Soil and Vegetation Patterns Along a Toposequence in a Dolomite Peak-cluster Depression Catchment

Qingmei Meng
Institute of Subtropical Agriculture Chinese Academy of Sciences
Zhiyong Fu (zyfu@isa.ac.cn)
Institute of Subtropical Agriculture Chinese Academy of Sciences https://orcid.org/0000-0002-8996-1179
Sheng Wang
Institute of Subtropical Agriculture Chinese Academy of Sciences
Hongsong Chen
Institute of Subtropical Agriculture Chinese Academy of Sciences

Research Article

Keywords: dolomite, soil catena, nutrient stocks, vegetation patterns, soil-epikarst system

Posted Date: November 8th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-1036345/v1

Soil and vegetation patterns along a toposequence in a dolomite peak-cluster depression catchment

Qingmei Meng[a,b,d], Zhiyong Fu[a,d *], Sheng Wang[c], Hongsong Chen[a,d]

[a]Key Laboratory of Agro-ecological Processes in Subtropical Region, Institute of Subtropical Agriculture, Chinese Academy of Sciences, Changsha, Hunan, 410125, China

[b]Forestry College, Guangxi University, No. 100 Daxue Road, Nanning 530004, China

[c]Key laboratory of Environment Change and Resources Use in Beibu Gulf, (Nanning Normal University), Ministry of Education, Nanning, Guangxi 530001, China

[d]Huanjiang Observation and Research Station for Karst Ecosystems, Chinese Academy of Sciences, Huanjiang, Guangxi 547100, China

[*] Corresponding author: Zhiyong Fu

Tel: +86-731- 84619720; Fax: +86-731-84612685; Email: zyfu@isa.ac.cn

Postal address: Institute of Subtropical Agriculture, Chinese Academy of Sciences, Changsha, Hunan, 410125, China

Abstract:

Aim A deeper understanding of relationships between soil and vegetation is a prerequisite for accelerating karst area vegetation restoration. 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 areas.

Methods Soils and vegetation were investigated along a toposequence (upper-, middle-, lower-slope, and depression) of a dolomite peak-cluster depression catchment.

Results A continuous soil catena pattern was developed along the toposequence. From the top to bottom of soil catena, soil thickness, fine soil mass ratio, nutrient stocks, and epikarst thickness gradually increased, while gravel mass ratio, pH, and saturated hydraulic conductivity gradually decreased. However, nutrient contents showed no significant change trends along the soil catena. There was a strong spatial association between soil types and dominant vegetation communities. The associations were as follows: herbs associated with entisols in the upper-slope; herbs and shrubs with inceptisols in the middle-slope; shrubs with semi-alfisols in the lower-slope; and trees with alfisols in the depression.

Conclusions The dolomite rocks displayed an evenly progressive karstification process. This led to an undeveloped underground karstic network incapable of transporting soil materials into underground. Soil materials still accumulated at different topographic positions surface and formed a continuous catena. Parameters for nutrient stock may be more suitable for assessing soil productivity and to guide vegetation restoration key factors in karst regions than nutrient content parameters.

Keywords: dolomite; soil catena; nutrient stocks; vegetation patterns; soil-epikarst

system

1. Introduction

A toposequence is a spatial object that maintains flow connectivity from summit or hillslope initiation to base, or hillslope conclusion. Catenary soils usually developed along a toposequence because the degree of transport and deposition of particulate constituents in the soil profile differs among soils with different topographic positions (Schlichting 1970; Brunner et al. 2004; Lozano-García and Parras-Alcántara, 2014).

Generally, upper-slope erosion and accompanying lower-slope sedimentation result in gradual soil layer and regolith thickening from the upper-slope to the depression. Regular changes of regolith thickness and soil profile morphological characteristics along a topographic gradient are represent as the primary conceptual model for the soil catenary process (Sommer and Schlichting 1997; Applegarth and Dahms 2001; Lozano-García and Parras-Alcántara 2014). The catena concept indicates soil-vegetation combination spatial patterns located on a specific landform. However, soil and vegetation characteristics can vary significantly along a toposequence among at 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 surrounded by slopes which, within a very short horizontal distance, shows rapid changes, from, for example, a close-to-90° -cliff to a relatively flat depression. Potential energy decreases sharply from the slope top to the depression leading to a remarkable 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

63 form a catenary pattern. However, for the karst landscape, knowledge about the soil-
64 vegetation relationships were mostly relied on the results carried out in regional or plant
65 individual scales. Related studies in catchment or catenary scales are relative rare due
66 to the ubiquitous extremely high structural heterogeneity in these scales. For instance,
67 in karst regional scale, Jiang et al. (2014) found that bedrock geochemistry via
68 influencing the regolith water-retention capacities determined the karstic vegetation
69 productivity. In individual plant scale, karstic site-specific characteristics such as
70 bedrock outcrops extent and soil thickness were the main controlling environment
71 factors and determining plant community composition (Liu et al. 2019). Thin soils were
72 dominated by shallow-rooted plants preferring surface soil water, while continuous
73 carbonate rock outcrops were usually dominated by deep-rooted plants preferring rock
74 crevices water (Nie et al. 2010, Ding et al. 2020). Considering that hillslopes and
75 catchments are often as basic management units for implementing ecological
76 restoration in severely degraded karst ecosystems (Jiang et al. 2014), there is a strong
77 need to conduct works to bridge the perception gap in the catenary scale.

78 Moreover, with regard to the soil forming characteristics of karst slope land, through
79 extensive implementation of pedon scale excavation at the complete landform scale of
80 peak-cluster depressions, systematic studies on soil formation processes and soil catena
81 patterns are also still insufficient. Scholars generally believe that the high Ca and Mg
82 content of carbonate rocks and unique karstification processes hinder the loss of salt-
83 based components in soil and desilicification and allitization. Researchers usually
84 regard calcareous soil as a soil category in entisols. There are four sub-categories of
85 calcareous soils: black; brown; yellow; and, red calcareous soil. Typically they are
86 shallow, not obviously stratified, clayey, and abruptly contact the underlying rock.

These results are based on the PRC's second national soil survey, which was aimed at cultivated soils on gentle slopes. Soil resources of mountainous areas were not comprehensively studied. Fully grasping 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, special hillslope hydrological processes, and topography, affects catena formation in many ways in karst areas. Three factors are in play: 1) The Southwestern China karst area is low in acid-insoluble and insufficient sources of soil-forming materials in carbonate rocks. When soil-forming materials are extremely scarce, whether it can form a soil catena with obvious soil development sequence? 2) Carbonate bedrock forming slopes are characterized by highly induced porosity resulting in a well-developed underground drainage system. These often outcrop at or near the surface. They facilitate rapidly surface water transport underground, even during rainfall and runoff events (Williams 1983; Feng et al. 2016). Hillslope scale overland flow rarely occurs in karst areas compared to non-karstic areas (primarily silicate rocks). How does this affect the hydrodynamic conditions that drive the downward and lateral migration of soil materials at different topographic positions? Will it affect the differential sorting and redistribution of soil particles across the slope? 3) In karst catchment, slopes and depressions, what the characteristics of rapid changes in short distances, and the transition between the two are not obvious. This is clearly different from non-karst area topographic position characteristics, where slope gradually descends and transitions to valley floor, thus forming a long slope. Whether karst slope land is able to form a soil catenary pattern similar to non-karst areas, it remains to be determined by field investigations.

Through catenary scale soil and vegetation investigation, the objective of this study was to verify the hypotheses that: (1) dolomite slope can still present a typical soil catena pattern; (2) vegetation communities and soil types are spatially associated in this dolomitic peak-cluster depression catchment.

2. Materials and Methods

2.1. Study area

This study was conducted in a typical karst catchment located at 24°43'58.9″~24°44'48.8″N, 108°18'56.9″~108°19'58.4″E 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 is in a subtropical mountain monsoon climate zone which has an average annual rainfall of 1389 mm. The rainy period is May-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℃. The lowest temperatures, about 3.4~8.7℃ occurs in January -March. The highest, 23.0-26.7℃, 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" policy. 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 is underlain by an early Carboniferous sandstone aquifer which is relatively impermeable (Fig. 1). The underlying rocks are very pure dolomite

rocks. Borehole analysis suggests that karstification degree decreases as depth increases. Study area karstification is characterized by penetrating dissolution pores, micro-tensile dissolution fractures, and local dissolution fractures. Its highly weathered dolomite is mostly lost its original rock structure and even deconstructed into dolomite sand. There is no obvious bubble reaction obtained after dropping dilute hydrochloric acid on it.

2.2. Methods

2.2.1. Soil, rock, and vegetation characteristics

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

Due to the strong spatial heterogeneity in the karst area, a total of 14 soil pits were used: three for both upper-slope and depression positions, and 4 for both mid-slope and lower-slope positions (Table S1), for soil profiles description and soil samples collection. Soil pits were excavated to the C horizon or the epikarst zone. The main topographic variables, including altitude, slope gradient and gravel content, and soil profile morphological characteristics for each soil pits were recorded and described according to FAO-ISRIC-ISSS (2006) (Wrb 2006). Triplicate bulk soil samples, of about 5 kg, were taken for each soil genetic horizons from all side 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

159 of 10 cm, and a volume 1178 cm^3 were fabricated and used as soil cylinders to obtain
160 undisturbed soil samples.

161 A series of boreholes (with a diameter of 15 cm) were made in the upper-, middle-,
162 lower-slopes and depressions in order to study near-surface hydrological processes in
163 the slope-depression system. Borehole core profiles were photographed and described
164 during the drilling process of the sampling of dolomite rocks from the middle-slope and
165 the depression which were collected to analyze chemical composition.

166 ***2.2.2. Determination of soil physical properties***

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

172 $$K_S = \frac{10QL}{A\Delta HT} \quad (1)$$

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

177 Determination of the soil material composition included gravel and fine soil
178 component: Soil cylinder was the total volume of soil material (V_T-cm^3). Soil cylinder
179 contents were transferred to an oven baked at 105℃, and dried for 12 hours. And then
180 weigh to obtain total soil cylinder mass. This was the total soil material mass (M_T-g).
181 Gravels, defined as having a diameter > 2 mm were selected and provided the gravel
182 component total mass (m_g-g). What remained was the fine soil component which were

components <2 mm. Fine soil mass was expressed as m_f(g). This was ground and sieved through a 2 mm sieve. Dried cylinders sample gravel was water-soaked for 12 hours fully saturation. Using drainage method determined gravel volume (v_g-cm^3) (Wang et al. 2017). Gravel density (ρ_g-g/cm^3) could be calculated as：

$$\rho_g = {}^{m_g}/_{v_g} \quad (2)$$

The values determined above were used to calculate fine soil mass ratio (M_F-%), gravel mass ratio (M_G-%), fine soil volume ratio (V_F-%), and gravel volume ratio (V_G-%). v_f is fine soil volume (cm^3), the formula was as follows:

$$v_f = V_T - v_g \quad (3)$$

$$M_F = {}^{m_f}/_{M_T} \times 100\% \quad (4)$$

$$M_G = {}^{m_g}/_{M_T} \times 100\% \quad (5)$$

$$V_F = {}^{v_f}/_{V_T} \times 100\% \quad (6)$$

$$V_G = {}^{v_g}/_{V_T} \times 100\% \quad (7)$$

Fine soil texture was determined using the hydrometer method.

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

$$BD = {}^{M_T}/_{V_T} \quad (8)$$

$$\delta_f = {}^{(M_T - m_g)}/_{(V_T - v_g)} \quad (9)$$

M_T(g) is total soil mass. V_T(cm^3) is total soil volume. m_g(g) is gravel mass. v_g(cm^3) is gravel volume.

2.2.3. 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

208 only solely controlled by the soil nutrient content. Karst slope soil was generally
209 shallow. Lower-slope and depression soils were relatively deep. Soil nutrient content
210 may not fully reflect actual soil productivity. This study compared average nutrient
211 content with nutrient stocks within the pedon scale to explore the appropriate index for
212 assessing shallow and high gravel soil productivity in peak-cluster depressions.

213 The soil nutrient content (N_c) parameters include total nitrogen (TN), total
214 phosphorus (TP), total potassium (TK) content, and soil organic matter content
215 parameters which were measured and calculated according using the techniques used
216 by Bao (2000).

217 This study used the calculation method of soil organic carbon stocks presented in the
218 second edition of the "2011 Soil Investigation Laboratory Information Handbook" of
219 the Natural Resources Conservation Service of the United States Department of
220 Agriculture for soil nutrient stocks index (U.S. Department of Agriculture; Fei et al.
221 2015).

222 The PVC tubes, with a volume of 1178 cm^3, described above to collect soil cylinders
223 were used. These soil cylinders did not all have the same height. The true soil cylinder
224 height was the sum of the fine soil height and gravel height. The gravel height of each
225 soil layer, represented by d_g (cm), fine soil height of each soil layer, represented by
226 d_f(cm). d_g and d_f could be calculated using the actual soil layer thickness, D (cm),
227 for each soil layer. According to the area of PVC tube bottom was equal, so the ratio of
228 gravel volume (v_g-cm^3) to fine soil volume (v_f-cm^3) was consistent with the ratio of
229 gravel height to fine soil height of soil cylinders. The ratio of d_g and d_f is
230 approximately equal the ratio of gravel height to fine soil height for a soil cylinder.
231 Therefore, it was equal to the ratio of gravel volume to fine soil volume. This is the

formula:

$$v_g/v_f = d_g/d_f \quad (10)$$

$$d_g + d_f = D \quad (11)$$

According to the gravel height and fine soil height for each soil layer, calculate the gravel volume (V_1-cm^3/m^2) and the fine soil volume (V_2-cm^3/m^2) of the soil layer per unit area. Gravel density (ρ_g-g/cm^3) were used to calculate the mass of gravel per unit area of soil (m_1-kg/m^2). Fine soil bulk density (δ_f-g/cm^3) were used to calculate the mass of fine soil per unit area of soil (m_2-kg/m^2). m_t represents the total mass of soil per unit area. This the formula:

$$V_1 = d_g \times 10^4 \quad (12)$$

$$V_2 = d_f \times 10^4 \quad (13)$$

$$m_1 = V_1 \times \rho_g \times 1000 \quad (14)$$

$$m_2 = V_2 \times \delta_f \times 1000 \quad (15)$$

$$m_t = m_1 + m_2 \quad (16)$$

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:

$$N_s = m_2 \times N_c \times 1000 \quad (17)$$

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

2.3 Data analysis

Excel 2019 was used to process data. One-way analysis of variance and Duncan

method analyzed soil physical and chemical properties differences. The significance level was set at α=0.05. Pearson correlation analysis tested correlation between topographic factors, soil properties, and vegetation factors. Origin 2021 drew related charts.

3. Results

3.1. Spatial variability of soil formation characteristics along the toposequence

3.1.1. Soil formation conditions at different topographic positions

Peak-cluster depressions have a unique landform resulting from the long-term karstification process. The hillside abruptly changes into a depression. The height difference from the peak-cluster top to 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. Slopes and depressions areas respectively accounted for 64% and 27% of the catchment area. The peak-cluster depression subdivides into four topographic positions. 1) exposed bedrock cliffs with a slope close to 90°. 2) an mostly exposed rock upper-slope with a slope of 32°; a greater exposed rock mid-slope with of 23°; and, less exposed rock lower-slope of 18°.

Soil-forming material spatial distributions 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 drilling cores's average mass contents for CaO and MgO were about 31% and 21%, respectively (Table 1). Average mass content of acid-insoluble account for about 0.17% of total rock mass. This suggests a very pure dolomite rocks in this study

281 catchment. As the slope decreases, the soil pH value of the soil gradually decreased
282 (Table 1). Upper-slope and mid-slope soil pH inherited the high alkaline characteristics
283 of the underlying weathered dolomite. Lower-slope soil pH, particularly in depressions,
284 reduced to neutral, or acidic. That soil's properties were less affected by the underlying
285 bedrock.

286 ***3.1.2. Soil profile morphological characteristics in different topographic positions***

287 Soil profile for different topographic positions can be divided into three soil genetic
288 horizons having dissimilar properties. They are a designated A; AC or B; and C. The
289 "A" layer is black surface layer. "AC or B" is a yellow illuvial horizon and "C" is a
290 white dolomite strongly weathered layer (Table 1). There is a deep dolomite weathering
291 layer in the study catchment. The degree of weathering decreases with depth (Table 1).
292 The differences in the degree of dolomite weathering at different topographic positions
293 are that weathering weakest on the upper-slope where the weathered layer was 1.5 m.
294 The thickness of the dolomite strongly weathered layer in other topographic positions
295 from 2.5 m to 10 m. The dolomite weathered layer was dominated by fine sand formed
296 by overall dissolution. There were no large pores, cracks, karst conduits and other
297 structures in the weathered layer. The boundary between soil and dolomite weathering
298 layer was clear to the naked eye. The contact surface between the two showed an
299 extremely irregular wavy shape. No soil particles had migrated vertically through the
300 rock weathering layer. From the upper-slope to the depression, soil profiles property
301 changes were obvious. Soil thickness increased gradually (Table 1). The A-C transition
302 layer become more visible. Gravel content decreased gradually. Soil fine particle
303 proportions gradually increased. Lower-slope and depression soil presented B layer
304 which was an obvious illuvial horizon.

Soil profiles development morphology analysis returned that upper-slope soil was entisolic and weakly developed. Differentiation between the various soil layers was not obvious. Upper-slope soil was shallow and black with a high gravel content. Middle slope soil was cambisolic, and soil profile development degrees were low. A light yellow weak illuvial horizon was observed under the black surface layer suggesting a weak eluvial and illuvial process. Lower-slope soils were semi-luvisolic having good drainage. The soil profile was moderately developed and a yellow-brown sedimentary layer was easily detected. Depression soil with a yellow surface was highly developed and alfisolic. It had an apparent illuvial horizon. The lower part of it is affected by lateral seepage and formed calcareous concretions and iron-manganese nodules.

3.2. Soil physico-chemical characteristics along the toposequence

3.2.1. Soil physical properties at different topographic positions

Upper- and middle-slope soil profiles were composed mainly of gravel. Upper slope average gravel mass and volume ratios were 73% and 64% respectively (Fig. 2). In the middle slope these 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 decreased. Fine soil mass and fine soil proportion volumes showed the opposite trend which are obvious slope colluvium characteristics (Fig. 2).

There was a high average clay content of between 32%-52% in lower-slope and depression profiles (Fig. 3). Lower-slope clay content relatively smoothly, with depth (Table 2). Upper and middle slopes have higher sand content which increases with depth.

328 The average profile sand content was between 68% and 81% (Fig. 3). This shows that
329 lower-slope and depression belong to the clay group. Saturated hydraulic conductivity
330 decreased as the soil depth increase (Table 2). Depression saturated hydraulic
331 conductivity was the least with a maximum value only 61 mm/h (Table 1). Middle slope
332 maximum saturated hydraulic reached 5095 mm/h. Dolomite slope land is entisolic
333 with high permeability and well drainage. Depression land soil is alfisolic with low
334 permeability and poorly drained.

335 ***3.2.2. Average nutrient content and nutrient stocks at different topographic positions***

336 If there is a "rule of nutrient content change" along a slope it was not obvious (Fig.
337 4). Soil nutrient stocks gradually increase at different topographic positions. This
338 largely agrees with soil thickness and apparent soil productivity trend changes along
339 the slope. Soil TN (2.07 kg/m^2), TP (1.19 kg/m^2), TK (9.68 kg/m^2), and organic matter
340 (47.68 kg/m^2) nutrient stocks were all significantly higher than for the upper- and
341 middle-slopes (Fig. 4). Soils of karst areas are commonly shallow and gravelly, thus
342 pedon scale nutrient stocks may be a more suitable measure than nutrient content to
343 assess soil productivity.

344 ***3.2.3. Nutrient accumulation in A-layer***

345 This study determined that soil nutrient surface accumulation was significant. A layer
346 nutrient, alone, are not an accurate measure of reflect soil fertility and productivity.
347 Upper-slope A layer have the greatest accumulation. It ranges from 63%-85% (Fig. 5).
348 Middle-slope accumulation ranges from 60%-76%. Lower-slope accumulation was
349 between 33%-56% and for depressions it was 22%-26% (Fig. 5). A layer of depression
350 accumulated relatively few nutrients. Along a slope, nutrient accumulate of A layer
351 gradually lessens. From the characteristics of the black soil layer (Table 1) of upper-

352 slope soil profile, it could also be derived that slope pedon scale surface nutrient
353 accumulation was significantly stronger than that of the depression.

354 Upper-slope surface layer fine soil volume was the greatest at 53.64% (Fig. 6).
355 Middle-, lower-, and depression values were 40.96%, 45.10%, and 33.29% respectively.
356 Surface accumulation increased as the amount of fine soil increased except for lower-
357 slopes.

358 ***3.3. Vegetation patterns responses to topographic change***

359 ***3.3.1. Vegetation changes along the toposequence***

360 On the upper-slope, herbs were about 45% of all plants and shrubs about 36% (Table
361 4). On the mid-slope, shrubs were 58% and herbs 26%. On lower-slopes shrubs and
362 herbs were 62% and 23%. In depressions, herbs were 55% and trees were 42%. Number
363 of trees increased as slope decreased. Initially the shrub increased as position decreased
364 and but then decreased. Plant population was greatest on lower-slopes mainly
365 consisting of shrubs and herbs. Middle-slopes had the least number of plants. Shrubs
366 and herbs predominated on upper- and middle-slopes. Depressions were mainly trees
367 and herbs. Vegetation patterns changed from shrubs to trees with the top to bottom of
368 slope.

369 ***3.3.2. Correlation among topographic, soil properties, and vegetation factors***

370 All measured factors were divided into three categories: 1) topographic factors which
371 includes slope position, soil thickness, gravel coverage, and slope; 2) soil properties
372 which includes, among other measures, soil bulk density, fine soil bulk density,
373 saturated hydraulic and conductivity; 3) vegetation factors which includes tree, shrubs
374 and herbs type and number. Topographical factors Sp and Sd significantly negatively

correlated to the soil properties of sand, pH, M_G, and m_1. Topographical factors Sp and Sd significantly positively correlated with Clay, M_F, m_2, pedon scale nutrient stocks. This suggests that topographic factors have an influence on the variation of soil properties. Sand, pedon scale nutrient stocks, and M_G, significantly correlated with vegetation factors, indicating that soil properties closely relate to vegetation factors. The four parameters in the topographic factors all significantly correlate with the vegetation factors.

4. Discussion

4.1. Dolomite-slope shallow soil forms a continuous soil catena pattern

In non-karst areas, the weathering of rock is dominated by physical weathering, supplemented by chemical weathering. Weathering usually occurs at, or close to, the surface. Weathering affected deep bedrock physical and chemical characteristics less (Worthington et al. 2016; Beven et al. 2021). Carbonate rock is generally solvable, therefore karst-area chemical rock 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. In limestone networks are formed. In dolomite the process is diffuse. This results in greater weathered rock layer depth in karst areas which may vary from 10-1000 m (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 thicknesses could beyond 50 m. Strongly-weathered and the weakly weathered layers alternated. This result provided field solid 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 to 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 even in strongly-weathered dolomite eluvium pore structures predominate. Water, but not soil particles, channels through small pores. This results in dolomite soil slopes having a soil catena pattern similar to non-karst areas where soil gradually thickens and continuous distributes 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 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. Tsai et al. (2010) studied a Taiwan soil catena composed of two-pyroxene andesites and two-pyroxene hornblende andesites. That soil catena had three soil types. The average distance between adjacent soil types was 1833 m. In the instant 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. The stronger karst slope vertical water flow drives soil profiles soil formation processes more quickly than for non-karst slopes. It seems likely that the more rapid vertical water flow present in a dolomite soil profiles replaces the lack of a hydrological driving force resulting from short slopes and a steep topography. A 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. Do these processes weaken soil material continuous distribution patterns on the slope surface? If so, does this weaken any soil catena pattern phenomenon?

4.2. Spatial correspondences between vegetation, and soil, patterns

Vegetation, and soil, patterns of the dolomitic peak-cluster depressions present a clear spatial correspondence. This is revealed soil catena distribution patterns being compared to vegetation spatial distribution pattern. (Fig. 8). Vegetation patterns can be inferred from soil patterns. The degree of soil development leads to the different structure of vegetation community. This suggests that the different soil types of this soil catena have significantly different vegetation carrying capacities. Herbs were the primary upper-slope entisolic vegetation (Fig. 8). Herb and shrubs were the primary

445 mid-slope inceptisolic vegetation. Shrubs were the primary lower-slope semi-alfisolic
446 vegetation. Trees were the primary depression alfisolic vegetation.

447 Water and soil nutrient limitations were the two primary factors leading to vegetation
448 spatial pattern changes (David A. Robinson et al. 2008). This study coupled the soil and
449 vegetation surveys at a complete catena in the dolomite peak-cluster depressions of
450 catchment. The close relationships between soil, and vegetation, distribution patterns
451 were disclosed. However, research results have yet to accurately determine the key
452 environmental factors controlling the spatial relationships between soil and vegetation
453 described above. This is because soil water-retention capacities and soil nutrient
454 capacities have strong synergism as slope decreases. The upper-slope soil was shallow
455 and more gravely. Soil profiles water retention capacities were poor. Soil nutrient stocks
456 were low. Depression soil was relatively deep and less gravelly. It had greater water
457 retention capacities. Soil nutrient stocks were higher (Fig. 8). Soil water retention
458 capacities and soil nutrient stocks show the same trend along the toposequence. A
459 simple factor correlation analysis did not distinguish among the relative contributions
460 of soil water-retention and soil nutrient stocks factor to vegetation distribution patterns.
461 Are dolomite peak-cluster depression vegetation distribution patterns caused by soil
462 moisture retention limitations or soil nutrient limitations, or by the interaction of these
463 two limiting factors, or some other reasons? In-depth research through large-scale
464 investigation and sampling and indoor tests are needed to answer these questions.

465 ***4.3. Quantitative index for evaluating shallow soils' productivity in karst regions***

466 Soil productivity is the ability of soil to support plant growth. Where climates are
467 similar, highly abundant vegetation and biomass usually indicates high productivity

(Wang et al. 2015). Non-karst area soil, generally, is deeper and less gravelly. Soil amount 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), and reflect soil productivity through soil fertility. 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. For shallow soils like this study, since the total soil amount significantly affects soil productivity, and the shallow soil exhibits significant A-layer nutrient accumulation. Only depend on the A-layer's nutrient content or stock parameters as criterions for assessing soil productivity would significantly overestimate the productivity of the karstic shallow soil.

In this study, it was found that the soil nutrient content was high, but the vegetation in the area was low in number and richness, and low in plant species and diversity. This shows that the nutrient content does not accurately reflect the vegetation characteristics. In this regard, we believe that in this karstic shallow soil zone, the nutrient content may not accurately reflect soil fertility. On the contrary, the nutrient stocks that varied along the toposequence showed the same 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 pattern of variation with vegetation, and the correlation analysis also reflected the significant relationship between the above indirect indicators and vegetation. In summary, comparing nutrient content and nutrient stocks, we propose that nutrient stocks is more applicable to assess soil productivity.

5. Conclusions

Dolomite rocks usually present an evenly progressive karstification pattern. This leads to an undeveloped, fissure-conduit network system. Underground soil creep and fill processes were not obvious for these dolomite hillslopes. Soils concentrated at the surface and show a soil catenary pattern similar to that present in non-karst areas. There was a strong spatial association between soil types and dominant vegetation species. Herbs associated with entisols are on the upper-slope. Herbs and shrubs associated with cambisols are on the middle-slope. Shrubs were associated with semi-luvisols are on the lower-slope. Trees were associated with luvisols are on the depression.

Considering karst hillslope rocky and shallow characteristics, the amount of fine soil was the critical factor controlling vegetation growth. Nutrient stock parameters, and other, the study of more easily measurable parameters, such as topographic position, soil thickness and, gravel mass ratio may more suitable for assessing soil productivity than soil nutrient content parameters in karst regions.

Borehole core characteristics suggest a positive correlation between soil thickness and epikarst thickness. Further research is needed to confirm whether a soil-epikarst-vegetation catenary pattern exists in dolomite karst catchments. This study focused on soil and vegetation relationships along a toposequence in this typical dolomite developed catchment. Dolomite rock and limestone are the two predominant types of carbonate rocks in karst regions. Their lithologic and dissolution characteristics differ. These differences lead to apparent different soil-epikarst structural differences between them. Weather soil-epikarst-vegetation catenary is also obvious in peak-cluster depression catchment developed from limestone but this remains to be elucidated.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (41930866, 42077077, 41671287), the Guangxi Natural Science Foundation of China (2020GXNSFAA297242) and the Central Guided Local Science and Technology Development Fund Project (ZY21195016).

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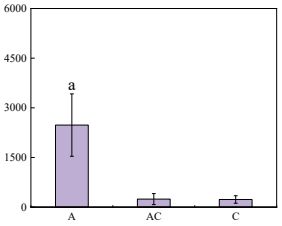
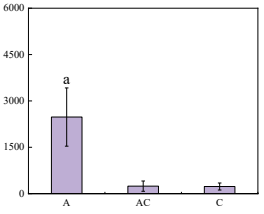
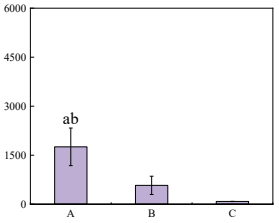
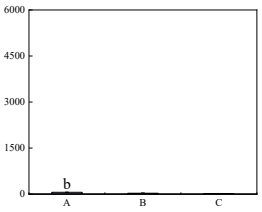
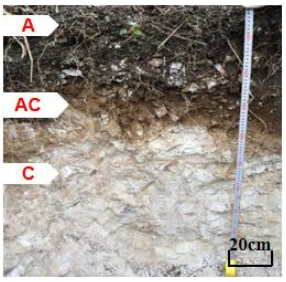
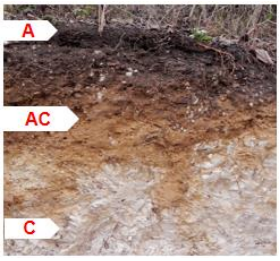
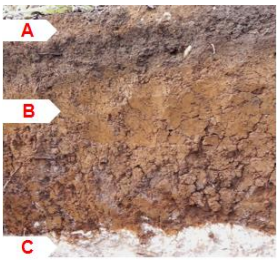
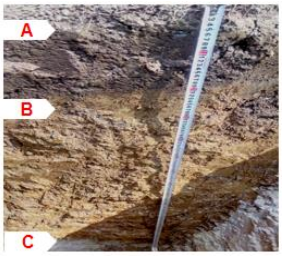
610

611 **Table 1** Site characteristics, soil hydrological conditions, and soil-rock profile morphology at
612 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%

613 Note: Lowercase（a, b）represent the Anova results in same parameters ($p<0.05$).
614 n.a.: not analysed.

615 **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.
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	220.73	0.01	0.05

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.

619 **Table 4** Vegetation characteristics for different topographic positions

Topographic positions	Vegetation Types	Number of plant species	Plants number	Percentage(%)
Upper-Slope	trees	3	63	18.10
	shrubs	10	126	36.21
	herbs	3	159	45.69
Middle-Slope	trees	1	41	15.53
	shrubs	7	154	58.33
	herbs	5	69	26.14
Lower-Slope	trees	9	54	13.95
	shrubs	10	241	62.27
	herbs	6	92	23.77
Depression	trees	4	121	42.01
	shrubs	2	7	2.43
	herbs	5	160	55.56

620 The statistics of the above values were on a 400m^2 sample. Percentage is the ratio different

621 vegetation types to the total plant number.

Figure Captions:

Fig. 1 Location and geohydrologic background of the study area

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

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

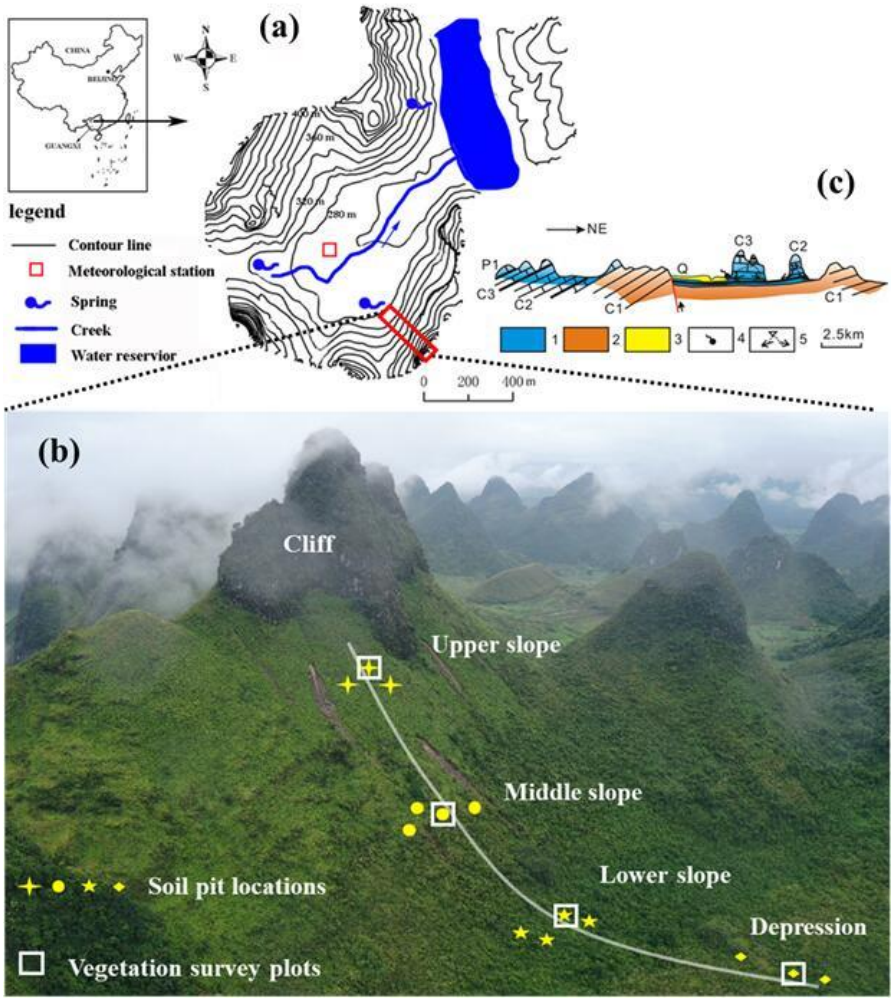
Fig. 4 Pedon scale average nutrient content and nutrient stocks for different topographic positions

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

Fig. 7 The correlation between topographic factors, soil properties, and vegetation factors

Fig. 8 A schematic representation of soil catena and its effects on vegetation spatial pattern along the toposequence in the peak-cluster depression catchment developed from dolomite rocks



(a) Mulian catchment in Huanjiang county, Guangxi, China, topographical map; (b) the peak-cluster depression karst landscape the soil and vegetation locations along the toposequence; and, (c) geohydrologic background of the study catchment. 1, 2, 3, 4, and 5 indicate the karst aquifer; the sandstone aquifer, a relatively impermeable layer; the porous quaternary aquifer; the spring and ground water flow paths, respectively. P1 is is early Permian. Q is Quaternary. C1, C2, and C3 indicate the early, middle and late Carboniferous, respectively.

Fig. 1 Location and geohydrologic background of the study area

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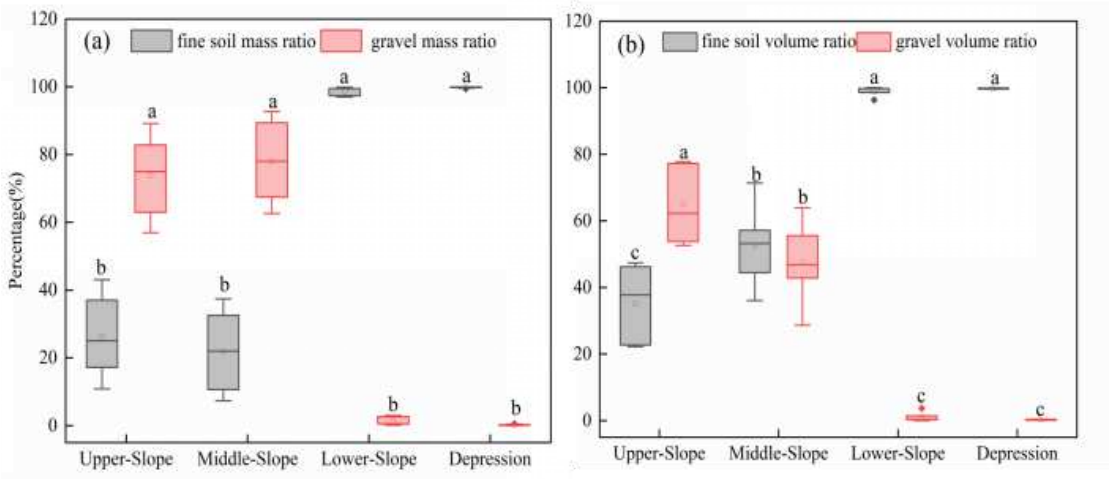

644

645 Note: The lowercase letters indicate significant differences between slope positions ($P<0.05$).

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

647 positions

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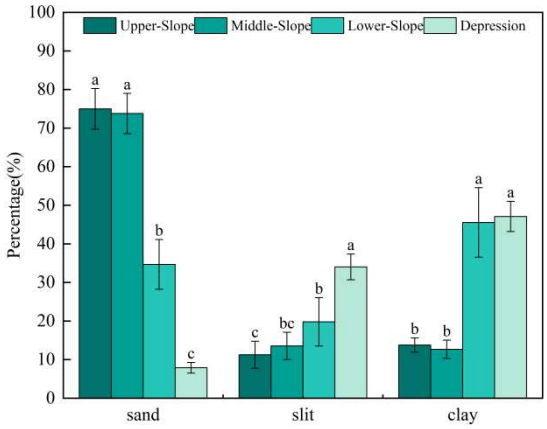
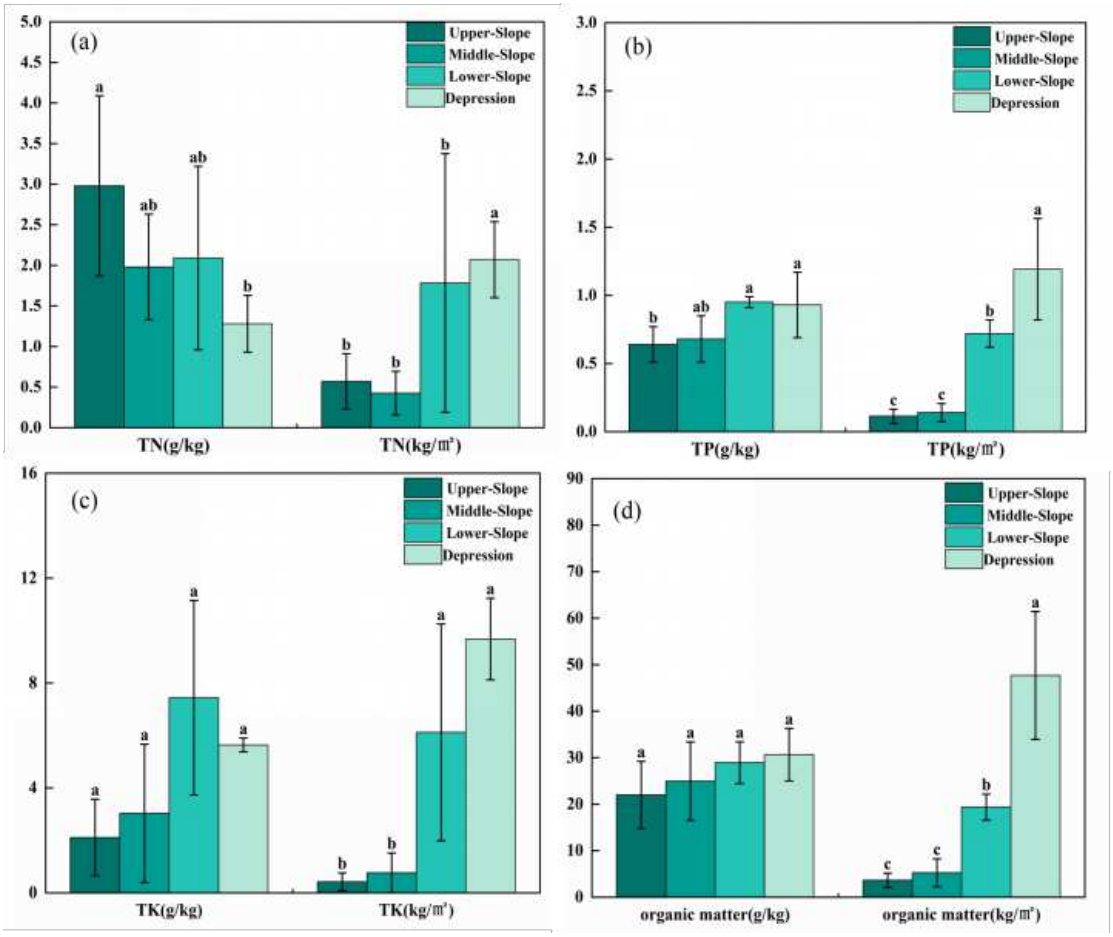


650

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

652 positions



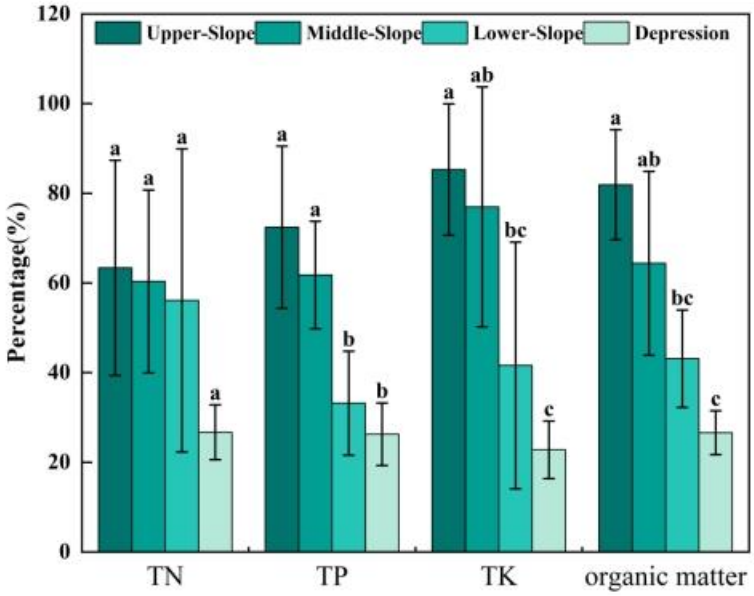
653

654 In Figures a, b, c, and d, the left is part represents the nutrient content and the right part represents

655 the nutrient stocks.

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

657



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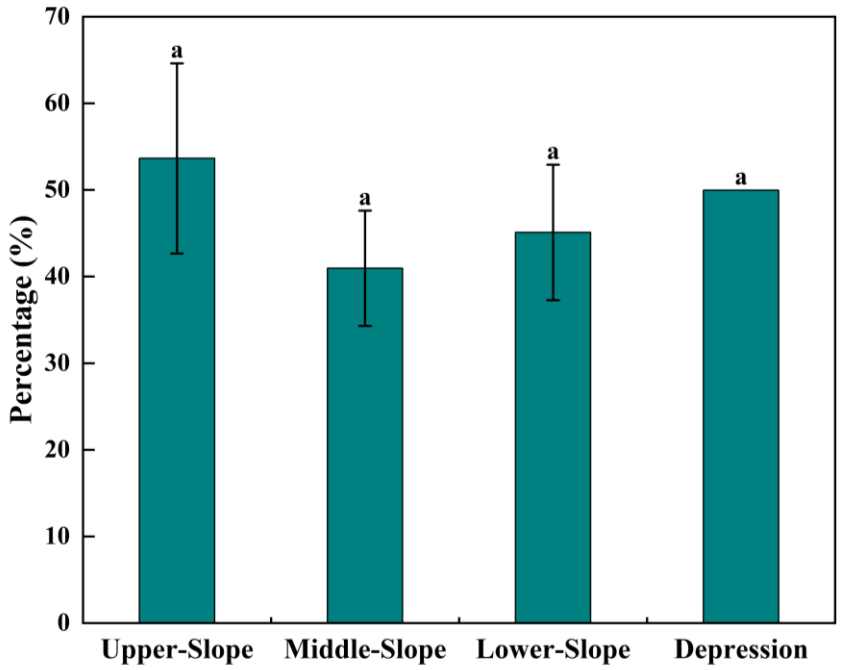
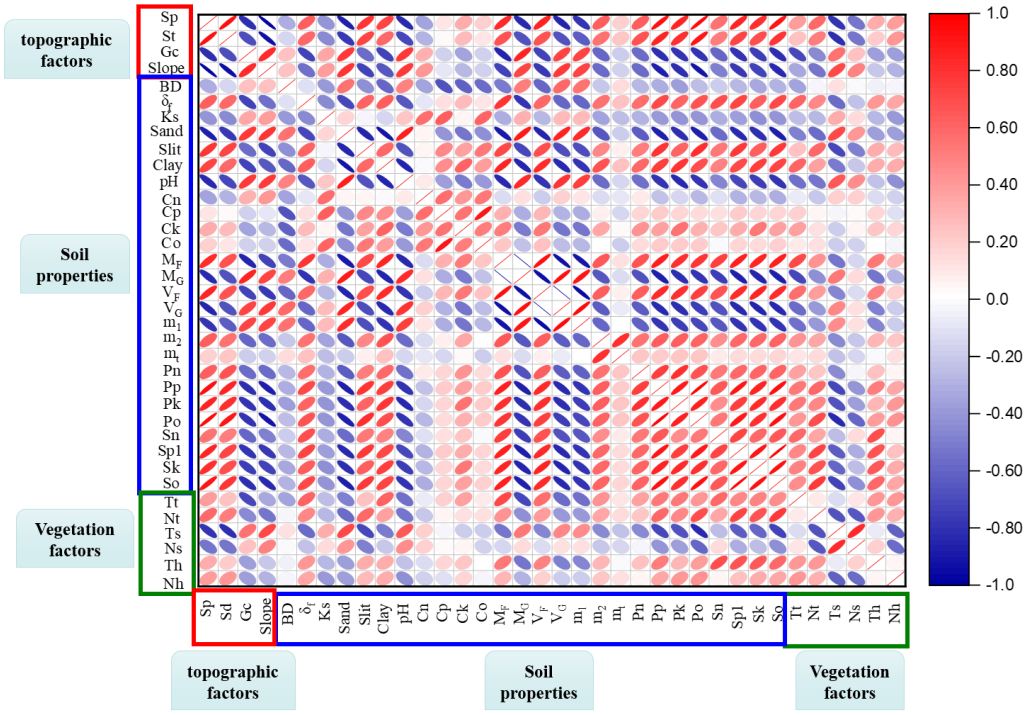
659 **Fig. 5** The ratio of A-horizon's nutrient stock to pedon scale nutrient stock

660



661

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



Note: Sp is slope position. Sd is Soil depth. Gc is gravel coverage. BD is bulk density. δ_f is fine soil BD. Cn is nitrogen content. Cp is phosphorus content. Ck is potassium content. Co is organic matter content. M_F is fine soil content. M_G is gravel content. V_F is fine soil volume ratio. V_G is gravel volume. m_1 is gravel per unit area mass. m_2 is fine soil per unit area mass. m_t is the total mass of soil per unit area, Pn is the pedon total nitrogen stocks, Pp is the pedon total phosphorus stocks, Pk is the pedon total potassium stocks, Po is the pedon organic matter stocks, Sn is the total nitrogen stocks of A layer, Sp1 is the total phosphorus stocks of A layer, Sk is the total potassium stocks of A layer, So is the stocks of organic matter in A layer, Tt is tree types, Nt is the number of trees, Ts is the type of shrub, Ns is the number of shrub, Th is the type of herb, Nh is the amount of herb.

Fig. 7 The correlation between topographic factors, soil properties, and vegetation factor

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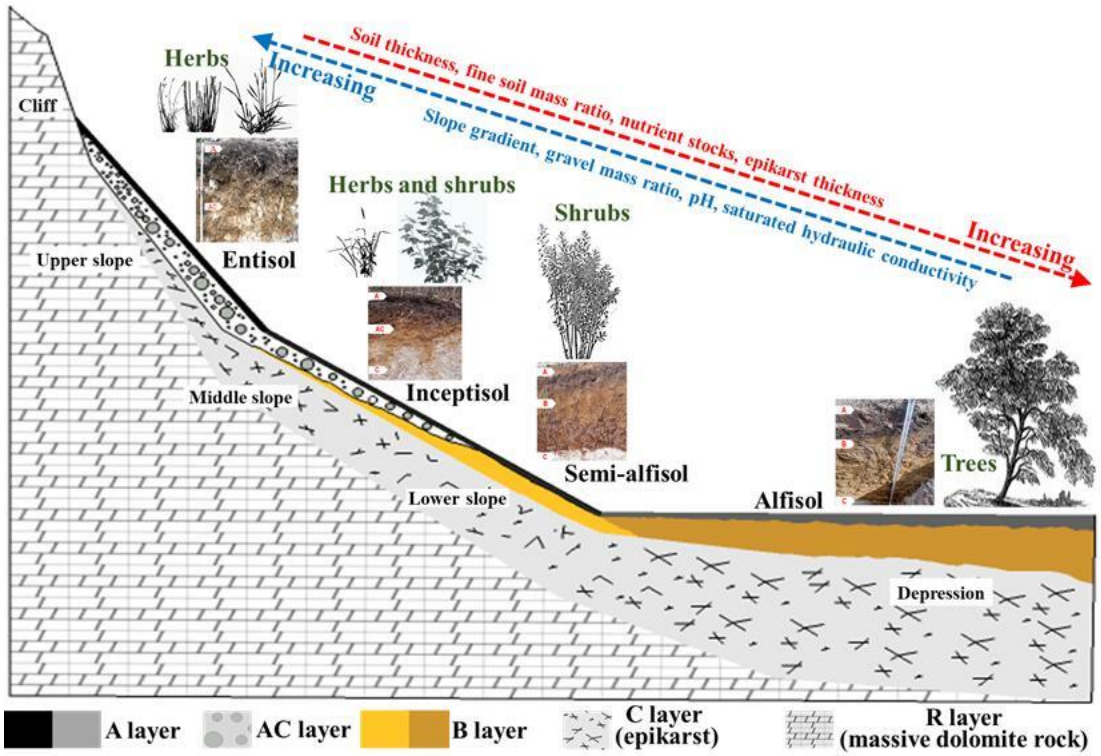

676

677 **Fig. 8** A schematic representation of soil catena and its effects on vegetation spatial pattern along

678 the toposequence in the peak-cluster depression catchment developed from dolomite rocks

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