distance between adjacent soils was 300 m. Deressa et al. (2018) studied a soil catena, which consisted of alluvium, granitic gneiss and basalt. That soil catena had five soil types. The average distance between adjacent soil types was 10 km. In this study, the dolomite soil catena consisted of four soil types. The average distance between adjacent soil types was 33 m.

For karst, underground carbonate rock dissolution is significant. Rainfall quickly recharges groundwater. The surface runoff coefficient was far less than non-karst mountain slopes. Compared with non-karst slopes, the stronger vertical water flow drives soil formation processes in karst slope. It likely seems that the more rapid vertical water flow present in a dolomite soil profiles compensated the lack of a hydrological driving force resulting from short slopes. Dolomite slope can also present a complete soil catena pattern.

The dissolution rate of limestone was 2 to 60 times higher than dolomite (Bai and Wang 2011). Limestone is characterized by highly differentiated dissolution. The fissures and large conduits network structure in the limestone weathered layer were extremely developed. These structures often become preferential channels for material migration underground (Fig. S1). In the limestone zone, the well-developed underground network void structure dominates the underground material migration process.

Correlation among topographic, soil properties, and vegetation factors

Structural equation modelling (SEM) was successfully established after RDA analysis (Fig. 9). The model explains the main pathways that lead to changes in the diversity of vegetation communities: slope gradient affects total phosphorus and organic matter nutrients in the soil; changes in nutrients directly affect plant community diversity. In previous studies, on the one hand topographic features were considered to have a direct effect on vegetation. On the other hand, the spatial redistribution of resource factors was controlled through changes in morphology, thus indirectly influencing vegetation distribution (Kikuchi 1990; Yang 2005). Our results suggest that topographic features indirectly determine the spatial variation of vegetation communities, and SEM analysis confirms our hypothesis. This is consistent with previous studies (Rastetter et al. 2004; Wu et al. 2005). Nutrients were positively correlated with tree and herbaceous diversity, while negatively correlated with shrub species diversity. This differs from non-karst areas where nutrients showed a significant positive correlation with vegetation diversity (Luo et al. 2014). This may be due to the disadvantage of shrubs in the later stages of succession. Trees have a strong advantage in competing for environmental resources. Thus, trees occupied resources and dominate in the process of continuous evolution. The fine soil mass

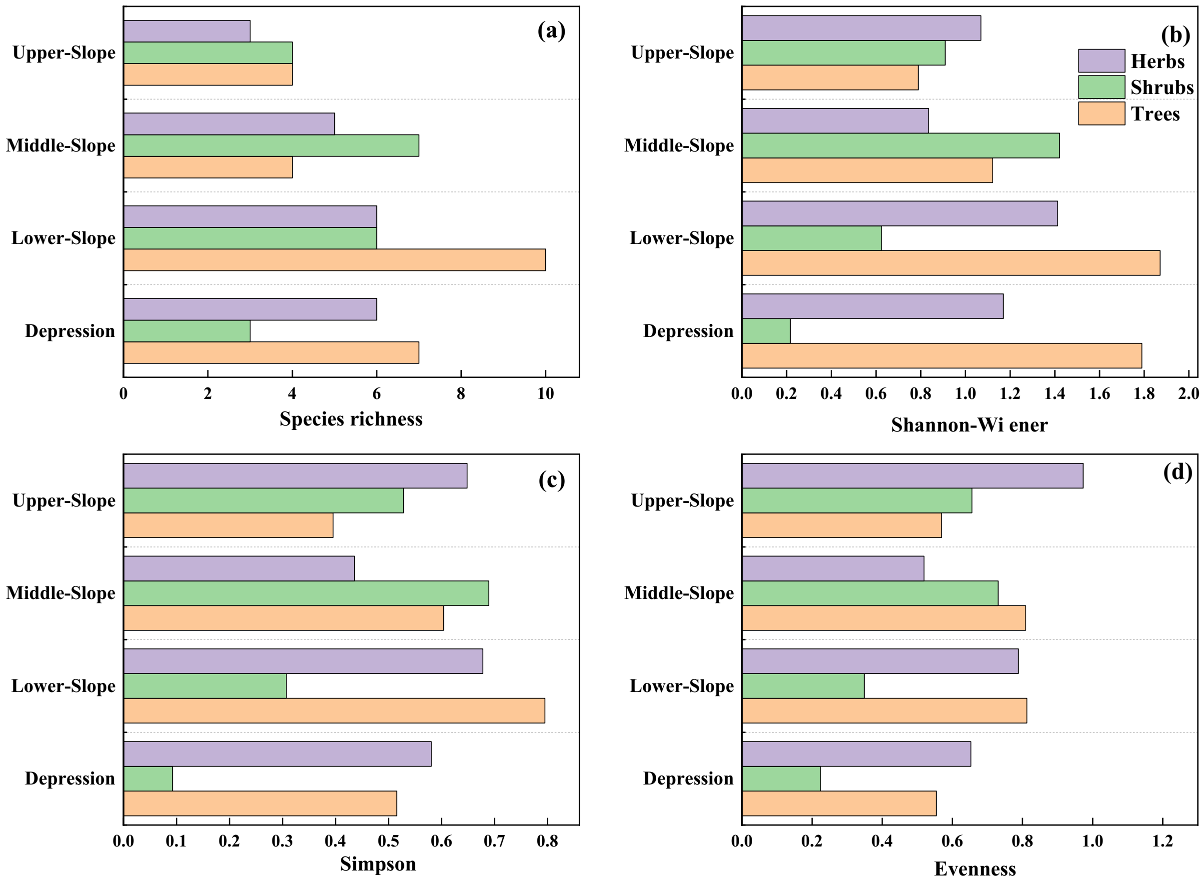


Fig. 7 Vegetation characteristics for different topographic positions

ratio contributed most to the variation in vegetation diversity. This reflects that gravels inhibited the plant development. Scotton and Andreatta (2021) also found that not only do gravels in the soil fail to act as a favourable resource for vegetation growth, but they also limit the growth of vegetation roots.

Soil and vegetation can present feedbacks between each other (Fig. 10). For this study, the results showed that the peak-cluster depression catchment's unique geomorphologic characteristics are the first-order influencing factors leading to a regular variation of soil-vegetation distribution pattern along the toposequence. We suggest that the gradual increase nutrient resources in the soil catena leads to a regular spatial pattern of vegetation communities. For the question of that whether vegetation influences the soil development or succession, there is still lack of solid evidence to support this issue. The underlying mechanism for feedbacks and con-evolution phenomenon of the soil-vegetation system in karst regions still needs further research.

Quantitative index for evaluating shallow soils' productivity in karst regions

Soil productivity is the ability of soil to support plant growth. When climates are similar, highly abundant vegetation and biomass usually indicates high soil productivity (Wang et al. 2015). Non-karst area soils, generally, are deeper and less gravelly. Total soil material mass maybe not an important factor limiting its productivity. Therefore, scholars evaluate soil productivity in the deep soil zone by evaluating soil fertility based on the nutrient content of the surface soil (about 0-20 cm). For example, Wu et al. (2018) assessed the productivity status of the black soil zone by taking 0-20 cm of soil and measuring its nutrient content. Due to the shallow soil exhibits significant

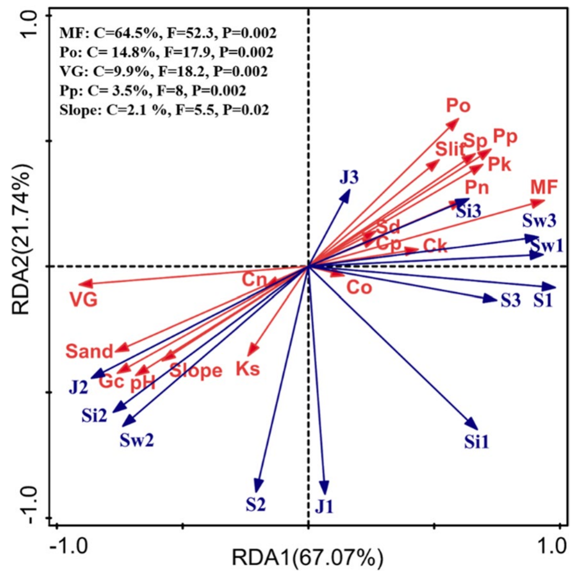


Fig. 8 RDA analysis of the relationships between topographic factors, soil properties and vegetation characteristics

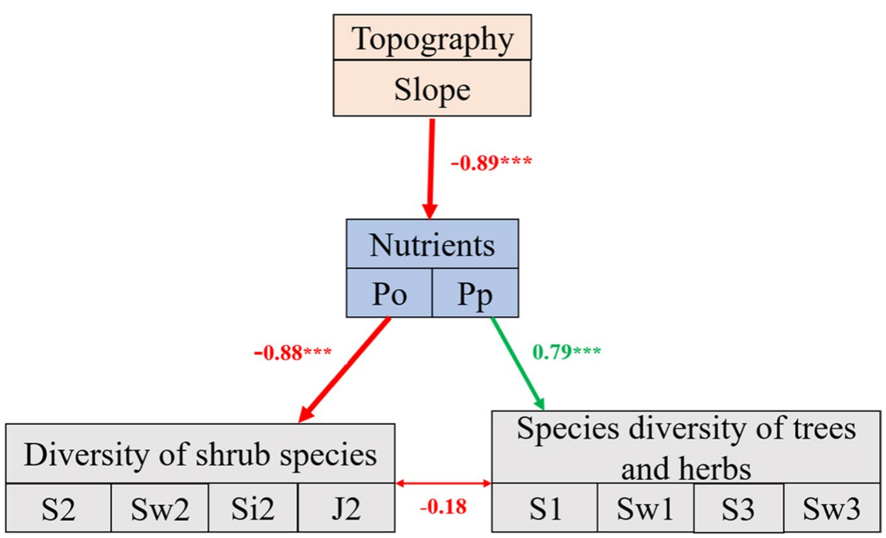
A-layer nutrient accumulation in this study area. Only depend on the A-layer's nutrient content parameters as criterions for assessing soil productivity would significantly overestimate the productivity of the karstic shallow soil.

Although the soil nutrient content was high, the vegetations in the study catchment were characterized by low number, richness, plant species and diversity. Thus, the nutrient content index did not accurately reflect the vegetation characteristics. On the contrary, the nutrient stocks that varied along the toposequence showed the same variation regularity as the vegetation, and the correlation between them was significant. In addition, the indicators affecting nutrient stocks, such as slope position, soil thickness, sand content, clay content, gravel mass ratio, and fine soil mass ratio, showed the same consistent variation pattern with vegetation. Moreover, the correlation analysis also reflected the significant relationship between the above indirect indicators and vegetation characteristics. Comparing with nutrient content and nutrient stocks, we propose that nutrient stocks is more applicable to assess soil productivity.

Conclusions

Despite the soil-forming material was deficient for the pure dolomite rocks, the soils in the dolomite peak-cluster depression catchment were evenly distributed on the surface, with a gradual transition in soil type along the toposequence, showing a typical soil catena. The vegetations along the toposequence also showed the same gradual transition pattern as the soils. The vegetation communities were predominantly herbaceous on the upper-slope, shrubs on the middle-slope and trees on the lower-slope and depression. Slope gradient, nutrient stocks and fine soil mass ratio were the most significant controlling factors determining catenary scale vegetation diversity

Fig. 9 The result of structural equation modeling relating topographic factors and nutrient to indices to vegetation species diversity



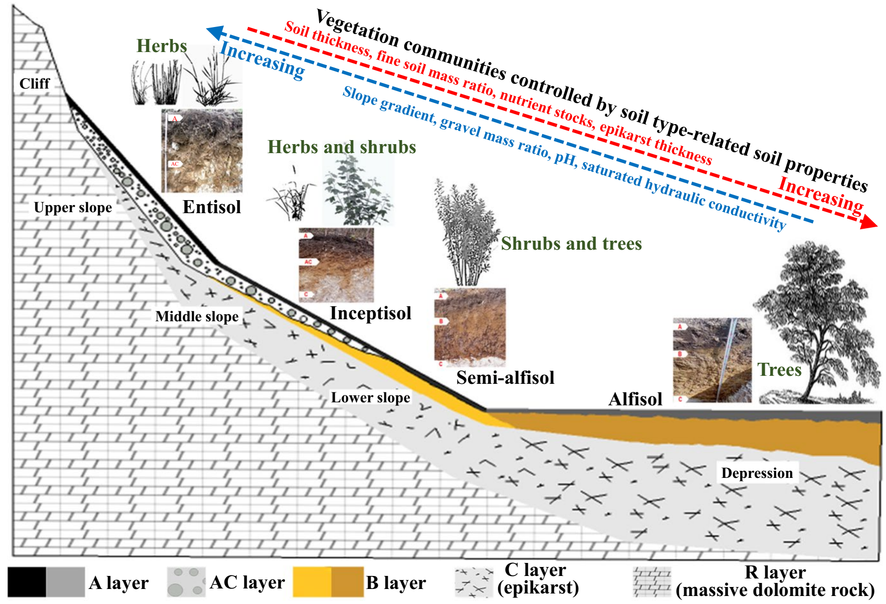


Fig. 10 A schematic representation of soil type-related soil properties determining vegetation communities along the toposequence in the peak-cluster depression catchment developed from dolomite rocks

in the dolomitic peak-cluster depression catchment. For the karst catchment, nutrient stock indexes were more strongly correlated with vegetation characteristics, thus they were more suitable for assessing soil productivity than soil nutrient content indexes. Our study verified the spatial correspondence between soil types and vegetation communities in the dolomite peak-cluster depression catchment. The research can provide theoretical guidance for adjusting land management practices in karst ecological degradation or stone desertification areas to promote sustainable land use.

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