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Spatial Heterogeneity of Soil Mineral Oxide Components in Depression Between Karst Hills, Southwest China

DU Hu[1, 2, 3], WANG Kelin[1, 2], PENG Wanxia[1, 2], ZENG Fuping[1, 2], SONG Tongqing[1, 2], ZHANG Hao[1, 2], LU Shiyang[1, 2]

(1. *Key Laboratory of Agro-ecological Processes in Subtropical Region*, *Institute of Subtropical Agriculture*, *Chinese Academy of Sciences*, *Changsha* 410125, *China*; 2. *Huanjiang Observation and Research Station for Karst Ecosystem*, *Chinese Academy of Sciences*, *Huanjiang* 547100, *China*; 3. *University of Chinese Academy of Sciences*, *Beijing* 100049, *China*)

Abstract: In karst regions, the spatial heterogeneity of soil mineral oxides and environmental variables is still not clear. We investigated the spatial heterogeneity of SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, P_2O_5, K_2O, and MnO contents in the soils of slope land, plantation forest, secondary forest, and primary forest, as well as their relationships with environmental variables in a karst region of Southwest China. Geostatistics, principal component analysis (PCA), and canonical correlation analysis (CCA) were applied to analyze the field data. The results show that SiO_2 was the predominant mineral in the soils (45.02%–67.33%), followed by Al_2O_3 and Fe_2O_3. Most soil mineral oxide components had a strong spatial dependence, except for CaO, MgO, and P_2O_5 in the plantation forest, MgO and P_2O_5 in the secondary forest, and CaO in the slope land. Dimensionality reduction in PCA was not appropriate due to the strong spatial heterogeneity in the ecosystems. Soil mineral oxide components, the main factors in all ecosystems, had greater influences on vegetation than those of conventional soil properties. There were close relationships between soil mineral oxide components and vegetation, topography, and conventional soil properties. Mineral oxide components affected species diversity, organic matter and nitrogen levels.

Keywords: karst; soil mineral oxide component; ecosystem; principal component analysis (PCA); canonical correlation analysis (CCA)

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1 Introduction

Soil minerals are the main constituents, and are regarded as the 'skeleton' of soil. Generally mineral components account for 95%–98% of a soil's solid weight, and have a significant effect on soil physical, chemical, and biological properties. They also directly participate in the processes of rock weathering, soil formation, and plant growth and development. Soil minerals are influenced by climate, vegetation, parent material, nutrients, microorganisms, and the degree of weathering and eluviation (Huang, 2000; Starr and Lindroos, 2006; Tian *et al.*, 2007; Houx III *et al.*, 2011). The knowledge of soil minerals is fundamental to the classification of soil types and the identification of soil-forming processes. An increase or decrease in soil mineral elements could impact directly soil fertility and plant growth (Zhang and Wang, 2009).

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Corresponding author: SONG Tongqing. E-mail: songtongq@isa.ac.cn

The spatial distribution pattern of soil properties, as a reflection of soil spatial heterogeneity, is a result of interactions between physical, chemical, and biological processes at a specific position (Huggett, 1998). Geostatistics is a spatial analysis method developed from traditional statistics, which not only reveals the spatial distribution, variation, and correlation characteristics of attribute variables, but also explain effectively the effects of spatial pattern on ecological process and function (Wang, 1999). Extensive research has been conducted on the spatial variability of soil properties, including soil chemical properties and soil physical properties, at local and regional scales (Herbst and Diekkruger, 2003; Kilic and Kilic, 2007; Liu *et al*., 2007; Yavitt *et al*., 2009; Li *et al*., 2011; Yang *et al*., 2011). However, there is still a limited understanding of the spatial patterns of soil mineral oxides, particularly at the ecosystem scale.

Carbonate rocks are the main parent material in karst areas, with more than 90% of them being limestone or dolostone, which are mainly made up of $CaCO_3$ and $CaMg(CO_3)_2$, respectively. Soluble calcium bicarbonate and magnesium bicarbonate are readily lost in the process of rock dissolution ($CaCO_3 + H_2CO_3 \rightleftharpoons Ca(HCO_3)_2$, $CaMg(CO_3)_2 + 2H_2CO_3 \rightleftharpoons Ca(HCO_3)_2 + Mg(HCO_3)_2$). Only minimal amounts of secondary minerals are formed, which can subsequently become soil components. The pedogenesis of carbonate rocks is very slow and can only form a shallow soil horizon, which is separated by an abundance of outcropping rocks. Moreover, the degree of weathering and the development of the rocks are low (Zhu, 1983). A depression between karst hills is located in Southwest China, which is one of three largest karst areas in the world, with a clearly dualistic hydrological structure (Peng *et al*., 2008), superficial soil layer, fragile ecological environment, and an acute conflict between human activity and land conservation. The climax community is a zonal limestone mixed evergreen and deciduous broadleaf forest (Zheng, 1999). Due to human disturbance, the forest has degenerated to different degrees (Zeng *et al*., 2007) into coexisting communities at different successional stages or forms of deflected succession stages (Song *et al*., 2010). Therefore, it is difficult to reconstruct, or improve, the ecological environment in such a karst area (Academic Divisions of Chinese Academy of Sciences, 2003). At present, most attention has focused on soil organic matter, nitrogen, phosphorus, potassium, and the water environment in the region (Song *et al*., 2009; Liu *et al*., 2010; Chen *et al*., 2011; Nie *et al*., 2011; Zhang *et al*., 2011). Some researchers have suggested that lack of mineral elements could be the most important restricting factor for plant growth and development in such karst regions (Zhang and Wang, 2009). However, a specific study is still not been conducted in this region of Southwest China.

We conducted the present study in dynamic monitoring plots within slope land, plantation forest, secondary forest, and primary forest, which are four typical ecosystems in Huanjiang County of the northwestern Guangxi, Southwest China. We applied classical statistics and geostatistics to determine the overall characteristics and spatial variability of soil mineral oxide components and then used principal component analysis (PCA) to reveal the importance of soil mineral oxides in the four ecosystems. We further analyzed the relationships between soil mineral oxides and vegetation, conventional soil properties, and topography by canonical correlation analysis (CCA). Our results would be meaningful for the efficient use of soil mineral resources, rational application of mineral fertilizers, improvement of soil fertility, and rapid vegetation recovery in this karst region of Southwest China.

2 Materials and Methods

2.1 Study area

The study area is located in Huanjiang County (24°44′–25°33′N, 107°51′–108°43′E) of the northwestern Zhuang Autonomous Region of Guangxi, Southwest China (Fig. 1). It is a depression between karst hills with its highest elevation of 1028 m above sea level. A subtropical monsoon climate dominates in the study area, with a mean annual precipitation of 1389.1 mm, a mean annual sunshine time of 1451 h, and a mean annual temperature of 15.7℃. The wet season usually lasts from April to September, with about 70% of the total annual precipitation. The coldest month is January, with an average daily temperature of 10.1℃ and the hottest month is July with an average daily temperature of 28.0℃. The mean annual frost-free period lasts for 290 days. The average annual evaporation is 1571.1 mm and the average humidity is 70%.

2.2 Experimental design and measurement

We selected four typical ecosystem plots, with the following characteristics. (Ⅰ) Slope land disturbed strongly. Maize (*Zea mays*), soybean (*Glycine max*), and sweet potatoes (*Ipomoea batatas*) are extensively cultivated in this area. (Ⅱ) Plantation forest disturbed moderately. This site is a demonstration zone for the integrated control of karst rock desertification. In 1996, approximately 50% of the local villagers migrated outside of the region and returned the farmland to forest with planted trees or grassland. The mountains were closed to returning villagers to facilitate forestation in 2001. (Ⅲ) Secondary forest disturbed weakly, which can also be referred to as naturally restored forests. This area was abandoned in 1985. The plot belongs to Huanjiang Observation and Research Station for Karst Ecosystem of Chinese Academy of Sciences, which was established in 2003. (Ⅳ) Primary forest disturbed slightly. This plot was in Mulun National Nature Reserve, which was established in 1996 to protect the subtropical limestone mixed evergreen-deciduous broadleaf forest ecosystem. This reserve has the largest and best-preserved area of karst primary forest in the world. The soil in the four plots is brown rendzina, which has formed under the same climate, parent material, landform, flora, and other natural background conditions. The distances between plots were less than 80 km. All general plot information is presented in Table 1, and Fig.1 shows the geographical location of the plots.

In each of the four ecosystems, we established four 0.8-ha plots in the form of a rectangle (200 m × 40 m) in a regular slope-depression continuum. The sites were established following the Centre for Tropical Forest Science (CTFS) standard (Condit, 1995). Each site was divided into 80 cells (10 m × 10 m), which were each further divided into 4 subcells (5 m × 5 m).

All trees with diameter at breast height (DBH) ≥ 1 cm were tagged, identified, measured, and georeferenced following the CTFS standard during the period of August to October 2007. Plant community structural indexes were determined, which included density (ind./m^2), crown width (m), coverage (%), DBH (cm), and height (m). Community diversity indexes were also determined, which included species richness, Shannon index, Simpson index, and evenness (Ma *et al.*, 1995). Vegetation in the slope land was not investigated as the study was conducted at the end of the harvesting period.

Table 1 Details of four ecosystems in a depression between hills in a karst region in Huanjiang County of Guangxi, China

Type	Disturbance intension	Dominant species
Ⅰ	Strong	*Zea mays*, *Glycine max*, *Ipomoea batatas*
Ⅱ	Moderate	*Citrus reticulate*, *Castanea mollissima*, *Zenia insignis*, *Toona sinensis*
Ⅲ	Weak	*Alangium chinense*, *Vitex negundo*, *Alchornea trewioides*
Ⅳ	Slight	*Pinus calcarea*, *Cinnamomum saxitilis*, *Sterculia lanceolata*, *Cyclobalanopsis glauca*

Notes: Ⅰ, Ⅱ, Ⅲ, Ⅳ refer to slope land, plantation forest, secondary forest, and primary forest, respectively. Same below.

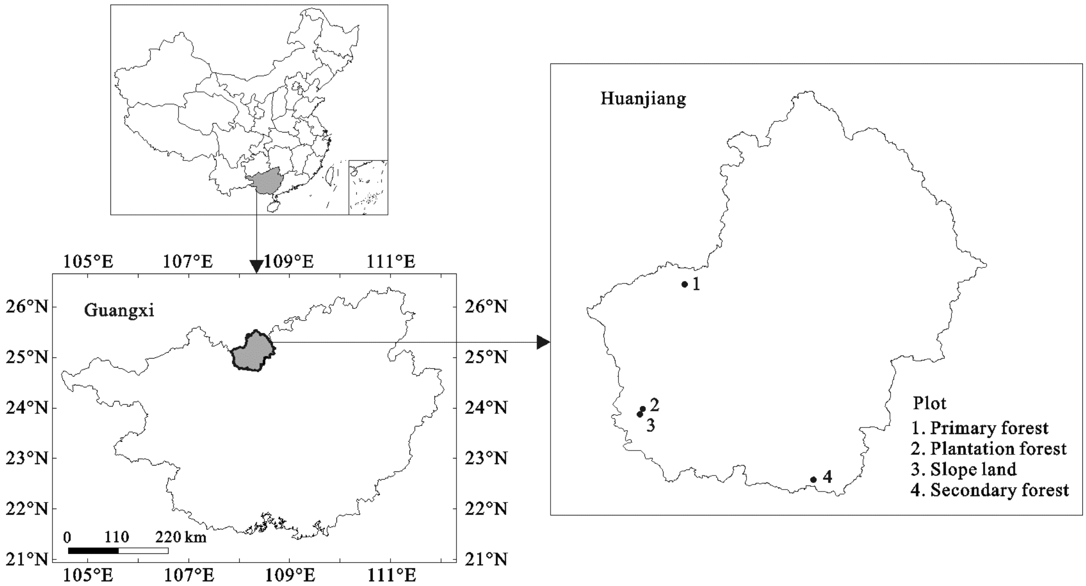

Fig. 1 Location of study area and plots

In each subcell, 8–10 soil sub-samples were collected to a depth of 15 cm, along an S-shaped transect, using a soil corer of 5 cm diameter. The sub-samples were pooled into one composite sample per cell of 10 m × 10 m. These samples were air dried, thoroughly mixed, and passed through a 2-mm sieve to remove gravel and roots. Soil characteristics including pH, soil organic matter (SOM), total nitrogen (total N), available nitrogen (available N), available phosphorus (available P), available potassium (available K) contents were analyzed in the laboratory according to Bao (2000), and SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, P_2O_5, K_2O, and MnO contents were analyzed according to Liu (1997). Root content and gravel content were obtained in the process of sieving as a percentage of the total weight. To improve the precision of the results, three replicates were analyzed and averaged for each of the soil analyses, with the exception of root and gravel contents.

Topography factors, including elevation, slope position, slope angle, and the percentage of covered rocks, were determined. Elevation was obtained from a Garmin GPSmap 60CSX (Beijing UniStrong Science & Technology Co., Ltd, China). The slope angle of each 10 m × 10 m cell was determined by using an electronic tacheometer. The percentage of covered rock was calculated from the ratio of rocks to the area of the grid by using a 100 cm × 100 cm grid with 25 sub-grids of 20 cm × 20 cm, and taking the average of five points along the diagonal for each cell. Slope position was converted into quantitative data (slope position: 1, 2, 3, and 4 for depression, lower, middle, and upper position of a slope, respectively) (Zhang and Zhang, 2003; Qiu and Zhang, 2000).

2.3 Statistical analysis

The 30 factors were classified into four groups: vegetation factors (species, Shannon index, Simpson index, evenness, density, crown width, coverage, DBH, height), conventional soil factors (moisture, gravel content, root content, pH, SOM, total N, available N, P, and K), soil mineral factors (SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, P_2O_5, K_2O, MnO contents), and topography factors (elevation, slope position, slope angle, percentage of covered rock). For mineral variables, we first applied a descriptive statistical analysis using SPSS 13.0 for windows (SPSS Inc., Chicago. IL, USA). The mean, standard error (SE), coefficient of variation (CV), and minimum and maximum values were determined for mineral contents. The distribution of the data was tested for normality by the Kolmogorov-Smirnov test before geostatistical analysis. Data were Box-Cox or log transformed if the normality was failed.

The spatial variability of soil mineral content was analyzed by using geostatistical techniques (Robertson *et al.*, 1993). The semivariogram model fitness and mapping were used in this study. The semivariogram was calculated by averaging one-half of the difference squared of the soil mineral contents, over all pairs of observations with the specified separation distance and direction (Isaaks and Srivastava, 1989). The equation is as follows:

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

where $\gamma(h)$ is the semivariance at a given distance h; $N(h)$ is the number of sample pairs at each distance interval h, $Z(x_i)$ is the value of the variable Z at the location x_i; and $Z(x_i+h)$ is a measured value at location (x_i+h). The spatial structure of the variable is determined by the best mathematical model to the experimental semivariogram, which generally fits with the theoretical model. A semivariogram model can be represented by the following parameters: range (a) is the separation distance at which the spatial dependence is apparent; nugget (C_0) is the variation found at a scale finer than that used in field sampling, and reflects the level of structural variation within the data; sill ($C_0 + C$) reflects the amount of spatial variability, which is the total variation at which the semivariogram levels for the patterned data. The nugget-to-sill ratio ($C_0 / (C_0 + C)$) is a particularly important parameter, which represents the relative structural variance. In this case, when $C_0 / (C_0 + C)$ is less than 25%, the spatial dependence is strong; when the ratio is greater than 75%, the spatial dependence is weak; and when the ratio is between 25% and 75%, the spatial dependence is moderate (Cambardella *et al.*, 1994). A gaussian, spherical, or exponential model was fitted to the mineral contents using GS^+ Version 7.0 (Gamma design software, Plainwell, MI, USA). With the information regarding the structure of the spatial variation as well as the input parameters provided by the theoretical model, we were able to develop spatial distribution maps by the Kriging interpolation method using ArcGIS 9.0 (Lane and Bassiri, 2005).

PCA was conducted on 30 factors to extract three principal components (PCs). This identified the main factors that dominate in four ecosystems. CCA was also used to analyse the relationship between mineral factors and the three other groups (Legendre and Legendre, 1998).

3 Results and Analyses

3.1 Classical statistics of soil mineral oxide components

There are large differences in the contents of the eight mineral oxide components. SiO_2 is the dominant mineral

Table 2 Statistical description for soil mineral oxide components in four plots

Index	Type	Number of samples	Min. Content (%)	Max. Content (%)	Mean Content (%)	SD	CV (%)	Kolmogorov-Smirnov
SiO_2	Ⅰ	80	55.41	82.84	67.33^a	7.23	10.80	0.39
	Ⅱ	80	42.92	59.48	48.62^b	3.48	7.17	0.13
	Ⅲ	80	12.24	98.95	45.02^b	19.89	44.18	0.32
	Ⅳ	80	23.59	86.53	63.77^a	11.76	18.43	0.44
Al_2O_3	Ⅰ	80	10.42	22.26	16.95^b	3.34	19.70	0.11
	Ⅱ	80	10.30	26.17	18.23^a	2.59	14.19	0.33
	Ⅲ	80	2.41	16.27	9.81^c	3.98	40.61	0.33
	Ⅳ	80	4.77	16.86	8.98^c	2.88	32.08	0.05
Fe_2O_3	Ⅰ	80	2.53	7.63	5.55^b	1.50	27.02	$0.05^{\#}$
	Ⅱ	80	5.74	8.88	7.32^a	0.59	8.04	0.31
	Ⅲ	80	0.96	8.70	5.26^b	1.99	37.77	0.71
	Ⅳ	80	2.14	6.96	3.99^c	1.27	31.93	$0.19^{\#}$
CaO	Ⅰ	80	0.11	0.37	0.19^c	0.06	31.58	$0.09^{\#}$
	Ⅱ	80	0.18	0.84	0.45^c	0.13	29.90	0.50
	Ⅲ	80	0.37	39.04	18.80^a	10.26	54.57	0.44
	Ⅳ	80	0.53	6.34	2.20^b	1.70	77.41	$0.41^{\#}$
MgO	Ⅰ	80	0.45	1.27	0.69^c	0.20	28.99	0.13
	Ⅱ	80	0.79	1.08	0.87^c	0.06	7.36	$0.17^{\#}$
	Ⅲ	80	0.00	13.18	6.74^a	2.66	39.48	0.87
	Ⅳ	80	0.45	4.66	2.02^b	0.95	47.16	0.34
P_2O_5	Ⅰ	80	0.08	0.19	0.11^c	0.02	23.28	$0.13^{\#}$
	Ⅱ	80	0.07	0.13	0.10^c	0.01	13.67	0.51
	Ⅲ	80	0.09	0.18	0.13^a	0.02	14.93	0.95
	Ⅳ	80	0.04	0.22	0.12^b	0.05	41.87	0.90
K_2O	Ⅰ	80	0.64	2.37	1.04^b	0.46	44.45	$0.19^{\#}$
	Ⅱ	80	0.90	1.60	1.33^a	0.15	11.43	0.09
	Ⅲ	80	0.07	0.93	0.50^c	0.21	41.78	0.81
	Ⅳ	80	0.14	1.40	0.52^c	0.28	53.73	0.22
MnO	Ⅰ	80	0.05	0.17	0.10^c	0.03	30.00	$0.08^{\#}$
	Ⅱ	80	0.25	0.61	0.37^a	0.08	21.62	0.24
	Ⅲ	80	0.01	0.29	0.13^b	0.06	46.15	0.99
	Ⅳ	80	0.02	0.19	0.10^c	0.04	40.00	0.95

Notes: Different letters for the same variable indicate a significant difference between the different forest ecosystems ($p < 0.05$); # represents the data that were transformed.

with a content of 45.02%–67.33%, followed by Al_2O_3 (8.98%–18.23%) and Fe_2O_3 (3.99%–7.32%) (Table 2). P_2O_5 (0.10%–0.13%) and MnO (0.10%–0.37%) are low in all the ecosystems, while CaO (0.19%–18.8%), MgO (0.69%–6.74%), and K_2O (0.50%–1.33%) are intermediate. The contents of SiO_2 of the slope land and primary forest soils are significantly more than those of soils of the plantation forest and secondary forest. The contents of Al_2O_3 and K_2O in plantation forest and slope land soils are greater than those of soils in secondary and primary forests, while the reverse is true for CaO, MgO, and P_2O_5. The content of Fe_2O_3 in the four ecosystems varies in the following order: plantation forest > slope land, secondary forest > primary forest. The content of MnO varies in the following order: plantation forest > secondary forest > slope land and primary forest.

Most soil mineral oxide components have moderate variability (10% < CV < 100%), except for SiO_2, Fe_2O_3, and MgO in the plantation forest soils. Plantation forest has the lowest coefficient of variation values in the eight mineral oxide components. Overall, the CV values for SiO_2, Al_2O_3, Fe_2O_3, and MnO contents vary in the following order: secondary forest > primary forest > slope land > plantation forest. The sequence for the CV values of CaO and MgO contents is primary forest > secondary forest > slope land > plantation forest, and that of P_2O_5 and K_2O contents is primary forest > slope land > secondary forest > plantation forest. Most of the mineral oxide components in the plantation forest and slope land soils are in relatively uniformly condition.

3.2 Spatial variability of soil mineral oxide components

The Kolmogorov-Smirnov test results indicate that most of the mineral oxide components are a normal distribution, except for Fe_2O_3, CaO, P_2O_5, K_2O, MnO in the slope land, Fe_2O_3 and CaO in the primary forest soil and MgO in the plantation forest soil. The data change as a normal distribution after Box-Cox or log transformation (Table 2).

Semivariograms of the soil mineral oxides fit well as the gaussian, spherical, and exponential models. The coefficients of determination (R^2) for most variables are greater than 0.640, except for that of Al_2O_3 in the plantation forest soil (Table 3 and Fig. 2). It is suggested that these models reflect well the spatial structural characteristics of soil mineral oxide components. All semivariogram models show there is a positive nugget effect. The fitted semivariograms indicate the existence of moderate to strong spatial dependency for all soil mineral oxides. Most mineral oxide components have a strong spatial dependence (C_0 / (C_0 + C) < 25%) (C_0 is nugget, (C_0 + C) is sill). CaO, MgO, and P_2O_5 in plantation forest soil, MgO and P_2O_5 in the secondary forest soil, and CaO in the slope land soil have moderate spatial dependence (25% < C_0 / (C_0 + C) < 75%). The semivariogram range of all variables is 20.10 m to 225.34 m (Table 3).

3.3 Spatial distribution maps of soil mineral oxide components

The Kriging interpolation reflect the spatial patterns of SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, P_2O_5, K_2O, and MnO contents in soil (Fig. 3). The mineral oxide components exhibit differences of spatial patterns in each ecosystem. In slope land, the kriging contour maps of CaO, MgO, K_2O, and P_2O_5 are similar, and the highest value appears in the downhill; Al_2O_3 and Fe_2O_3 exhibit similar spatial patterns, increasing with landform slopes; SiO_2 and MnO have a distribution pattern of high in mid-low slope. In plantation forest, CaO and MgO exhibit similar spatial patterns; Al_2O_3, Fe_2O_3 and K_2O present fragmented patch distribution, showing high heterogeneity, while SiO_2, MnO and P_2O_5 change gently, high in mid-low slope and low in mid-up slope. In secondary forest, a similar pattern of higher Al_2O_3, Fe_2O_3, K_2O and MnO is observed in mid-low slope; SiO_2 and P_2O_5 contents are low in the middle; the kriging contour map of CaO is similar with that of MgO. In primary forest, SiO_2, P_2O_5 and K_2O contents exhibit similar spatial patterns, low in middle and high in two sides, but opposite to those of CaO, MgO and MnO. In addition, the high values of Al_2O_3 and Fe_2O_3 contents appear on upper slope.

Spatial patterns for soil variables also differ in both magnitude and space. Al_2O_3 and Fe_2O_3 contents exhibit similar spatial patterns in the slope land and secondary forest soils, and CaO and MgO contents exhibit similar spatial patterns in plantation forest, secondary forest, and primary forest soils. Moreover, Al_2O_3, Fe_2O_3, K_2O, and MnO contents show similar patterns, while MgO, P_2O_5, and K_2O contents do not. The kriging maps of SiO_2 and MnO in the plantation forest soil are similar, and those of Fe_2O_3 and Al_2O_3 contents indicate a spatial distribution of fragmented patches. The contents for

Table 3 Semivariogram theoretical models and parameters for soil mineral oxides in study area

Index	Type	Model	C_0	$C_0 + C$	$C_0 / (C_0 + C)$	a (m)	R^2	D
SiO_2	Ⅰ	Guassian	1.60000	80.63000	0.020	77.77	0.998	1.420
	Ⅱ	Guassian	4.45000	26.67000	0.167	204.90	0.988	1.703
	Ⅲ	Spherical	104.00000	442.00000	0.235	61.60	0.906	1.815
	Ⅳ	Guassian	48.90000	230.50000	0.212	111.03	0.999	1.654
Al_2O_3	Ⅰ	Guassian	0.58000	20.87000	0.028	133.89	0.995	1.269
	Ⅱ	Exponential	0.87000	7.03800	0.124	20.10	0.105	1.966
	Ⅲ	Spherical	5.30000	26.83000	0.198	151.40	0.991	1.733
	Ⅳ	Exponential	0.07000	14.51000	0.005	213.60	0.997	1.622
Fe_2O_3	Ⅰ	Guassian	0.00190	0.22880	0.008	171.65	0.992	1.168
	Ⅱ	Spherical	0.00100	0.32000	0.003	23.00	0.659	1.963
	Ⅲ	Spherical	0.53000	5.52700	0.096	75.80	0.953	1.715
	Ⅳ	Guassian	0.00500	0.03100	0.159	150.17	0.990	1.619
CaO	Ⅰ	Spherical	7.11000	21.63000	0.329	90.30	0.983	1.802
	Ⅱ	Spherical	0.01000	0.02100	0.498	83.00	0.835	1.875
	Ⅲ	Spherical	7.40000	136.10000	0.054	61.10	0.897	1.740
	Ⅳ	Guassian	0.02300	0.21600	0.107	155.71	0.997	1.575
MgO	Ⅰ	Guassian	0.00010	0.05500	0.002	65.64	0.939	1.347
	Ⅱ	Spherical	0.00360	0.01450	0.348	37.70	0.796	1.905
	Ⅲ	Spherical	2.25000	8.77700	0.256	54.90	0.743	1.853
	Ⅳ	Guassian	0.32000	1.57900	0.203	130.42	0.996	1.662
P_2O_5	Ⅰ	Spherical	0.00135	0.01190	0.113	147.30	0.952	1.640
	Ⅱ	Guassian	0.00009	0.00034	0.254	146.01	0.987	1.734
	Ⅲ	Spherical	0.00016	0.00052	0.310	77.50	0.981	1.808
	Ⅳ	Guassian	0.00072	0.00409	0.176	90.07	0.988	1.608
K_2O	Ⅰ	Guassian	0.00010	0.10620	0.001	51.27	0.706	1.535
	Ⅱ	Exponential	0.00002	0.02064	0.001	24.60	0.640	1.949
	Ⅲ	Spherical	0.00360	0.06070	0.059	72.70	0.977	1.693
	Ⅳ	Spherical	0.02420	0.11240	0.215	75.30	0.792	1.787
MnO	Ⅰ	Spherical	0.00100	0.02400	0.042	134.50	0.993	1.584
	Ⅱ	Guassian	0.00300	0.01400	0.214	225.34	0.932	1.789
	Ⅲ	Guassian	0.00090	0.00630	0.142	73.09	0.985	1.614
	Ⅳ	Spherical	0.00010	0.00270	0.054	110.60	0.992	1.620

Notes: C_0, $C_0 + C$, a, and D represent nugget, sill, range, and fractal dimension, respectively

SiO_2, P_2O_5, and K_2O show similar spatial patterns (Fig. 3).

3.4 Factor set formulation for soil indicators

The first three PCs of the 30 variables in the four ecosystems are obtained when eigenvalues are greater than 1 and could account for 61.61%, 51.44%, 68.02%, and 63.94% of the total variation in the slope land, plantation forest, secondary forest, and primary forest, respectively (Table 4).

In the slope land, the highly weighted factor loading variables for PC1 include total N, K_2O, MgO, available N, CaO, available K, and P_2O_5. For PC2, Al_2O_3, SiO_2, and Fe_2O_3 are highly weighted variables, while moisture and root content are highly weighted variables in PC3. In the plantation forest, the highly weighted factor loading variables for PC1 are percentage of covered rock, elevation, slop angle, and slope position. For PC2, CaO is the highly weighted variable, while DBH and height are highly weighted variables for PC3. In the secondary forest, the highly weighted factor loading variables for PC1 include the evenness, Simpson index, Shannon index, DBH, slope angle, percentage of covered rock,

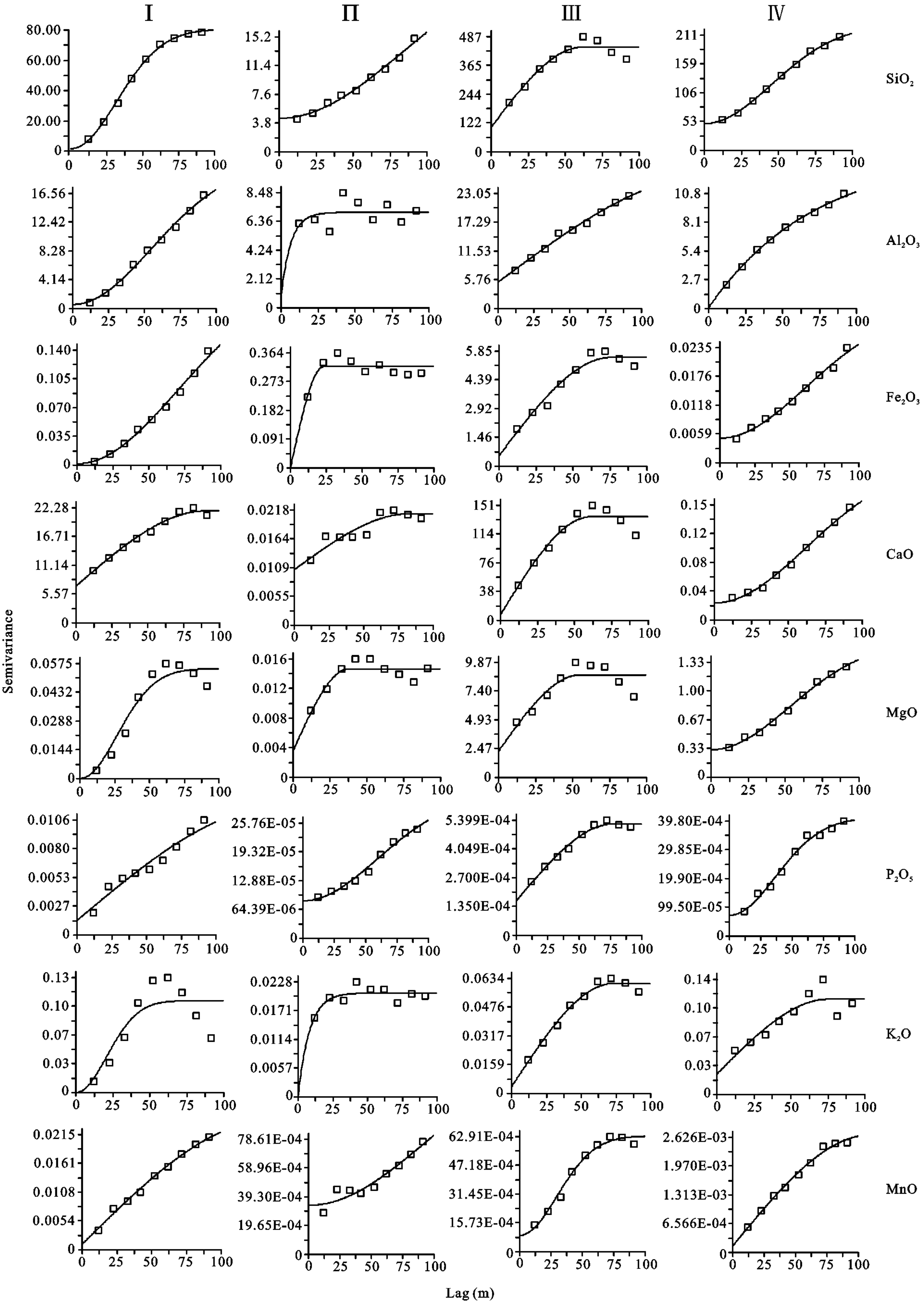

Fig. 2 Semivariogram of soil mineral oxides in study area

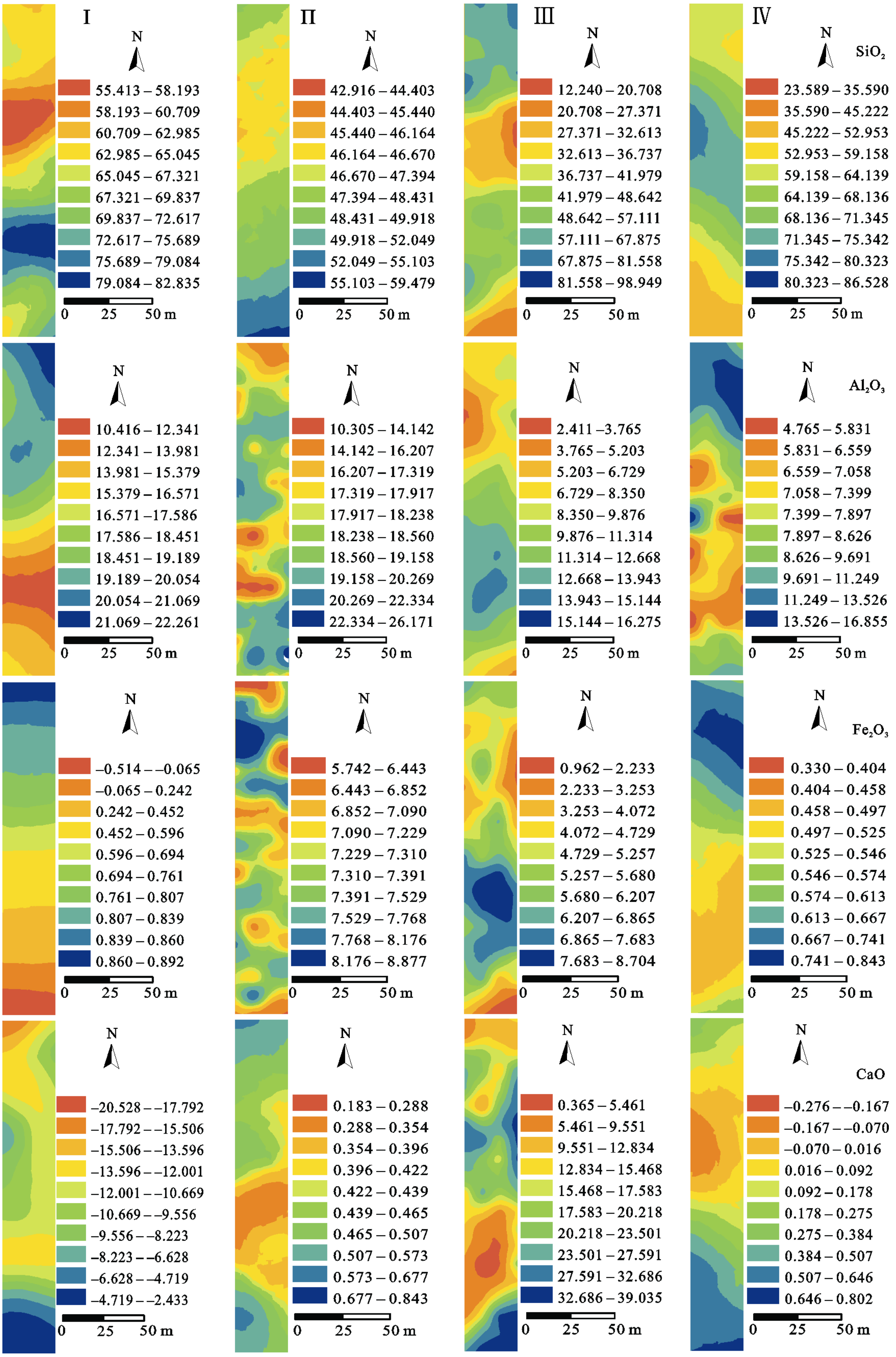

Fig. 3 Kriging maps of spatial distribution of soil minerals in study area

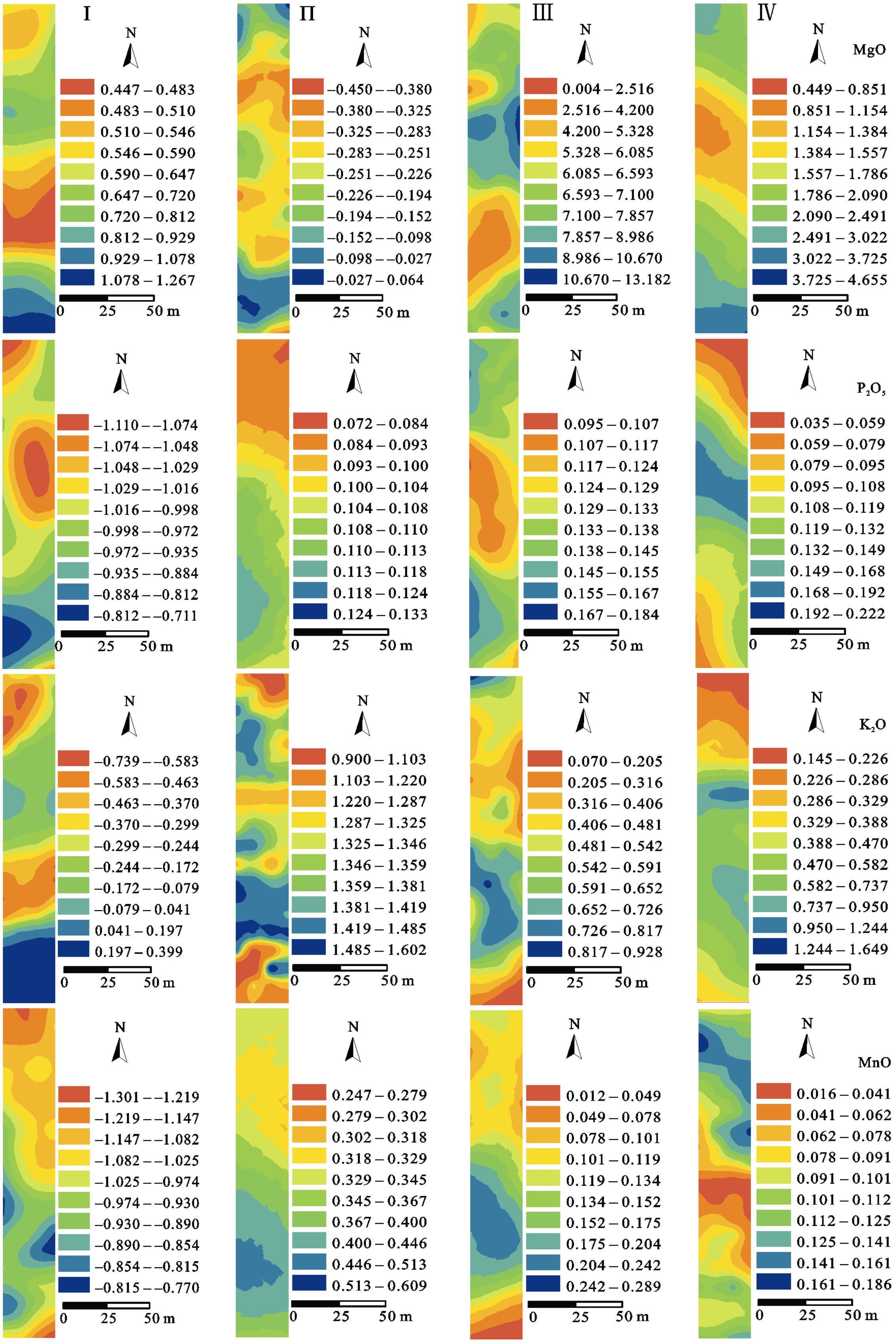

Fig. 3 Kriging maps of spatial distribution of soil minerals in study area (continued)

Table 4 Principal component analysis of four ecosystems in study area

Item	Ⅰ			Ⅱ			Ⅲ			Ⅳ		
	PC1	PC2	PC3	PC1	PC2	PC3	PC1	PC2	PC3	PC1	PC2	PC3
Species				0.3651	–0.0924	0.1058	0.7840	0.2487	–0.0170	0.8789	0.0268	–0.2731
Shannon index				0.3186	–0.2288	0.1531	0.9283	0.0071	0.0354	0.8434	0.1076	–0.2317
Simpson index				0.0967	0.0056	–0.0116	0.9429	0.0156	0.0170	0.6615	0.1055	–0.1955
Evenness				0.1244	–0.3327	0.1840	0.9537	0.0255	–0.0167	0.0213	0.0620	–0.0469
Density				0.1653	–0.0547	0.0124	0.1720	0.5696	–0.1649	0.7105	0.0637	–0.2032
Crown width				–0.0415	–0.0315	–0.0017	0.7800	0.0684	–0.1049	–0.0106	–0.1232	0.8527
Coverage				0.1332	0.0037	0.0861	0.4291	0.2553	–0.1213	0.6955	–0.0055	0.5050
DBH				–0.0368	–0.0435	0.9750	0.9145	–0.0451	0.0467	–0.1251	–0.0312	0.5170
Height				–0.0058	–0.0206	0.9747	0.8603	0.1550	–0.0827	–0.1488	0.0699	0.7456
Moisture	–0.4071	–0.3443	0.7472	0.3522	0.0802	0.1568	–0.2380	–0.1912	0.5171	–0.0952	–0.0670	–0.1254
Gravel content	0.0422	0.0271	0.1321	–0.1175	0.0918	–0.0354	0.3340	–0.2556	–0.1555	–0.2234	–0.1482	0.1189
Root content	–0.0408	–0.1763	–0.8791	–0.0757	–0.5352	–0.0891	–0.3376	–0.1612	0.2907	–0.0635	0.1744	–0.0342
pH	0.4386	0.0103	–0.0231	–0.0164	0.1139	0.0158	–0.1679	–0.0742	–0.1727	–0.4222	–0.3983	–0.2583
OM	–0.2684	–0.1817	0.0338	0.6107	0.1522	0.0697	0.0608	0.0844	0.9240	0.1988	0.2873	0.2583
Total N	0.9444	–0.2587	–0.0453	0.5584	0.1854	0.0817	0.0310	–0.1386	0.9148	–0.1596	–0.6439	0.0896
Available N	0.9261	–0.2662	–0.0495	0.4250	0.0336	0.0515	–0.2182	–0.0650	0.9129	0.1179	0.4724	0.1680
Available P	0.0738	0.6507	0.1128	0.0761	0.7794	0.0080	0.1376	0.0119	0.3314	–0.0387	0.0706	0.1745
Available K	0.8909	–0.3183	0.0295	0.3165	0.0736	0.1193	0.7768	0.3748	0.1861	–0.0870	0.4407	0.1714
SiO_2	–0.2089	0.8993	–0.0051	–0.1489	0.0593	0.0552	0.3262	0.2385	0.1807	0.1327	0.7718	–0.0861
Al_2O_3	0.0098	–0.9145	0.0721	–0.1123	0.0350	–0.1470	–0.2036	0.7276	–0.1026	0.4632	–0.1029	–0.1338
Fe_2O_3	0.1681	–0.8476	0.0383	–0.0179	–0.0996	–0.0618	0.0360	0.9261	0.0483	0.4350	0.0752	0.0725
CaO	0.9143	–0.0978	–0.0695	0.1680	0.8543	–0.0691	–0.2033	–0.8239	–0.1435	–0.3824	–0.8271	0.0942
MgO	0.9271	–0.1312	–0.0480	0.1150	0.2151	–0.0859	0.0447	–0.5582	–0.1611	–0.1416	–0.8326	0.0132
P_2O_5	0.8459	0.1975	–0.0261	–0.6548	0.2068	0.1010	0.0262	0.0384	0.8722	–0.2235	0.3215	0.1204
K_2O	0.9424	0.0391	–0.1533	–0.0830	–0.5052	0.0676	0.1580	0.8755	–0.0742	–0.3153	0.2967	–0.0363
MnO	–0.0134	0.0946	0.0704	–0.2155	–0.0260	–0.0305	0.1121	0.9077	–0.1789	0.3236	–0.3361	0.3467
Elevation	–0.1959	–0.4143	–0.1068	0.8671	0.1242	–0.0316	0.7750	–0.1644	0.1522	0.8571	0.1473	–0.0021
Slope position	0.1411	–0.4328	–0.0572	0.8311	0.0338	0.0259	0.8505	–0.0388	–0.1554	0.8829	0.2352	0.1208
Slope angle	0.4797	–0.7227	–0.1476	0.8357	0.0743	–0.0067	0.9084	0.0941	–0.1846	0.8124	0.3637	0.2234
Percentage of covered rock	0.5338	–0.6267	0.0591	0.9094	0.0658	–0.0376	0.8837	0.2160	–0.1556	0.6147	0.6275	0.0613
Eigenvalue	6.9269	4.5599	1.4512	9.6137	3.5823	2.2357	11.0343	4.8700	4.5020	8.9638	6.9616	3.2552
Accumulative contribution	0.3299	0.5470	0.6161	0.3205	0.4399	0.5144	0.3678	0.5301	0.6802	0.2988	0.5308	0.6394

height, and slope position. For PC2, Fe_2O_3, MnO, K_2O, and CaO are highly weighted variables, while, OM, total N, available N, and P_2O_5 are highly weighted variables for PC3. In primary forest, the highly weighted factor loading variables for PC1 includ slope position, species, elevation, Shannon index, and slope angle. For PC2, MgO, CaO, and SiO_2 are highly weighted variables, while crown width and height were highly weighted variables for PC3.

3.5 Relationships between soil mineral oxides and other factors

CCA is used to determine correlations between the two groups of variables. The cumulative contribution rates of the first four typical vectors are 62.47%–79.37%, 76.42%–94.92%, and 64.56%–86.56% between soil mineral oxides and vegetation, topography, and soil in the four studied ecosystems (Table 5), which reflects information regarding most variables. We further de-

Table 5 Chi-square tests of canonical correlation coefficients between soil mineral oxides and vegetation, topography, and soil of four ecosystems

Type	Factor	Typical vector	Canonical correlation coefficient	Eigenvalue	Chi-square value	Freedom degree	Significant level	Cumulative contribution (%)
Ⅰ	Topography	1	0.9870	5.3913	100.8659	32	0.0001	44.93
		2	0.9520	4.4740	54.9857	21	0.0001	82.21
		3	0.8970	1.0546	25.3580	12	0.0132	91.00
		4	0.5720	0.4707	4.9460	5	0.4225	94.92
	Soil	1	0.9990	5.7215	191.9326	72	0.0001	44.01
		2	0.9960	2.8216	132.4549	56	0.0001	65.75
		3	0.9950	1.5995	83.5424	42	0.0001	78.02
		4	0.9480	1.1098	38.1500	30	0.1459	86.56
Ⅱ	Vegetation	1	0.8000	4.6719	162.6523	72	0.0001	27.48
		2	0.6740	2.2867	91.0054	56	0.0021	40.93
		3	0.5900	2.0585	48.5999	42	0.2244	53.04
		4	0.3430	1.6020	18.6296	30	0.9474	62.47
	Topography	1	0.8580	4.4312	206.9833	32	0.0001	36.93
		2	0.7830	2.000	110.3302	21	0.0001	53.60
		3	0.5560	1.4639	41.3687	12	0.0001	65.80
		4	0.4270	1.2750	14.6025	5	0.0122	76.42
	Soil	1	0.8520	5.2297	219.4225	72	0.0001	30.76
		2	0.7520	2.5548	128.9351	56	0.0001	45.79
		3	0.5640	1.6875	70.5237	42	0.0038	55.72
		4	0.5360	1.5027	43.7281	30	0.0505	64.56
Ⅲ	Vegetation	1	0.7630	6.6270	167.6168	72	0.0001	38.98
		2	0.6700	3.9693	106.6006	56	0.0001	62.33
		3	0.5450	2.0525	64.9777	42	0.0130	74.40
		4	0.5040	0.8439	40.3191	30	0.0988	79.37
	Topography	1	0.7750	4.5875	154.9447	32	0.0001	38.23
		2	0.7080	4.0673	88.4544	21	0.0001	72.13
		3	0.5630	1.1184	37.9553	12	0.0002	81.44
		4	0.3640	0.5999	10.3184	5	0.0667	86.44
	Soil	1	0.8830	4.9109	241.9929	72	0.0001	28.89
		2	0.7960	3.8687	136.3683	56	0.0001	51.64
		3	0.5540	1.8130	66.0490	42	0.0103	62.31
		4	0.4600	1.4588	40.3997	30	0.0974	70.89
Ⅳ	Vegetation	1	0.8030	5.4514	170.1893	72	0.0001	32.07
		2	0.6570	3.4471	97.7182	56	0.0005	52.34
		3	0.5960	2.5931	58.1591	42	0.0497	67.60
		4	0.4370	1.5784	27.4334	30	0.6004	76.88
	Topography	1	0.8640	5.0727	216.3496	32	0.0001	42.27
		2	0.8502	3.8016	116.9584	21	0.0001	73.95
		3	0.4897	0.8356	23.9236	12	0.0208	80.92
		4	0.2329	0.6274	4.0423	5	0.5433	86.14
	Soil	1	0.9351	6.5524	328.6285	72	0.0001	38.54
		2	0.8342	3.6267	183.435	56	0.0001	59.88
		3	0.7493	1.8871	100.1198	42	0.0001	70.98
		4	0.4943	1.0252	42.4192	30	0.0659	77.01

Table 6 Composition of canonical variables between soil mineral oxides and vegetation, topography, and soil of four ecosystems

Type	Factor	Equations of standardized canonical coefficients
I	Topography	$M_1=-0.0997X_1-0.4238X_2-0.4025X_3-0.1378X_4+0.5800X_5-0.5702X_6-0.0122X_7+0.7445X_8$
		$M_2=0.5353X_1-0.8566X_2+0.9669X_3+0.3473X_4-0.8372X_5-0.4529X_6-0.0008X_7-0.1438X_8$
		$T_1=-0.3801Z_1-0.6239Z_2+0.0547Z_3-0.2441Z_4$
		$T_2=1.1740Z_1-0.4861Z_2-0.7783Z_3-0.1789Z_4$
	Soil	$M_1=1.0387X_1+0.5127X_2+0.5761X_3+0.2860X_4-1.1405X_5+1.0971X_6+0.0918X_7+0.05820X_8$
		$M_2=-0.7949X_1-0.6639X_2-0.5284X_3+0.0786X_4-0.4197X_5-0.4282X_6+0.3274X_7+0.5459X_8$
		$N_1=0.2074W_1-0.0428W_2+0.1222W_3-0.0646W_4+0.0062W_5-2.0749W_6+2.9661W_7+0.8031W_8-0.7918W_9$
		$N_2=0.0823W_1-0.1544W_2+0.0209W_3-0.2199W_4+0.1990W_5+6.0426W_6-4.3475W_7+0.2614W_8-1.9865W_9$
II	Vegetation	$M_1=-0.8869X_1-0.0165X_2-0.0942X_3-0.1517X_4-0.0900X_5-0.2427X_6-0.0938X_7-0.15500X_8$
		$M_2=-0.2807X_1+0.0751X_2+0.0516X_3-0.1135X_4-0.0084X_5+0.2435X_6+0.4351X_7+0.5638X_8$
		$V_1=0.0616Y_1+0.7753Y_2+0.1160Y_3-0.0496Y_4+0.1624Y_5+0.0063Y_6-0.0343Y_7+0.4052Y_8-0.5747Y_9$
		$V_2=-1.3661Y_1+0.2281Y_2+0.6034Y_3-0.1495Y_4+0.6085Y_5+0.1432Y_6+0.0384Y_7+1.4916Y_8-1.4552Y_9$
	Topography	$M_1=-0.7925X_1-0.1360X_2-0.0651X_3-0.0997X_4-0.2019X_5-0.1654X_6+0.0505X_7-0.2494X_8$
		$M_2=0.1137X_1+0.2834X_2+0.0922X_3+0.5411X_4-0.1523X_5-0.7338X_6-0.3968X_7+0.0768X_8$
		$T_1=-0.1633Z_1+0.1258Z_2+0.9828Z_3+0.0114Z_4$
		$T_2=0.8560Z_1+0.9711Z_2-0.6391Z_3-0.7792Z_4$
	Soil	$M_1=-0.8277X_1-0.1974X_2-0.0769X_3+0.1005X_4-0.0386X_5-0.2856X_6-0.0113X_7-0.1678X_8$
		$M_2=-0.2110X_1-0.0050X_2-0.1306X_3-0.8093X_4+0.1457X_5+0.2493X_6+0.3612X_7-0.0292X_8$
		$N_1=0.2588W_1+0.0352W_2-0.1254W_3-0.0073W_4+1.0811W_5-0.4936W_6+0.0173W_7-0.3151W_8+0.1796W_9$
		$N_2=0.1489W_1+0.0826W_2+0.0715W_3-0.0213W_4-1.0905W_5+0.3501W_6-0.0139W_7-0.8765W_8+0.4499W_9$
III	Vegetation	$M_1=0.17251X_1+0.0103X_2+0.3725X_3+0.4967X_4-0.2452X_5+0.1746X_6+0.0330X_7-1.0597X_8$
		$M_2=0.6258X_1-0.2791X_2-1.1103X_3-1.0154X_4+0.5757X_5-0.2131X_6+0.3767X_7+0.1618X_8$
		$V_1=-1.4266Y_1+3.0040Y_2-2.4064Y_3+0.2971Y_4+0.0481Y_5+0.6525Y_6-0.5723Y_7+0.0794Y_8+0.0830Y_9$
		$V_2=-0.8791Y_1+3.6626Y_2-1.2857Y_3-1.5805Y_4-1.3528Y_5-0.0842Y_6+0.6777Y_7-0.1077Y_8-0.7926Y_9$
	Topography	$M_1=-0.6720X_1+0.3894X_2+0.2776X_3+0.4719X_4-0.3587X_5+0.0535X_6-0.1238X_7+0.4421X_8$
		$M_2=0.2646X_1-0.0397X_2-0.4345X_3-0.6567X_4+0.0352X_{5-}+0.0495X_5+0.2419X_7+0.4764X_8$
		$T_1=-0.4283Z_1+0.8666Z_2-0.961Z_3-0.4762Z_4$
		$T_2=-0.3388Z_1+2.4888Z_2-1.8121Z_3+0.0760Z_4$
	Soil	$M_1=0.1934X_1-0.0977X_2-0.7188-0.2116X_4+0.2954X_5-0.6891X_6+0.1436X_7+0.8579X_8$
		$M_2=-0.1646X_1+0.4147X_2+0.4181X_3+0.8482X_4-0.2264X_5-0.2497X_6-0.4011X_7-0.3017X_8$
		$N_1=-0.4657W_1-0.0647W_2-0.2070W_3-0.0413W_4-0.0168W_5-0.6894W_6+0.1791W_7-0.3571W_8+0.2118W_9$
		$N_2=-0.2858W_1+0.2832W_2+0.0958W_3+0.1313W_4-0.0838W_5+0.3847W_6-0.2796W_7+0.066W_8-0.9820W_9$
Ⅳ	Vegetation	$M_1=-0.1986X_1+0.4686X_2-0.3806X_3-0.9837X_4+0.1489X_5-0.3073X_6-0.169X_7+0.3404X_8$
		$M_2=-0.0515X_1-0.151X_2-0.2084X_3-0.2906X_4-0.1091X_5+0.8552X_6-0.2789X_7+0.747X_8$
		$V_1=1.2269Y_1-0.4467Y_2-0.0959Y_3+0.1626Y_4-0.3642Y_5-0.2334Y_6+0.3969Y_7-0.4046Y_8+0.3383Y_9$
		$V_2=-2.2581Y_1+2.6836Y_2-0.2719Y_3-0.2335Y_4+0.2067Y_5+0.5095Y_6-0.0703Y_7+0.0456Y_8+0.2969Y_9$
	Topography	$M_1=0.5522X_1-0.254X_2+0.5343X_3+0.0318X_4-0.5116X_5-0.0041X_6-0.0065X_7+0.0597X_8$
		$M_2=-0.0202X_1+0.5403X_2-0.2244X_3-0.4888X_4+0.2453X_5-0.1675X_6-0.2729X_7+0.3821X_8$
		$T_1=-0.5599Z_1+0.0091Z_2+0.6971Z_3+0.7054Z_4$
		$T_2=1.3977Z_1-0.4201Z_2+0.1515Z_3-0.4363Z_4$
	Soil	$M_1=-0.3227X_1+0.0271X_2-0.3618X_3+0.3948X_4-0.2116X_5-0.6322X_6-0.0328X_7+0.0906X_8$
		$M_2=-0.2780X_1-0.1463X_2-0.4330X_3+0.4143X_4-0.3997X_5+0.5729X_6-0.1346X_7+0.0727X_8$
		$N_1=-0.0621W_1+0.0116W_2+0.0468W_3+0.1382W_4+0.0991W_5+0.5480W_6-0.4016W_7-0.1541W_8-0.0641W_9$
		$N_2=0.1709W_1+0.3294W_2+0.0061W_3+0.3652W_4+0.0292W_5+0.4939W_6+0.5171W_7+0.0649W_8+0.2621W_9$

Notes: X_1, SiO$_2$; X_2, Al$_2$O$_3$; X_3, Fe$_2$O$_3$; X_4, CaO; X_5, MgO; X_6, P$_2$O$_5$; X_7, K$_2$O; X_8, MnO; Y_1, Species; Y_2, Shannon index; Y_3, Evenness; Y_4, Simpson index; Y_5, Density; Y_6, Crown width; Y_7, Coverage; Y_8, BH; Y_9, Height; Z_1, Elevation; Z_2, Slope position; Z_3, Slope angle; Z_4, Percentage of covered rock; W_1, Moisture; W_2, Gravel content; W_3, Root content; W_4, pH; W_5, Organic matter; W_6, Total N; W_7, Available N; W_8, Available P; W_9, Available K; M_1 and M_2, first and second groups of canonical variables of soil mineral oxides; V_1 and V_2, first and second groups of canonical variables of vegetation; T_1 and T_2, first and second groups of canonical variables of topography; N_1 and N_2, first and second groups of canonical variables of soil velop the composition of canonical variables in the four study ecosystems (Table 6). Only the first two pairs of canonical variables are listed, due to the lesser effect of the third and fourth pair of variables.

In the slope land, the first and second canonical correlation between soil mineral oxides and topography are significant at the 0.01 level (Table 5). Fe_2O_3, MnO, elevation, and slope position have higher loading values in the relationship between soil mineral oxide components and topography, suggesting that topography has more influence on Fe_2O_3 and MnO contents than others in the slope land. And the SiO_2 and MgO contents mainly influence total N and available N.

In the plantation forest, the correlation coefficients of the first three pairs of variables between soil mineral oxide components and topography, soil conventional properties and the first two pairs of variables between soil mineral oxide components and vegetation range from 0.556 to 0.858 ($p < 0.01$). The variables of SiO_2, MnO, Shannon index, and DBH have higher loading values in the relationship between soil mineral oxide components and vegetation, indicating that SiO_2 and MnO affect plant community diversity and structure. Moreover, the variables of SiO_2, P_2O_5, and slope angle and slope position are closely related. SiO_2 and CaO contents also have closely relationship with organic matter and available N.

In the secondary forest, the correlation coefficients of the first two pairs of variables between soil mineral oxide components and vegetation, soil conventional properties are significant ($p < 0.01$), and that of the first three pair of variables between soil mineral oxide components and topography is also significant. MnO, Fe_2O_3 and Shannon index, Simpson index have high loading values, indicating there is closely relationship. Similarly, SiO_2, CaO are strongly correlated with slope angle, slope position, and MnO, CaO with total N, and moisture also be.

In the primary forest, the correlation coefficients of the first two pairs of variables betweeen soil mineral oxide components and vegetation, topography are statistically significant ($p < 0.01$), and also those of the first three pairs of variables between soil mineral oxide components and soil conventional properties be. In canonical variables, CaO, P_2O_5 are strongly correlated with species and Shannon index, and also SiO_2, Al_2O_3 are strongly correlated with percentage of covered rock and elevation. Moreover, CaO, P_2O_5 are strongly correlated with total N, and available N.

4 Discussion

Compared to red soils of similar latitudes, the karst soil in the study area had more soil water, organic matter, total nitrogen, total phosphorus, available nitrogen, and is better suited for plant growth (Song *et al.*, 2006). However, soil mineral elements and nutrients from rock weathering are limited. For example, the contents of Si, Al, Fe, Mn, and K in the surface soil of the primary forest were 29.76%, 4.45%, 2.79%, 0.08%, and 0.86%, respectively, far less than both the global average values and those for red soils at similar latitudes in China (Li, 1983; CNEMC, 1990). In addition to the very low total volume of soil in the region, the dearth of mineral nutrients greatly impairs the growth and development of plants. The biomass of primary forest in Mulun National Nature Reserve was only 131.42 t/ha (Song *et al.*, 2008), far lower than that of non-karst forest within the same ecological niche, and clearly less than that of the desert edge or the north Taiga forest (Yang, 1994).

Land utilization patterns can induce changes in ecological processes and soil physicochemical properties. Due to the influence of human activity on karst ecosystem, this research has been apportioned into slope land, plantation forest, secondary forest, and primary forest along strong, moderate, weak, and slight disturbance gradients, respectively. Soil mineral oxide contents were different in four typical ecosystems. Leaching and runoff of Ca, Mg, and K were obvious (Chang *et al.*, 1997). The contents of CaO, MgO, and P_2O_5 in the soils of the slope land and plantation forest with strong and moderate disturbance and lower forest cover were lower than those in the soils of the primary and secondary forests. The K_2O contents in the soils of the slope land and plantation forest were higher than those in the soils of primary and secondary forest due to plant ash application. The Si, Al, and Fe contents of the soils were dominated by weathering and pedogenesis (Chang et al., 1997). Both the plantation forest and slope land had a high weathering intensity, and subsequently the Al_2O_3 and Fe_2O_3 contents were greater than those of the soils in the primary and secondary forests. Mn is a hard-weathering and leachable element, which is influenced by soil parent material, landform, and geological structure. The contents of MnO were very low in this study area.

The degradation of fragile ecosystems is a complex process and human disturbance is a driving force for vegetation and land productivity loss, and the ultimate occurrence of a rocky desert landscape. Soil mineral oxide components could reflect the type and degree of rocky desertification. Generally, contents of $SiO_2 > 70\%$, $CaO > 5.0\%$, $Fe_2O_3 < 4.0\%$, and $MgO < 0.9\%$ signifies rocky desertification, whereas contents of $SiO_2 < 65\%$, $Fe_2O_3 > 7.0\%$, and $MgO > 1.0\%$ signifies that there is no rocky desertification (Huang, 2000). Although there was no rocky desertification in the four ecosystems, there was still confronted with this risk. For example, the content of SiO_2 in the slope land soil reached 67.33%, and that of Fe_2O_3 in the slope land, secondary forest, and primary forest soils was less than 7.0%.

Spatial heterogeneity is one of the most important soil attributes. Data for the different mineral oxide components in the four typical ecosystems fit different models and spatial patterns with higher coefficients of determination (R^2) for most variables. Most mineral oxide components had a low nugget-to-sill ratio ($C_0 / (C_0 + C) < 25\%$), suggesting that structural factors were the main factors of the soil mineral oxides spatial pattern. These structural factors include the variable of parent material, vegetation, topography, and microtopography. Human activity, as a random factor, affects the spatial pattern of soil mineral oxides. Spatial patterns of these soil mineral oxide components in the four typical ecosystems could be reflected clearly by kriging maps.

PCA indicated that the four typical ecosystems had high degrees of complexity and heterogeneity. The ecosystem development was influenced by many factors. It should take into account the interactions among vegetation, topography, soil mineral oxide, and other factors of the soil physicochemical environment. PC1 in the slope land and PC3 in the secondary forest had high loading values for main soil nutrients. However, soil mineral oxide content was the major factor in all four ecosystems. CaO, MgO, P_2O_5, K_2O, SiO_2, Al_2O_3, and Fe_2O_3 of the slope land had high loading values for PC1 and PC2. CaO showed a high loading value in the PC2 of the plantation forest. Fe_2O_3, CaO, K_2O, and MnO contents were the major factors in the PC2 of the secondary forest, whereas SiO_2, CaO, and MgO were the major factors in the PC2 of primary forest. Hence, soil mineral oxide content, particularly CaO, is a major factor affecting the fragile ecosystems in the depression between the karst hills. Understanding the composition and its effects of soil mineral oxide components is helpful for efficient mineral resources utilization and rational fertilizer usage.

In this karst region, secondary minerals formed from carbonate rock weathering are continuously released. These minerals, as the material basis of soil, improve soil fertility and promote plant growth. The accumulation of abundant plant biomass improves the plant growth environment by enhancing soil mineral composition and physicochemical properties. Topography can affect soil mineral oxide components and physicochemical properties through the redistribution of water and heat resources, which could regulate vegetation composition, community type, and the growth and development of plants. Therefore, vegetation, topography, soil mineral oxide, and the soil physicochemical environment all interact with each other. Soil mineral oxide components were highly correlated with vegetation, topography, and other soil physicochemical properties. The correlation coefficients of the first two pairs of variables were highly significant ($p < 0.01$), and some of the third and fourth pairs of variables were also as significant. Soil mineral oxide content was the most closely related variable to other soil physicochemical properties, topography and vegetation were the next. Canonical variables among soil mineral oxide components and vegetation, topography, other soil physicochemical properties were different in the four ecosystems. Interaction factors and intensity were also different. The general tendency was that topography had the most influence on SiO_2 and CaO, and these mineral oxides mainly affected the species diversity of vegetation, soil organic matter, nitrogen, and other soil physicochemical properties. It was different from the important role that Al_2O_3 and Fe_2O_3 contents play in zonal red soil.

5 Conclusions

The contents of soil mineral oxide component (SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, P_2O_5, K_2O, and MnO) are 45.02%–67.33%, 8.98%–18.23%, 3.99%–7.32%, 0.19%–18.8%, 0.69%–6.74%, 0.10%–0.13%, 0.50%–1.33% and 0.10%–0.37%, respectively, in four ecosystems. The best semivariogram models of soil mineral oxides content differ between the four ecosystems. Most mineral oxide components for all four ecosystems have strong spatial dependence, except CaO in plantation forest and slope land, MgO and P_2O_5 in plantation and secondary forests. In karst region, vegetation, topography, soil mineral oxide, and the soil physicochemical environment have close relationships. Soil mineral oxides are the important factors affecting soil fertility and vegetation growth and development in depression between karst hills.

References

Academic Divisions of Chinese Academy of Sciences, 2003. Some propositions on advancing the comprehensive control of karst mountain areas in Southeast China. *Advance in Earth Science*, 18(4): 489–492. (in Chinese)

Bao Shidan, 2000. *Soil and Agricultural Chemistry Analysis*. Beijing: China Agriculture Press. (in Chinese)

Cambardella C A, Moorman T B, Novak J M *et al*., 1994. Field-scale variability of soil properties in central Iowa soils. *Soil Science Society of America Journal*, 58(5): 1501–1511.

Chang Qingrui, Li Xinping, Lei Mei *et al*., 1997. Distribution law of soil mineral elements in Southern Ningxia. *Bulletin of Soil and Water Conservation*, 17(2): 7–10, 22. (in Chinese)

Chen H S, Zhang W, Wang K L *et al*., 2011. Soil organic carbon and total nitrogen as affected by land use types in karst and non-karst areas of northwest Guangxi, China. *Journal of the Science of Food and Agriculture*, 92(5): 1086–1093. doi: 10.1002/jsfa.4591

CNEMC (China National Environmental Monitoring Centre), 1990. *China Soil Elements Background Values*. Beijing: China Environmental Science Press. (in Chinese)

Condit R, 1995. Research in large, long-term tropical forest plots. *Trends in Ecology and Evolution*, 10(1): 18–22.

Herbst M, Diekkruger B, 2003. Modelling the spatial variability of soil moisture in a micro-scale catchment and comparison with field data using geostatistics. *Physics and Chemistry of the Earth*, 28(6): 239–245. doi: 10.1016/S1474-7065(03)00033-0

Houx III J H, Wiebold W J, Fritschi F B, 2011. Long-term tillage and crop rotation determines the mineral nutrient distributions of some elements in a Vertic Epiaqualf. *Soil and Tillage Research*, 112(1): 27–35. doi: 10.1016/j.still.2010.11.003

Huang Changyong, 2000. *Pedology*. Beijing: China Agricultural Press. (in Chinese)

Huggett R J, 1998. Soil chronosequences, soil development, and soil evolution: A critical review. *Catena*, 32(3/4): 155–172.

Isaaks E, Srivastava R, 1989. *Applied Geostatistics*. New York: Oxford University Press.

Kilic K, Kilic S, 2007. Spatial variability of salinity and alkalinity of a field having salination risk in semi-arid climate in northern Turkey. *Environmental Monitoring and Assessment*, 127(1): 55–65. doi: 10.1007/s10661-006-9258-x

Lane D R, Bassiri R H, 2005. Diminishing spatial heterogeneity in soil organic matter across a prairie restoration chronosequence. *Restoration Ecology*, 13(2): 403–412. doi: 10.1111/j.1526-100X.2005.00050.x

Legendre P, Legendre L, 1998. *Numerical Ecology*. 2nd edition. Amsterdam: Elsevier Science BV.

Li C J, Li Y, Ma J, 2011. Spatial heterogeneity of soil chemical properties at fine scales induced by *Haloxylon ammodendron* (Chenopodiaceae) plants in a sandy desert. *Ecological Research*, 26(2): 385–394. doi: 10.1007/s11284-010-0793-0

Li Qingkui, 1983. *China Red Soils*. Beijing: Science Press. (in Chinese)

Liu Guangsong, 1997. *Standard Methods for Observation and Analysis in Chinese Ecosystem Research Network-soil Physical and Chemical Analysis & Description of Soil Profile*. Beijing: Standards Press of China. (in Chinese)

Liu Lu, Zeng Fuping, Song Tongqing *et al*., 2010. Spatial heterogeneity characteristics of soil nutrients in Mulun National Nature Reserve in Karst area. *Chinese Journal of Applied Ecology*, 21(7): 1667–1673. (in Chinese)

Liu X M, Xu J M, Zhang M H *et al*., 2007. Spatial variability of soil available Zn and Cu in paddy rice fields of China. *Environmental Geology*, 55(7): 1569–1576. doi: 10.1007/s00254-007-1107-x

Ma Keping, Huang Jianhui, Yu Shunlin *et al*., 1995. Plant community diversity in Dongling Mountain Beijing, China: Species richness, evenness and species diversity. *Acta Ecologica Sinica*, 15(3): 268–277. (in Chinese)

Nie Y P, Chen H S, Wang K L *et al*., 2011. Seasonal water use patterns of woody species growing on the continuous dolostone outcrops and nearby thin soils in subtropical China. *Plant Soil*, 341(2): 399–412.

Peng Wanxia, Wang Kelin, Song Tongqing *et al*., 2008. Controlling and restoration models of complex degradation vulnerable karst ecosystem. *Acta Ecologica Sinica*, 28(2): 811–820. (in Chinese)

Qiu Yang, Zhang Jintun, 2000. The ordination axes clustering based on detrended canonical correspondence analysis ordination and its application of the ecological gradients of plant communities. *Acta Ecologica Sinica*, 20(2): 199–206. (in Chinese)

Robertson G P, Crum J R, Ellis B G, 1993. The spatial variability of soil resources following long-term disturbance. *Oecologia*, 96(4): 451–456.

Song, Tongqing, Peng Wanxia, Zeng Fuping *et al*., 2009. Spatial heterogeneity of surface soil water in Mulun National Natural Reserve in dry season in Karst area. *Chinese Journal of Applied Ecology*, 20(1): 98–104. (in Chinese)

Song Tongqing, Peng Wanxia, Zeng Fuping *et al*., 2008. Vegetation succession rule and regeneration strategies in disturbed karst area, Northern Guangxi. *Journal of Mountain Science*, 26(5): 597–604. (in Chinese)

Song Tongqing, Peng Wanxia, Zeng Fuping *et al*., 2010. Spatial pattern of forest communities and environmental interpretation in Mulun National Nature Resere, karst cluster-peak depression region. *Chinese Journal of Plant Ecology*, 34(3): 298–308. (in Chinese)

Song Tongqing, Wang Kelin, Peng Wanxia *et al.*, 2006. Ecological effects of intercropping white clover on tea plantation in a subtropical hilly region. *Acta Ecologica Sinica*, 26(11): 3647–3655. (in Chinese)

Starr M, Lindroos A J, 2006. Changes in the rate of release of Ca and Mg and normative mineralogy due to weathering along a 5300-year chronosequence of boreal forest soils. *Geoderma*, 133(3): 269–280. doi: 10.1016/j.geoderma.2005.07.013

Tian D L, Xiang W H, Yan W D *et al.*, 2007. Biological cycles of mineral elements in a young mixed stand in abandoned mining soils. *Journal of Integration Plant Biology*, 49(9): 1284–1293. doi: 10.1111/j.1672-9072.2007.00535.x

Wang Zhengquan, 1999. *Geostatistics and Its Application in Ecology*. Beijing: Science Press. (in Chinese)

Webster R, Oliver M A, 2001. *Geostatistics for Environmental Scientists*. Chichester: Wiley.

Yang H K, 1994. Discussion on variation of karst environmental quality. In: Xie *et al*. (eds.). *Human Activity and Karst Environment*. Beijing: Beijing Science and Technology Press. (in Chinese)

Yang Z P, Ouyang H, Zhang X Z *et al.*, 2011. Spatial variability of soil moisture at typical alpine meadow and steppe sites in the Qinghai-Tibetan Plateau permafrost region. *Environmental Earth Science*, 63(3): 477–488. doi: 10.1007/s12665-010-0716-y

Yavitt J B, Harms K E, Garcia M N *et al.*, 2009. Spatial heterogeneity of soil chemical properties in a lowland tropical moist forest, Panama. *Soil Research*, 47(7): 674–687.

Zeng Fuping, Peng Wanxia, Song Tongqing *et al.*, 2007. Changes in vegetation after 22 years′ natural restoration in the karst disturbed area in Northwest Guangxi. *Acta Ecologica Sinica*, 27(12): 5110–5119. (in Chinese)

Zhang Feng, Zhang Jintun. 2003. Pattern of forest vegetation and its environmental interpretation in Zhuweigou, Lishan Mountain Nature Reserve. *Acta Ecologica Sinica*, 23(3): 421–427. (in Chinese)

Zhang Jiguang, Chen Hongsong, Su Yirong *et al.*, 2011. Spatial variability and patterns of surface soil moisture in a field plot of karst area in southwest China. *Plant Soil and Environment*, 57(9): 409–417.

Zhang Xinbao, Wang Kelin, 2009. Ponderation on the shortage of mineral nutrients in the soil-vegetation ecosystem in carbonate rock-distributed mountain regions in Southwest. *Earth and Environment*, 37(4): 337–341. (in Chinese)

Zheng Yinwu, 1999. *Introduction to Mulun Karst Forest Region*. Beijing: Science Press. (in Chinese)

Zhu Zuxiang, 1983. *Pedology*. Beijing: China Agricultural Press. (in Chinese)