Postprint: Spatial Heterogeneity of Soil Phosphorus and Potassium Nutrients in Karst Evergreen-Deciduous Broad-Leaved Mixed Forests

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Abstract

A 500 m × 500 m long-term monitoring plot was established in a karst evergreen-deciduous broad-leaved mixed forest within Mulun National Nature Reserve to investigate soil phosphorus and potassium nutrient contents and their spatial variability characteristics using classical statistical and geostatistical methods. The results showed that the contents of soil total phosphorus (TP), total potassium (TK), available phosphorus (AP), and available potassium (AK) in the study area were $(1.60\$\pm0.76)g/kg, (5.42\pm2.74)g/kg, (5.74\pm3.63)mg/kg, and (5.20\pm\$2.96)$ mg/kg, respectively; all phosphorus and potassium nutrients exhibited moderate variation, with the variation intensity following the order AP > AK > TK > TP. The best-fitting models for the variogram values of soil TP, TK, AP, and AK in the study area were all exponential models, with high coefficients of determination (0.671–0.995). TP and AP showed moderate spatial autocorrelation, while TK and AK exhibited weak spatial autocorrelation. TP and AP had longer ranges of 336.00 m and 373.50 m, respectively, indicating better spatial continuity, whereas TK and AK had shorter ranges (33.30 m and 64.50 m), showing stronger spatial dependence. Soil TP content was higher in lower slopes (including depressions) and lower in upper slopes; AK content was higher in middle slopes than in depressions; AP and TK showed patchy fragmented distributions. Elevation, slope gradient, and surface convexity were the main factors influencing the spatial heterogeneity of soil phosphorus and potassium nutrients. The existence of different spatial heterogeneities and spatial associations of soil phosphorus and potassium nutrients in karst evergreen-deciduous broad-leaved mixed forests provides a theoretical basis for soil nutrient management, sustainable utilization strategies, and ecological

restoration of degraded karst ecosystems at the small watershed scale.

Full Text

Preamble

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Spatial Heterogeneity of Soil Phosphorus and Potassium in a Mixed Evergreen and Deciduous Broad-Leaved Forest in Karst Region of Southwest China

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Abstract

A long-term monitoring plot was established in a karst evergreen-deciduous broad-leaved mixed forest within the Mulun National Nature Reserve to investigate soil phosphorus and potassium nutrient content and their spatial variability using classical statistics and geostatistical methods. The results showed that the average contents of total phosphorus (TP), total potassium (TK), available phosphorus (AP), and available potassium (AK) in the study area were (1.60 ± 0.76) g/kg, (5.42 ± 2.74) g/kg, (5.74 ± 3.63) mg/kg, and (5.20 ± 2.96) mg/kg, respectively. All soil phosphorus and potassium nutrients exhibited moderate variability, with the order of variation intensity being AP > AK > TK > TP. The best-fitting model for the semivariograms of TP, TK, AP, and AK was the exponential model, with high determination coefficients ranging from 0.671 to 0.995. TP and AP showed moderate spatial autocorrelation, indicating that their variation was caused by both structural and random factors, whereas TK and AK exhibited weak spatial autocorrelation. TP and AP had relatively long autocorrelation distances (336.00 m and 373.50 m, respectively), indicating good spatial continuity, while TK and AK had shorter autocorrelation distances (33.30 m and 64.50 m, respectively), suggesting strong spatial dependence. The distribution of TP was high on toe slopes (including depressions) and low on upslopes, while AK content was higher on slopes than in depressions. Both AP and TK showed patchy distributions. Elevation, slope, and convex topography were the main factors determining the spatial heterogeneity of soil phosphorus and potassium. Overall, soil phosphorus and potassium showed different patterns of spatial heterogeneity and spatial correlation in the karst mixed evergreen-deciduous broad-leaved forest, providing a reference for site-specific soil nutrient management and designing strategies for ecological restoration of degraded ecosystems in the karst region.

Keywords: soil phosphorus and potassium; spatial heterogeneity; geostatistics; dynamic monitoring plots; karst evergreen and deciduous broad-leaved mixed forest

1. Study Area Overview

The study area is located in the Mulun National Nature Reserve in northwestern Huanjiang Maonan Autonomous County, Guangxi, on the southern margin of the Yunnan-Guizhou Plateau and connected to the Maolan National Nature Reserve in Guizhou to the north (107°54 01 -108°05 51 E, 25°07 01 -25°12 22 N). The reserve covers an area of 8,969 hm^2 with elevations ranging from 400 to 1,000 m. The region has a mid-subtropical monsoon climate with an average annual temperature of 15–18.7°C (average 3.4–8.7°C in January and 23–26.7°C in July), $ $10°C accumulated temperature of 4,700–6,300°C, and annual precipitation of 1,530–1,820 mm. The average annual relative humidity is 80–90%. Rainfall is unevenly distributed both temporally and spatially, with significant regional water availability differences. The soil is primarily limestone soil with sporadic distribution of siliceous soil. The vegetation is mid-subtropical limestone evergreen-deciduous broad-leaved mixed forest, representing a zonal climax community type and one of the only relatively stable karst forest ecosystems remaining at this latitude worldwide. This area also has the largest distribution of primary forest in the karst region, with distinct vegetation stratification.

2. Sample Collection and Analysis

In July 2014, a 500 m × 500 m plot was established as a long-term monitoring site. A regular grid method was used for sample point layout, with 20 m × 20 m quadrats. A total station and base station were used for measurement and demarcation, with permanent markers set at each corner of the quadrats using cement posts. Within each 20 m × 20 m quadrat, a five-point sampling method was used within a 5 m radius of the center point, and the five samples were mixed into one composite sample. Simultaneously, slope position, slope aspect, slope gradient, rock exposure rate, ground convexity, and soil layer thickness were recorded for each quadrat. Slope aspect was measured as the direction the slope faces using a compass, measured in degrees counterclockwise. Rock exposure rate was estimated as the percentage of rock outcrop area within a 5 m radius of the sampling point. Ground convexity was calculated as the elevation of the quadrat minus the average elevation of its eight adjacent quadrats.

All mixed soil samples were brought back to the laboratory, air-dried, and passed through a 2 mm sieve for analysis. Total phosphorus (TP) was determined using NaOH fusion-molybdenum antimony colorimetry with UV spectrophotometry. Total potassium (TK) was determined using NaOH fusion-flame atomic absorption spectrophotometry. Available phosphorus (AP) was determined using 0.5 mol/L $NaHCO_3$ extraction-molybdenum antimony colorimetry with UV spectrophotometry. Available potassium (AK) was determined using 1 mol/L NH_4OAc extraction-flame atomic absorption spectrophotometry.

3. Data Processing

Classical statistical and geostatistical methods were used for data analysis with SPSS 18.0 (for statistical analysis and tests), GS+ (for geostatistical analysis), Minitab 16 (for Box-Cox transformation), and ArcGIS 9.2 (for Kriging interpolation maps).

3.1 Semivariogram Analysis

The semivariogram is a fundamental tool in geostatistics used to describe the degree of spatial difference in attribute variables and is the most widely used tool for spatial pattern description. The formula is:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2$$

where $\gamma(h)$ is the semivariance function value, h is the spatial distance between two sample points, $Z(x_i)$ is the measured value at position x_i, $Z(x_i + h)$ is the value at a point distance h from x_i, and $N(h)$ is the number of point pairs with separation distance h. The semivariogram is generally considered effective only within half of the maximum sampling interval. The ratio of nugget to sill ($C_0/(C_0 + C)$) indicates the degree of spatial variation and is an important parameter in semivariogram analysis. A nugget-to-sill ratio $< 25\%$ indicates strong spatial autocorrelation, 25-75% indicates moderate spatial autocorrelation, and $> 75\%$ indicates weak spatial autocorrelation. In this study, the effective lag distance for all semivariograms was set at 1/2 of the maximum lag distance, and the exponential model was used for fitting.

3.2 Kriging Interpolation

Kriging interpolation is a method for unbiased optimal estimation of variable values within a certain region based on semivariogram theory. Ordinary Kriging is the simplest and most widely used interpolation method. For any estimated point (x_0), the value is obtained through a linear combination of n effective sample points around it:

$$Z^*(x_0) = \sum_{i=1}^{n} \lambda_i Z(x_i)$$

where λ_i are weight coefficients. Under the condition of unbiasedness, the estimation variance is minimized:

$$\sigma^2 = \mathrm{Var}[Z(x_0) - Z^*(x_0)] = \min$$

4. Results and Analysis

4.1 Classical Statistical Description of Soil Phosphorus and Potassium Nutrients

Outliers were identified using the sample mean ± 3 standard deviations, with values outside this range replaced by the maximum and minimum values. All subsequent calculations used the processed original data. The contents of TP, TK, AP, and AK were (1.60 ± 0.76) g/kg, (5.42 ± 2.74) g/kg, (5.74 ± 3.63) mg/kg, and (5.20 ± 2.96) mg/kg, respectively. The coefficients of variation ranged from 47.66% to 63.22%, all indicating moderate variation, with AP showing the highest variability at 63.22%.

Non-parametric tests (Kolmogorov-Smirnov) were performed on the four soil nutrient datasets. The results showed that none followed a normal distribution. Box-Cox transformation was applied to non-normal samples, and the transformed data passed the one-sample K-S test at the 0.05 significance level, indicating normal distribution.

TABLE:1 Descriptive statistical analysis and normality test of soil phosphorus and potassium nutrient contents

The Moran' s I coefficient reflects the degree of spatial autocorrelation of soil nutrient indicators. All nutrient indices in the study area showed certain spatial structure, with similar spatial structures among them. The Moran' s I coefficients ranged from -0.043 to 0.497, decreasing with increasing lag distance and becoming negative around 220 m, indicating that the spatial dependence of soil phosphorus and potassium nutrients was relatively large. The order of spatial autocorrelation was AP > TP > AK > TK, with AP showing the strongest spatial autocorrelation (Moran' s I = 0.497).

4.2 Spatial Autocorrelation Analysis of Soil Phosphorus and Potassium Nutrients

FIGURE:2 Spatial correlation diagram of soil phosphorus and potassium nutrients in the study area

4.3 Semivariogram of Soil Phosphorus and Potassium Nutrients

In classical statistical analysis of soil spatial heterogeneity, soil properties are often treated as random and independent. However, in reality, soil properties show certain spatial dependence within a certain range. The best-fitting model for the semivariograms of TP, TK, AP, and AK in the study area was the exponential model, with high determination coefficients (R^2) ranging from 0.671 to 0.995, which can well reflect the spatial structural characteristics of soil phosphorus and potassium nutrients.

The nugget-to-sill ratios ($C_0/(C_0 + C)$) for TP and AP were 50.4% and 64.4%, respectively, indicating moderate spatial autocorrelation primarily influenced by structural factors. The ratios for TK and AK were 88.4% and 86.6%, respectively, indicating weak spatial autocorrelation. The ranges (autocorrelation distances) for TP and AP were 336.00 m and 373.50 m, respectively, showing relatively good spatial continuity. The ranges for TK and AK were 33.30–64.50 m, indicating strong spatial dependence.

TABLE:2 Semivariogram theoretical models and parameters for soil phosphorus and potassium nutrients in the study area

FIGURE:3 Semivariogram of soil phosphorus and potassium nutrients in the study area

4.4 Spatial Distribution Pattern of Soil Phosphorus and Potassium Nutrients

To more intuitively reflect the spatial distribution characteristics of soil parameters in the study area, spatial distribution maps of TP, TK, AP, and AK were generated using ArcGIS 9.2 based on the semivariogram models. The results showed that TP was high on lower slopes (including depressions) and low on upper slopes, with maximum values appearing in the northwest direction. TK showed weak regularity, with maximum values in the north direction. AP and AK showed higher content on mid-slopes than in depressions, with patchy distributions and high fragmentation.

FIGURE:4 Spatial distribution diagram of soil phosphorus and potassium nutrients—Kriging interpolation maps

4.5 Influencing Factors of Soil Phosphorus and Potassium Spatial Variation

Pearson correlation analysis was used to calculate the correlation matrix between the four soil phosphorus and potassium nutrient indices and environmental factors. The results showed that TP, TK, AP, and AK were all negatively correlated with elevation, with TK and AP showing extremely significant negative correlations ($p < 0.01$). All indices were negatively correlated with slope aspect and ground convexity, with TP, TK, and AP showing extremely significant negative correlations with ground convexity. Slope gradient showed extremely significant negative correlations with TP and TK, and a significant negative correlation with AP. Soil thickness was positively correlated with TP and AP, and extremely significantly negatively correlated with TK. Rock exposure rate showed extremely significant negative correlations with TP, TK, and AP. These results indicate that slope gradient and ground convexity were the main factors affecting the spatial distribution of soil phosphorus and potassium nutrients.

TABLE:3 Pearson correlation analysis of soil phosphorus and potassium nutrients with environmental factors

5. Discussion

The study area is located in the buffer zone of the Mulun Nature Reserve, with complex and variable topography and rich microhabitats, representing a typical peak-cluster depression unit. Classical descriptive statistical analysis revealed large differences in soil phosphorus and potassium nutrient indices, with coefficients of variation ranging from 47.66% to 63.22%, all showing moderate variation. The variation ranges are consistent with the results of Liu et al. [30], indicating that well-preserved karst forests show relatively high nutrient levels, which is also closely related to the ecological structure and function of the nature reserve and the advantages of the climax community.

The basic characteristics of soil factors in the evergreen-deciduous broad-leaved mixed forest in this study area differ from other subtropical forests. Compared with evergreen broad-leaved forest soil in Zhejiang [31], the mean TP and AP contents in this study area are higher. Compared with southwestern subtropical evergreen-deciduous broad-leaved mixed forest [32], the spatial heterogeneity patterns differ. Building on previous studies of spatial heterogeneity of major nutrients and water in karst soils [33-36], this analysis of soil phosphorus and potassium nutrients in karst evergreen-deciduous broad-leaved mixed forest revealed that all nutrient indices showed certain spatial structure, with Moran' s I coefficients decreasing with increasing lag distance. The best-fitting model for all semivariograms was the exponential model, with high fitting degrees, indicating good spatial structure of soil in the study area.

Spatial heterogeneity of soil properties results from the combined effects of structural and random factors. Structural factors include parent material and topography, while random factors include sampling design, measurement errors, and human disturbances. TP and AP showed moderate spatial autocorrelation, indicating their variation was caused by both structural and random factors. TK and AK showed weak spatial autocorrelation, suggesting that random factors had greater influence on their spatial distribution, possibly related to disturbance and experimental errors. The relatively long ranges of TP and AP indicate good spatial continuity. Compared with similar studies in Hubei [32] and Zhejiang [37], there are both similarities and differences. The difference lies in the finding that AP had the largest semivariogram range and relatively high variation coefficient, suggesting it is more susceptible to other factors than other nutrients. This may be related to the unique dual hydrological structure and complex microhabitats of karst ecosystems, where ecosystem structure and function significantly influence soil spatial distribution patterns.

Kriging interpolation maps can comprehensively and intuitively reflect the spatial distribution of soil phosphorus and potassium. The distribution of TP was high on lower slopes and low on upper slopes, mainly because TP originates from bedrock weathering and accumulates in surface soil through plant enrichment, with litter being the direct source of surface soil TP [38-39]. Pan et al. [40] showed that in peak-cluster depressions, TP shows obvious spatial differentiation along slopes, decreasing with increasing slope position. AP and TK showed patchy fragmentation, which may be related to soil leaching characteristics and requires further analysis of topographic factors.

Environmental factors play crucial roles in the spatial distribution and variation of karst forest soil phosphorus and potassium nutrients [41]. Elevation, slope gradient, and ground convexity were the main influencing factors. Negative correlations with slope gradient indicate that steeper slopes have lower soil phosphorus and potassium content, possibly due to strong leaching. The karst region of southwestern China, centered on Guizhou, is one of the world's three major karst areas. Its strong carbonate rock dissolution, obvious two-dimensional hydrological structure, and calcium-loving adapted plants result in highly heterogeneous habitats and vegetation, poor ecosystem stability and resistance to disturbance, and characteristics of easy degradation but difficult recovery [42]. Studies on spatial variation of soil properties can provide theoretical basis for soil quality restoration and improvement, and for rapid vegetation recovery and ecological reconstruction in fragile karst ecosystems.

6. Conclusion

The contents of soil phosphorus and potassium nutrients in the karst evergreen-deciduous broad-leaved mixed forest followed the order AP > TK > AK > TP, with all showing moderate variation. The best-fitting model for the semi-variograms of all nutrients was the exponential model with high determination coefficients. TP and AP showed moderate spatial autocorrelation, while TK and AK showed weak spatial autocorrelation. TP distribution was high on lower slopes and low on upper slopes, while AP and TK showed patchy fragmentation. Slope gradient and ground convexity were the main factors affecting the distribution of soil phosphorus and potassium nutrients.

References

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