Distribution Characteristics of Soil Organic Carbon and Their Influencing Factors in Karst Rocky Desertification Ecosystems of Southwest China: Postprint

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Abstract

Karst rocky desertification has become the most severe eco-geological environmental problem constraining sustainable socio-economic development in Southwest China, and its restoration and reconstruction have become an important component of China' s socio-economic construction. Soil organic carbon, as a crucial indicator for soil quality assessment, can comprehensively reflect land productivity and environmental health functions. Furthermore, soil organic carbon indirectly influences the terrestrial biological carbon pool and serves as a primary factor in terrestrial ecosystem carbon balance; changes in its transformation and accumulation directly affect global carbon cycle dynamics, making it a hot topic in ecological science research. This study systematically summarizes the spatial and seasonal distribution characteristics of soil organic carbon under different land cover/land use types and varying grades of rocky desertification environments in Southwest China' s karst regions. Combining previous research findings, it further analyzes various natural (climate, topography and soil properties, vegetation, etc.) and anthropogenic (land cover/land use change, agricultural management measures, etc.) factors affecting soil organic carbon distribution in karst rocky desertification areas, and proposes countermeasures to increase soil organic carbon content in these regions. The research results provide important scientific references for the restoration and reconstruction of degraded ecosystems in karst rocky desertification areas, comprehensive soil utilization in desertification regions, and increasing carbon sequestration to address carbon source reduction and sink enhancement in the global carbon cycle.

Full Text

Preamble

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Distribution Characteristics of Soil Organic Carbon and Its Influence Factors in the Karst Rocky Desertification Ecosystem of Southwest China

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Abstract

Karst rocky desertification has become one of the most severe ecological and geological environmental problems constraining socioeconomic sustainable development in Southwest China, and its restoration and reconstruction have become critical priorities in China' s socioeconomic development agenda. Soil organic carbon (SOC) serves as a key indicator for soil quality evaluation, reflecting land productivity and environmental health status. As the primary factor regulating terrestrial ecosystem carbon balance, SOC indirectly influences the terrestrial biological carbon pool, and its transformation and accumulation dynamics directly affect global carbon cycling processes, making it a major research focus in ecological science. This study systematically summarizes the spatial and seasonal distribution characteristics of SOC across different land cover/land use types and varying rocky desertification grades in Southwest China' s karst ecosystems. Building upon previous research and field surveys, we further analyze the natural and anthropogenic factors influencing SOC distribution, including climate, topography, soil properties, vegetation cover, land use change, and agricultural management practices. Finally, we propose measures to enhance SOC content in karst rocky desertification ecosystems. Our findings provide an important scientific basis for the restoration and reconstruction of degraded karst ecosystems, rational soil utilization in rocky desertification areas, and increasing carbon sequestration to mitigate global carbon cycle impacts.

Keywords: karst; rocky desertification; soil organic carbon; distribution characteristic; influence factor

Karst landforms are distributed globally in soluble rock regions, covering approximately 12% of Earth' s land surface. Southwest China' s karst region exceeds 540,000 km^2, representing the world' s largest contiguous karst area and a typical ecologically fragile zone characterized by strong landscape heterogeneity and weak disturbance resistance. Karst rocky desertification refers to the evolutionary process and outcome where, under fragile ecological conditions in karst regions, unreasonable human socioeconomic activities intensify human-land conflicts, leading to vegetation destruction, gradual bedrock exposure, declining land productivity, and eventual loss, creating a stony desert landscape. This phenomenon has become the most serious ecological and geological environmental issue restricting sustainable development in Southwest China. Soil forms the core link in material cycling within karst ecosystems, and the soil ecosystem is highly sensitive to environmental responses. The active biological and chemical processes in these systems create substantial carbon storage potential, making them potentially important carbon sinks in the global carbon cycle under elevated atmospheric CO_2 conditions. Soil carbon constitutes a major component of terrestrial carbon pools and forms the foundation of soil fertility. SOC, accounting for over half of soil carbon pools and approximately 2-3 times terrestrial biomass carbon, enters adjacent spheres through the CO_2-H_2O-$CaCO_3$ system. SOC serves as a critical indicator for soil quality assessment, comprehensively reflecting land productivity and environmental health functions. It also indirectly affects terrestrial biological carbon pools as a primary factor in terrestrial ecosystem carbon balance. As the dynamic medium for karst processes and carbon cycling and the main pathway for carbon flux, SOC enables dynamic equilibrium between CO_2 assimilation and organic carbon decomposition/respiration in karst systems. Understanding SOC distribution characteristics and influencing factors in karst rocky desertification ecosystems is crucial for ecosystem restoration, carbon sequestration enhancement, and comprehensive soil utilization in response to global carbon cycling.

1. SOC Distribution Under Different Land Cover and Land Use

Land cover change fundamentally alters ecosystem structure and function both qualitatively and quantitatively, directly affecting SOC storage and distribution while indirectly influencing SOC formation and transformation through changes in soil structure, physicochemical properties, and microorganisms. Significant differences in SOC content exist among different land cover types in Southwest China's karst region, generally following the pattern: primary forest > secondary forest > shrubland > grassland > farmland. Studies show that SOC storage in shrub and tree-shrub communities within the same secondary successional sequence increases with successional stage. SOC content also changes markedly with land use intensity. Yang et al. reported that converting grassland to farmland reduced SOC content and density by 19.64%-57.12% and 12.22%-50.73%, respectively. Zhang et al. demonstrated that paddy fields represent an advantageous land use type for long-term carbon sequestration in karst mountainous areas. Zhen et al. similarly found that karst cave wetland soils exhibited higher SOC content than dryland soils, with paddy fields helping maintain higher SOC levels in wetland ecosystems.

2. Spatial and Seasonal Distribution Characteristics

The strong spatial heterogeneity of karst soils creates significant differences in SOC distribution. Current research on horizontal distribution patterns remains limited, with most studies focusing on vertical distribution characteristics across different land use types. Zhang et al. revealed significant correlations between SOC and topographic factors in karst peak-cluster depression areas, showing positive relationships with slope gradient and bare rock rate and negative correlation with topographic wetness index. He et al. demonstrated clear vertical distribution patterns, with surface SOC content being significantly higher than deeper layers, decreasing with soil depth in a well-fitted linear relationship. Xu et al. obtained similar results in southwestern Hunan' s rocky desertification region. Microhabitats determine SOC distribution patterns in karst peak-cluster depressions, with microtopography significantly influencing spatial distribution. Research indicates that topographic factors in karst regions differ markedly from other areas—intense karst processes mean landform development substantially affects soil nutrient accumulation and cycling. Steep slopes and high positions tend to form dark habitats like stone slots and caves that favor organic matter accumulation and relatively high nutrient content. SOC and total nitrogen show significant positive correlations with slope and bare rock rate, with stone slots and caves in karst slopes creating dark habitats that lead to SOC accumulation.

SOC also exhibits seasonal variation. Zhu et al. found that shrub and tree-shrub communities in Guangxi' s Huanjiang karst region showed decreased SOC after the rainy season, likely because rapid litter decomposition exceeded seasonal litter input. Liang et al. reported distinct seasonal patterns with higher SOC in winter. Our research in typical karst plateau-canyon regions yielded similar results. Li et al. analyzed seasonal differences in SOC under the same vegetation type in Guizhou's Puding karst area, finding higher values in spring and autumn but lower in summer and winter. Seasonal SOC variation is primarily controlled by temperature and moisture factors. Southwest China' s subtropical monsoon climate with abundant rainfall creates seasonal effects on SOC, though land use/land cover change remains the primary influencing factor while seasonality plays a secondary role.

3. SOC Distribution Across Different Rocky Desertification Grades

Compared with other zonal ecosystems, karst rocky desertification soils have significantly lower SOC, with reported values ranging from 9.81 to 76.49 g/kg. Clear differences exist among desertification grades. While conventional wisdom suggests SOC content decreases with intensifying degradation, with the lowest values in severe rocky desertification, reality proves more complex. Wei et al. found that extremely severe rocky desertification soils in peak-cluster depressions had significantly higher SOC than mild and potential desertification. Wu et al. reported that high SOC areas corresponded to locations with rock outcrop rates exceeding 30%, showing extremely significant positive correlation between SOC and rock exposure rate. Numerous studies have obtained similar results.

Sheng et al., based on extensive systematic monitoring, revealed that SOC evolution in karst rocky desertification does not continuously degrade with increasing desertification grade but follows a decreasing-then-increasing trend, with the highest SOC content in extremely severe rocky desertification. This anomaly relates to the soil-rock binary heterogeneous structure of karst desertification surfaces. When severe desertification occurs and surface soils are eroded, low-growing plants like mosses and lichens form crusts that effectively prevent soil erosion loss. Combined with micro-negative terrain that intercepts surface runoff carrying litter and fine soil particles, these conditions create nutrient accumulation advantages, ultimately causing SOC content to increase rather than decrease at severe desertification stages.

Influencing Factors

3.1 Climate

Climate affects ecosystem photosynthesis and respiration processes, with temperature, precipitation, and atmospheric CO_2 concentration all controlling SOC pool dynamics. Temperature and moisture are key climatic factors regulating SOC input and decomposition. SOC content generally correlates negatively with temperature but positively with soil moisture. Precipitation changes affect soil water content, altering plant litter input and soil respiration rates, thereby changing SOC pools. Soil water content shows significant positive correlation with SOC, with extremely significant positive correlations during both dry and rainy seasons.

3.2 Topographic Factors

Topography represents a primary controlling factor for SOC spatial distribution in karst regions, determining the migration direction and flux of water, solutes, and sediments, which shapes the gradients and patterns of soil property development. Generally, SOC density and storage decrease with increasing slope gradient, while soil carbon density increases from sunny to shady slopes with increasing aspect angle. In karst areas, however, gully slopes have better light and heat conditions than tablelands but less water resources, resulting in stronger SOC mineralization. Microhabitat types, rock exposure rate, and soil layer depth significantly influence SOC distribution.

3.3 Vegetation

Vegetation type affects SOC primarily through root exudates and litter. Vegetation destruction directly causes soil loss and SOC reduction, while vegetation coverage shows significant correlation with SOC content. Zhang et al. found that SOC in typical karst peak-cluster depressions correlated significantly with the Simpson diversity index. During degraded karst vegetation restoration, soil microbial biomass carbon increases significantly and correlates positively with SOC. Huang et al. similarly concluded that natural recovery of karst forest vegetation benefits soil carbon accumulation and quality improvement.

3.4 Soil Physicochemical Properties

As an important component of the soil solid phase, SOC serves with soil minerals as a source of forest nutrients. Soil physicochemical and biological properties directly and indirectly influence SOC. Wang et al. demonstrated that SOC correlates significantly with most soil physicochemical factors, showing significant positive correlations with total nitrogen, capillary water holding capacity, natural water content, capillary porosity, and lower layer permeability, but no significant correlation with non-capillary porosity. SOC content shows extremely significant positive correlation with soil total nitrogen and C/N ratio, and extremely significant negative correlation with bulk density. Correlation with soil water content varies by layer—extremely significant in the 15-30 cm layer but weaker in the 0-15 cm layer.

3.5 Soil Layer Depth

The surface soil layer is the primary site for vegetation litter and animal residue/manure accumulation. After soil microorganisms decompose litter into nutrients, they first replenish the surface layer, which then gradually transfers to deeper layers with soil water, causing SOC content to decrease with increasing soil depth. Li et al. showed that the 0-15 cm layer had higher SOC content, storage, and total nitrogen content/storage than the 15-30 cm layer, with extremely significant negative correlation between SOC and bulk density.

4. Anthropogenic Factors

4.1 Land Use/Land Cover Change

Land use/land cover change is the most direct factor affecting soil carbon pools. Different land use types in karst regions create varying soil microenvironments and vegetation composition, leading to SOC differences. When forestland converts to farmland, tillage destroys soil aggregate structure, exposes soil organic matter to air, and causes carbon decomposition and release, resulting in 30%-50% carbon loss. Grassland conversion to farmland operates similarly. Therefore, rational protection and restoration of vegetation are crucial for increasing SOC storage in karst peak-cluster depression landscapes.

4.2 Agricultural Management Measures

Different agricultural management practices alter soil properties and affect SOC pools. Karst regions have thin soil layers and fragile ecosystems where SOC is vulnerable to land use changes and fertilization activities. Reasonable agricultural management can increase SOC storage—applying organic fertilizer alone or combined with chemical fertilizer can significantly improve SOC content and enhance active organic carbon and carbon pool management indices. Other practices like irrigation also influence SOC.

5. Strategies for Enhancing Carbon Sequestration in Karst Rocky Desertification Soils

5.1 Improving Land Use

Implement reforestation and forest vegetation restoration programs in karst regions, combining hill closure for natural regeneration with artificial afforestation. Forests reduce direct raindrop erosion, the organic layer conserves water, and tree roots increase soil cohesion. On gentle slopes with good site conditions and minimal bedrock outcrops, develop agroforestry systems to restore complex forest-agriculture ecosystems dominated by forest vegetation.

5.2 Establishing Scientific Agricultural Management

Optimize land use/land cover structure to increase SOC content. Add water conservation and economic forests to sloping farmland to improve both water conservation benefits and carbon sequestration. Strengthen comprehensive rocky desertification control—vegetation protection and construction projects, basic farmland development, and water resource engineering all generate additional carbon sequestration benefits. Promote coordinated development of agriculture and animal husbandry, transforming traditional livestock farming toward sustainable ecological animal husbandry to create a virtuous cycle of ecological improvement and economic development.

5.3 Enhancing Education for Local Farmers

Focus on training rural technicians, conducting extensive environmental protection and resource utilization education, and establishing sound agricultural technology training systems. This fosters scientific literacy, enhances sustainable development awareness, and creates an atmosphere of resource conservation and environmental protection.

6. Unresolved Scientific Questions

Rocky desertification has become the most serious environmental issue restricting sustainable development in Southwest China' s karst mountainous regions, with annual SOC loss flux increases exceeding 55$×10^{28}$ Tg. Despite extensive research, several critical scientific questions remain:

1. **Unclear dominant mechanisms of SOC stability**: The high heterogeneity of karst SOC and complex influencing factors obscure its stability mechanisms, necessitating comprehensive studies of multiple stabilization mechanisms.

2. **Lack of measurement methods for SOC storage and spatial distribution**: Karst rocky desertification soils exhibit discontinuous distribution, diverse microhabitats, minimal soil stock, and extensive bedrock exposure, severely constraining accurate SOC estimation and increasing uncertainty in regional carbon balance studies.

3. **Insufficient research on influencing factors**: Continued in-depth studies on correlations between SOC and soil physicochemical properties, management practices, and surface cover, along with accumulation mechanisms, are essential for developing appropriate soil management measures and enhancing carbon sequestration.

4. **Research gap on microclimate effects**: How microclimate affects SOC remains unstudied. Karst rocky desertification areas feature diverse microhabitats with distinct microclimate characteristics, yet research on microclimate-SOC relationships is still blank, severely constraining scientific desertification control and soil carbon sink enhancement.

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Note: Figure translations are in progress. See original paper for figures.