

## Spatiotemporal Distribution Patterns of Soil Organic Carbon and Their Correlation with Environmental Factors in Typical Karst Rocky Desertification Ecosystems: Postprint

**Authors:** Wang Linjiao, Li Rui, Sheng Maoyin

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### Abstract

Three typical karst rocky desertification ecosystems in Southwest China (the Yachi plateau-mountain rocky desertification area in Bijie, Guizhou, the Hongfeng Lake plateau-basin rocky desertification area in Guiyang, and the Huajiang plateau-canyon rocky desertification area in Guanling) were selected as study areas, where extensive field plots were established to investigate the distribution of soil organic carbon and its correlation with environmental factors such as rocky desertification grade, topography and landform, vegetation, and soil properties. The results show that: 1) Soil organic carbon content in karst rocky desertification ecosystems is relatively low, with average values of 23.42, 25.78, and 26.03 g/kg for the three ecosystems in Bijie Yachi, Guiyang Hongfeng Lake, and Guanling Huajiang, respectively, and no significant difference in soil organic carbon content among the three different geomorphological types of rocky desertification. 2) Land cover change significantly affects soil organic carbon content, with primary forest having the highest average soil organic carbon content of 31.32 g/kg among all types. As land cover degrades from primary forest to rocky land, soil organic carbon content exhibits a trend of first decreasing and then increasing. 3) Soil organic carbon shows significant correlations with soil properties, being extremely significantly positively correlated with total nitrogen, hydrolytic nitrogen, available potassium, total porosity, natural water content, capillary water holding capacity, field capacity, and upper layer permeability, significantly positively correlated with total phosphorus and lower layer permeability, and extremely significantly negatively correlated with bulk density. 4) Plant diversity indices including the richness index (R) and diversity index (H) show significant correlations with soil organic carbon content, reaching extremely significant levels. 5) Soil organic carbon content differs significantly among

different rocky desertification grades, showing a trend of first decreasing and then increasing with increasing rocky desertification disturbance intensity. The research results hold important theoretical significance and practical guidance value for forest ecological protection, restoration and reconstruction of rocky desertification ecosystems, and source reduction and sink enhancement in the carbon cycle to address global climate change in Southwest China's karst regions.

## Full Text

## Preamble

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### **Distribution of Soil Organic Carbon Related to Environmental Factors in Typical Rocky Desertification Ecosystems**

WANG Linjiao<sup>1,2,\*</sup>, LI Rui<sup>3</sup>, SHENG Maoyin<sup>1</sup>

<sup>1</sup> Karst Research Institute, Guizhou Normal University

<sup>2</sup> National Engineering Research Center for Karst Rocky Desertification Control

<sup>3</sup> Guizhou Provincial Monitoring Station of Soil and Water Conservation

State Key Laboratory Incubation Base for Karst Mountain Ecology Environment of Guizhou Province, Guiyang 550001, China

## Abstract

Karst rocky desertification is a critical ecological issue hindering socioeconomic development in the South China Karst region. This study selected three typical rocky desertification regions in Guizhou Province—Bijie Yachi (plateau mountain), Qingzhen Hongfenghu (plateau basin), and Guanling Huajiang (plateau gorge)—representing three distinct karst landform types. Ninety sample plots (20 m × 20 m each) were established to investigate the distribution of soil organic carbon (SOC) in relation to environmental factors (degree of rocky desertification, landform, vegetation, soil properties, etc.) through field measurements, laboratory analysis, and statistical methods. Key findings include: (1) SOC content in karst rocky desertification ecosystems was low, with average values of 23.42, 25.78, and 26.03 g/kg for the three study areas, respectively, showing no significant difference ( $P = 0.23$ ) among landform types. (2) Land cover change significantly affected SOC content, which exhibited a decreasing-then-increasing trend from virgin forest to gravel land, with virgin forest showing the highest SOC content (31.32 g/kg). (3) SOC content was significantly correlated with soil physicochemical properties, showing extremely significant positive correlations with total nitrogen, hydrolyzed nitrogen, available potassium, total porosity, natural moisture capacity, field moisture capacity, capillary moisture capacity, and upper strata saturated permeability; significant positive correlations with total phosphorus and lower strata saturated permeability; and ex-

tremely significant negative correlation with bulk density. (4) SOC content was extremely positively correlated with plant diversity richness and Shannon-Wiener indices. (5) Significant differences in SOC content existed among different rocky desertification grades, showing a decreasing-then-increasing trend with increasing desertification severity. These results clarify the distribution patterns and driving factors of SOC in karst rocky desertification ecosystems, providing important theoretical and practical guidance for karst forest conservation, rocky desertification restoration, and climate change mitigation through carbon sequestration.

**Keywords:** karst; rocky desertification; soil organic carbon; distribution pattern; impact factors

## Introduction

As global climate change garners increasing worldwide attention, soil carbon pools—the largest component of terrestrial ecosystem carbon storage—have become a focal point of global carbon cycle research [1]. The role of soils in global carbon balance and their carbon sequestration capacity have received extensive attention [2-3]. Soil organic carbon is critically related to nutrient supply and erosion prevention; its depletion directly leads to soil quality degradation, manifested by rapid declines in nutrient supply capacity, tilth, aeration, and water permeability [4].

Karst rocky desertification refers to the evolution process or outcome where, under fragile ecological conditions in karst regions, unreasonable human activities create prominent human-land conflicts, leading to gradual rock exposure, declining land productivity, and eventual loss, creating a stony desert landscape [5-6]. The succession process can be divided into several typical stages: non-desertification, potential desertification, slight desertification, moderate desertification, and severe desertification. Karst rocky desertification has become the most serious ecological and geological environmental problem constraining sustainable development in Southwest China [7-10]. Its essence is soil quality degradation, primarily manifested in changes to soil physical, chemical, and biological properties [10-11]. Previous research on soil ecosystem degradation caused by karst rocky desertification has focused on desertification causes, soil degradation characteristics, and vegetation restoration in degraded ecosystems, with minimal investigation into carbon cycling and SOC distribution across different desertification grades [12-14].

Carbon input pathways in karst ecosystems include atmospheric precipitation, plant growth and atmospheric CO<sub>2</sub> absorption, and carbonate rock dissolution through karst processes. Output pathways primarily involve soil surface CO<sub>2</sub> emissions to the atmosphere and carbonate output in karst water [15-16]. Carbon distribution, transfer, and cycling in these systems are dominated by plant carbon absorption and soil carbon release under ecosystem processes and biological activity, with soil carbon transformation as the central link. Soil organic

carbon accumulation constitutes the largest carbon pool, while soil respiration represents the largest carbon flux pathway [17]. These processes are dynamically changing due to soil formation characteristics, environmental conditions, and land use patterns. Investigating SOC distribution patterns and their influencing factors in typical karst rocky desertification ecosystems is crucial for understanding the driving mechanisms of karst dynamics systems.

This study examines SOC distribution and its relationships with desertification grade, landform, vegetation, and soil properties in typical karst rocky desertification ecosystems in Southwest China, including the Yachi plateau-mountain region, Hongfenghu plateau-basin region, and Guanling Huajiang plateau-gorge region in Guizhou. The objectives are to elucidate spatiotemporal SOC distribution patterns and environmental factors, explore SOC response patterns and internal mechanisms during ecosystem degradation and restoration, and provide references for rocky desertification ecosystem reconstruction and climate change mitigation.

## 1. Study Area Overview

Three typical karst rocky desertification regions in Guizhou Province were selected, representing plateau mountain, plateau basin, and plateau gorge landforms. Basic geographic information is presented in .

**Experiment Site I (Bijie Yachi):** Located 13 km southeast of Yachi Town, Bijie City, Guizhou, within the Baipu River tributary of the Wujiang River system (Yangtze River basin). The region features typical plateau-mountain karst topography with strong relief (1,400–1,742 m elevation). Carbonate limestone dominates the geology, with some Jurassic purple sandstone. The climate is north subtropical humid monsoon with mean annual precipitation of 863 mm, concentrated in May–October (85% of annual rainfall). Mean annual temperature is 14.03°C, 10°C accumulated temperature is 4,116°C, and frost-free period is 255 days. Soils are primarily yellow earth and purple sandy soil. Original subtropical evergreen-deciduous mixed forest has been largely destroyed, with secondary vegetation now dominated by *Pyracantha fortuneana*, *Rosa roxburghii*, *Cyclobalanopsis glauca*, *Pinus massoniana*, and *Betula luminifera*, with vines like *Clematis florida*.

**Experiment Site II (Qingzhen Hongfenghu):** Located in Wangjiazhai Group, Boluo Village, Hongfeng Town, Qingzhen City, 12 km from the city center (1,271–1,451 m elevation). This typical karst plateau basin belongs to the Maiweng River tributary of the Wujiang system. Mean annual precipitation is 1,200 mm, concentrated in May–September (78% of annual total). Mean annual temperature is 10.8–18.6°C, with 2,777.3 sunshine hours annually and 278 frost-free days. Limestone dominates, with some Triassic dolomite, argillaceous dolomite, and shale. Soils are yellow earth and yellow limestone soil. Vegetation is primarily agricultural, with common trees including *Cupressus funebris* and typical limestone thorn shrubs (*Rosa multiflora*, *Rubus corchorifolius*). Herba-

ceous species include *Imperata cylindrica*, *Miscanthus floridulus*, and *Arthraxon hispidus*.

**Experiment Site III (Guanling Huajiang):** Located along both sides of the Beipan River gorge in Anshun City, Guizhou. This typical karst plateau gorge has elevations of 450-1,450 m with relative relief of 1,000 m. Mean annual precipitation is 1,100 mm, concentrated in May-September (76% of annual total). The area has a subtropical valley climate above 450 m and south subtropical dry-hot valley climate below. Limestone dominates with some Triassic dolomite and shale. Soils are yellow earth. Original subtropical evergreen-deciduous mixed forest has been largely destroyed, with remnants of *Cyclobalanopsis glauca*, *Betula luminifera*, and vines like *Clematis*.

## 2. Methods

### 2.1 Desertification Grade Classification and Plot Establishment

Based on detailed field surveys and following the classification method of Xiong Kangning et al. [18], rocky desertification succession was divided into five grades: non-desertification, potential desertification, slight desertification, moderate desertification, and severe desertification. Five typical successional stages were selected as study objects: virgin forest (non-desertification), open forest land (potential desertification), shrub grassland (slight desertification), sparse grassland (moderate desertification), and gravel land (severe desertification). In each of the three study areas, six 20 m × 20 m sample plots were established for each stage, totaling 90 plots. All plots had homogeneous yellow limestone soil. Rock exposure rates and other details are shown in .

### 2.2 Soil Sampling and SOC Determination

In April and August 2014, soil samples were collected from the center of each plot using an S-shaped sampling pattern. Five subsamples were taken and mixed to form composite samples. Given the shallow soil depth (0-15 cm) in karst rocky desertification areas, the 0-15 cm layer was selected for study. Soil organic carbon was determined using the potassium dichromate external heating method [19].

### 2.3 Soil Physicochemical Factor Determination

Soil bulk density was measured using the core method. Total porosity was calculated as:

$$p = (1 - b/2.65) \times 100\%$$

where  $b$  is bulk density and  $p$  is total porosity. Capillary porosity was measured by the core method, and non-capillary porosity was calculated as the difference between total and capillary porosity.

Natural moisture capacity, field moisture capacity, and capillary moisture capacity were determined by the core method. Permeability was measured using

the double-ring infiltrometer method. Total nitrogen was analyzed by the Kjeldahl method after  $\text{K}_2\text{SO}_4$ - $\text{CuSO}_4$ -Se digestion. Hydrolyzed nitrogen was determined by alkali diffusion method. Total phosphorus was measured by Mo-Sb colorimetry after  $\text{H}_2\text{SO}_4$ - $\text{HClO}_4$  digestion. Available phosphorus was extracted with  $\text{NaHCO}_3$  and analyzed by Mo-Sb colorimetry. Total potassium was determined by flame photometry after  $\text{HF}$ - $\text{HClO}_4$  digestion. Available potassium was extracted with neutral ammonium acetate and measured by flame photometry. Soil respiration was measured using the chamber method. Soil pH was determined potentiometrically. All methods followed standard forest soil analysis procedures [19].

## 2.4 Plant Diversity Analysis

Plant diversity indices were calculated as:

Richness:  $R = S$

Shannon-Wiener index:  $H = -\sum P \log P$

Evenness:  $E = H/\log S$

Simpson dominance index:  $D = \sum P^2$

where  $S$  is species number,  $P$  is relative importance value of species  $i$  (calculated as  $N_i/N$ , where  $N_i$  is importance value of species  $i$  and  $N$  is sum of all importance values). Importance value = relative density + relative dominance (basal area) + relative frequency. Methods followed forest ecosystem research protocols [20].

## 2.5 Data Processing

SPSS 16.0 software was used for variance analysis (Duncan's test), correlation analysis, and principal component analysis [21]. Excel was used for graphing.

## 3. Results and Analysis

### 3.1 Relationship Between Karst Landform Characteristics and SOC Distribution

Landform affects soil water infiltration, evaporation, and material cycling processes, thereby influencing SOC pools [22]. Soil properties also affect SOC storage. This study investigated SOC distribution across three representative karst landform types in Southwest China: plateau mountain, plateau basin, and plateau gorge. Natural geographic characteristics are summarized in .

Analysis of 90 soil samples from the three landform types showed mean SOC contents of 23.42 g/kg (plateau mountain), 25.78 g/kg (plateau basin), and 26.03 g/kg (plateau gorge), with ranges of 17.02-33.21, 16.17-34.82, and 13.55-33.18 g/kg, respectively. Duncan's test revealed no significant differences among the three landform types ( $P > 0.05$ ), indicating that karst landform type had no significant effect on SOC content .

## 3.2 Relationship Between Vegetation Characteristics and SOC Distribution

**3.2.1 SOC Distribution Under Different Land Cover Types** Five typical land cover types were examined across the karst rocky desertification ecosystems: virgin forest, open forest land, shrub grassland, sparse grassland, and gravel land. Six plots were selected for each type with consistent geographic backgrounds, yielding 30 total plots and 180 SOC measurements.

Results showed virgin forest had the highest mean SOC content ( $31.32 \pm 1.23$  g/kg), while open forest land had the lowest ( $20.92 \pm 1.54$  g/kg). Multiple comparisons revealed virgin forest SOC was significantly higher than open forest land ( $P < 0.05$ ), but not significantly different from shrub grassland (28.19 g/kg), sparse grassland (27.59 g/kg), or gravel land (26.98 g/kg). SOC showed a decreasing-then-increasing trend from virgin forest to gravel land .

**3.2.2 Correlation Between Plant Diversity and SOC** Land cover change significantly affected SOC content. This study examined correlations between SOC and four plant diversity indices across all 90 plots in spring and summer. Richness index ( $R$ ) and Shannon-Wiener index ( $H$ ) showed extremely significant positive correlations with SOC ( $P < 0.01$ ), while evenness index ( $E$ ) and dominance index ( $D$ ) showed no significant correlation .

## 3.3 Relationship Between Soil Characteristics and SOC Distribution

**3.3.1 Soil Physicochemical Properties in Rocky Desertification Ecosystems** To understand soil characteristics across desertification grades, 11 soil physicochemical indicators were analyzed: bulk density, total porosity, capillary porosity, non-capillary porosity, natural moisture capacity, field moisture capacity, capillary moisture capacity, upper/lower saturated permeability, pH, and soil respiration.

Results showed bulk density ranged 1.13-1.28 g/cm<sup>3</sup>, with moderate desertification having the highest value (1.28 g/cm<sup>3</sup>). Total porosity averaged 55.76% (range 52.56-57.48%). Capillary porosity averaged 37.56% (range 33.71-40.63%). Non-capillary porosity averaged 18.10% (range 16.40-18.92%) with no significant differences among grades. Natural moisture capacity averaged 26.06% (range 23.90-28.57%). Field moisture capacity averaged 31.09% (range 28.12-34.42%). Capillary moisture capacity averaged 39.03% (range 35.09-45.06%). Upper saturated permeability averaged 11.26 mm/min (range 8.35-15.67 mm/min), while lower saturated permeability averaged 7.19 mm/min (range 3.74-10.33 mm/min). Soil pH was acidic (6.96-7.49). Soil respiration averaged 0.13 mg/g/h (range 0.05-0.31 mg/g/h). Total nitrogen averaged 2.63 g/kg, hydrolyzed nitrogen 175.36 mg/g, total phosphorus 0.73 g/kg, available phosphorus 4.63 mg/kg, total potassium 19.53 g/kg, and available potassium 99.02 mg/kg .

### 3.3.2 Correlation Between Soil Physicochemical Properties and SOC

SOC is a critical component of the soil solid phase and, together with soil minerals, serves as a nutrient source for vegetation [23–25]. Correlation analysis between SOC and 11 soil physicochemical factors across 90 plots showed SOC was significantly correlated with most factors. Extremely significant positive correlations were found with total nitrogen, hydrolyzed nitrogen, available potassium, total porosity, natural moisture capacity, field moisture capacity, capillary moisture capacity, and upper saturated permeability ( $P < 0.01$ ). Significant positive correlations were found with total phosphorus and lower saturated permeability ( $P < 0.05$ ). An extremely significant negative correlation was found with bulk density ( $P < 0.01$ ). No significant correlations were found with capillary porosity or non-capillary porosity.

### 3.4 Temporal Dynamics of SOC During Rocky Desertification Succession

Using the space-for-time substitution method, SOC content was examined across five successional stages: non-desertification, potential desertification, slight desertification, moderate desertification, and severe desertification. Mean SOC contents were 30.59, 20.44, 27.54, 26.96, and 26.36 mg/kg, respectively, with ranges of 20.36–38.89, 16.35–36.87, 17.67–36.72, 17.34–32.89, and 14.65–33.78 mg/kg. Multiple comparisons showed significant differences among desertification grades ( $P < 0.05$ ). SOC content did not continuously decline with increasing desertification severity but showed a decreasing-then-increasing pattern.

### 3.5 Seasonal Variation of SOC in Karst Rocky Desertification Ecosystems

SOC storage represents the balance between plant residue input and decomposition by soil microorganisms [25–27]. Climate factors like CO<sub>2</sub> concentration, temperature, and precipitation affect SOC input and decomposition rates [27]. To examine annual variation, SOC was measured in April (spring) and August (summer) 2014 across 90 sampling points.

Spring SOC averaged 26.81 g/kg (range 18.35–32.34 g/kg), while summer SOC averaged 24.99 g/kg (range 17.25–30.18 g/kg). No significant difference was found between seasons ( $P > 0.05$ ).

## 4. Discussion

### 4.1 SOC Distribution Characteristics and Driving Mechanisms in Karst Rocky Desertification Ecosystems

SOC content and its dynamic balance are important indicators of soil quality and health, directly affecting soil fertility and crop productivity [1, 28]. SOC influences soil structure formation and stability, water-holding capacity, nutri-

ent bioavailability, buffering capacity, and biodiversity, thereby regulating soil degradation processes [29]. This study found mean SOC contents of 23.42–26.03 g/kg across the three study areas, consistent with previous research in other karst rocky desertification regions in South China [15, 17] but significantly lower than other ecosystems, demonstrating the poverty of karst rocky desertification soils and confirming the fragility of these ecosystems.

Karst ecosystem degradation is a complex process driven by intense human disturbance, characterized by land productivity decline, vegetation reduction, and desertification-like landscapes [5]. Contrary to the assumption that soil degradation worsens continuously with desertification severity, this study revealed that SOC evolution does not progressively degrade but follows a degradation-then-improvement pattern. This has important implications for degraded ecosystem restoration and climate change adaptation.

Sheng et al. [25] proposed the “bare rock aggregation effect” hypothesis, where exposed rocks collect atmospheric nutrients and karst products in surrounding soils. As desertification progresses, this aggregation effect strengthens, particularly in severely desertified environments, improving degraded soil nutrient status and physical properties while reducing water erosion. This mechanism may drive the observed SOC evolution pattern.

Seasonal comparison showed no significant difference between spring and summer SOC contents, indicating relatively stable seasonal dynamics.

#### **4.2 Influencing Factors of SOC Distribution in Karst Rocky Desertification Ecosystems**

Soil organic carbon storage is controlled by multiple physical, biological, and anthropogenic factors, including climate, soil attributes, and land management practices, with complex interactions among them [3, 17]. Natural and human factors affecting SOC storage, SOC emissions to the atmosphere, and impacts of land cover change on SOC transformation are research hotspots [3, 17].

This study examined effects of soil physicochemical properties, land cover change, and landform on SOC content. Results showed SOC was significantly correlated with most soil factors, particularly extremely significant positive correlations with total nitrogen, hydrolyzed nitrogen, available potassium, total porosity, moisture capacities, and upper permeability, and negative correlation with bulk density, consistent with previous studies [17, 22, 25]. These findings demonstrate that soil properties are crucial factors influencing SOC content and stability.

Landform is also an important factor [3]. However, this study found no significant SOC differences among the three karst landform types, possibly due to differences in research scale and plot selection compared to other studies [3, 28].

Land use change caused by human activity is the most direct factor affecting soil carbon pools and cycling [29]. This study confirmed that different land cover

types significantly influenced SOC content in karst rocky desertification ecosystems. These results are important not only for degraded ecosystem restoration but also for climate change mitigation through carbon source reduction and sink enhancement.

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## Figures

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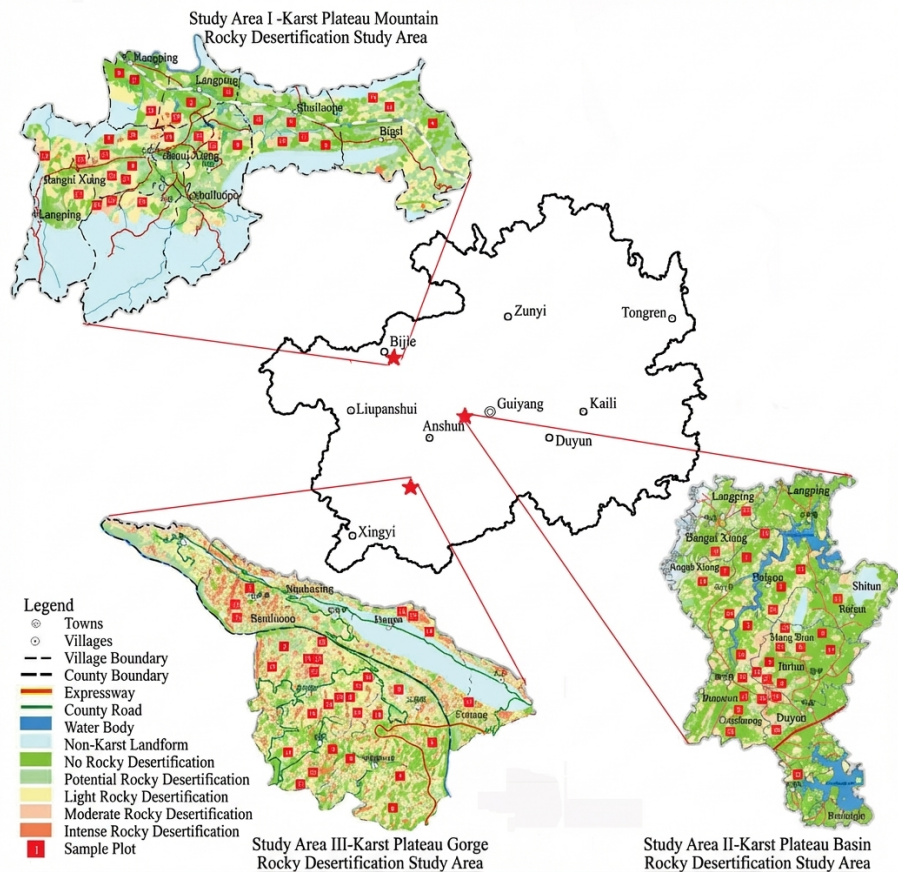


Figure 1: Figure 1