



# A geostatistic investigation of the comprehensive evaluation of fertility and spatial heterogeneity of forest soil nutrients in hilly and mountainous regions of southern China

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## Abstract

The objective of this study was to investigate five nutrient factors of the forest topsoil (0–20 cm), including pH, soil organic matter (SOM), total nitrogen (STN), available phosphorus (AP), and available potassium (AK). This study adopted the revised Nemerow index method to conduct a comprehensive quantitative evaluation on the soil nutrition contents, and using geostatistical method to address the spatial variability of soil properties in hilly and mountainous regions, southern China. Data were analyzed both statistically and geostatistically on the basis of semivariogram. Our results indicate that the soil is generally acidic, containing rich SOM and STN, but lacks AP and AK. Most of the sub-indexes of fertility were at grade III, showing a middle level. According to the coefficient of variations (CV), the five soil nutrient factors can be ranked in decreasing order as follows: AP > SOM > AK > STN > pH. There were differences between the sub-indexes of fertility, which could be ranked as follows:  $P_{SOM} > P_{AK} > P_{STN} > P_{pH} > P_{AP}$ . The semi-variation functions for the five soil nutrient factors studied here show some spatial structure features, over a range of 23–274 km. All nutrient factors had different nugget-to-sill ratios in each region, which varied from 10 to 50%, suggesting a strong or medium correlation. Thus, it can be concluded that the nutrient spatial distribution of the study area was the result of the combined action of structural factors and random factors, and the factors affecting the soil nutrients of the research area are highly complex. We will develop more targeted research plans about soil nutrients of study area in the next time.

**Keywords** Hilly and mountainous regions · Forest soil nutrients and soil fertility · Geostatistics · Spatial heterogeneity

## Introduction

Soil quality is one of the most important factors affecting the sustainable development of the global biosphere and the sustainability of agricultural development, soil management, and land utilization. Sourced from the interaction of living things and the environment in the ecosystem, soil stores a huge amount of carbon, nitrogen, phosphorus, and potassium. While soil provides nutrient elements for forest existence and development, forest vegetation also affects soil development and nutrient change (Deng et al., 2014). Because soil is a

complex natural resource in internal nature, there is a strong spatial heterogeneity; the study found that even in a few centimeters on the space, the distance of soil properties also has strong variations (Mallarino 1996; Li et al. 2015); differences in the spatial distribution of the soil property determines its structure function. Soil has spatial and temporal heterogeneity of different scales. Some studies have shown that the changes of soil parent matter, soil type, and soil texture and other large scales have been observed. It plays a decisive role in the large-scale forest pattern (Robertson and Gross 1994; Reza et al. 2016). Much research has studied the role of the spatial heterogeneity of forest soil nutrients on different climatic, regional, and spatial and temporal scales and its relationship with environmental factors (Robert et al. 2007; Yavitt et al. 2009; Liu et al. 2012; Horad et al. 2013; Liu et al. 2015). The study of soil spatial variability is of guiding significance to the exploration of vegetation litter structure and soil fertility in the ecosystem.

Geostatistics has been shown to be the most effective method for analyzing the spatial distribution features and variation

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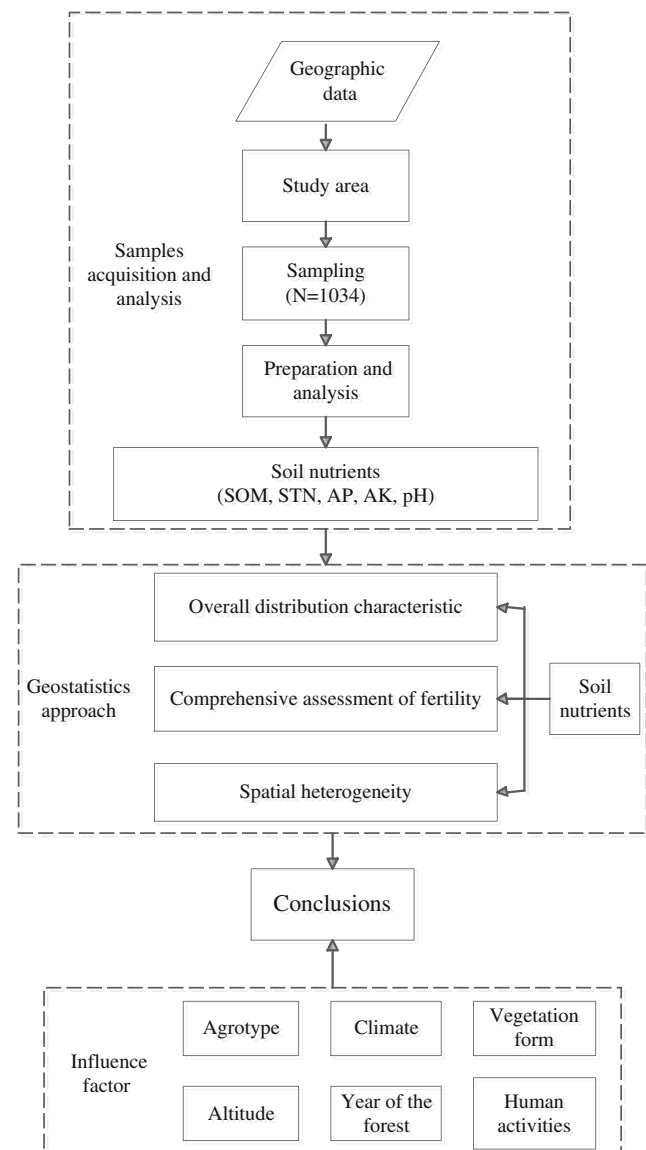
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patterns of the soil properties (Webster 1985; Silver et al. 1994; Zhang et al. 2014; Reza et al. 2016). The semi-variance function can be used to describe the spatial variability of soil properties; it is a characteristic function of geostatistical analysis (Burgess and Webster 1980; Andivia et al. 2015). Liu et al. (2016)'s results revealed the spatial heterogeneity distribution of STN and STP and addressed the influences of forest vegetation coverage, elevation, and other topographic factors on the spatial distribution of STN and STP at the watershed scale. The spatial distribution characteristics of forest soil nutrients are analyzed by geostatistical methods, and the spatial variation law of soil nutrients in the region is revealed.

In recent years, the continuous expansion of artificial forest has increased the economic value of the region, but has also caused a sharp decrease in the natural evergreen broad-leaved forests, leading to the growth of homogenous tree species and too many young forests. These pose a hidden threat, promoting the deterioration of the soil quality and soil fertility loss. However, the knowledge about the soil nutrient conditions in the hilly and mountainous regions of south China, which cover much of the southern area, is mostly based on obsolete data from a soil census conducted 30 years ago. We base on the field sampling, geostatistical methods and semi-variance functions to study forest soil of China's southern hilly and mountainous areas, study of comprehensive evaluation of forest soil nutrient content, and spatial variability of soil nutrients and soil fertility. Thus, the objective of this study is to determine the spatial variability of selected soil properties, such as pH, soil organic matter (SOM), total nitrogen (STN), available phosphorus (AP), and available potassium (AK), with the comprehensive fertility index and geostatistical analysis. We hypothesize that there is a strong spatial heterogeneity of soil nutrient content and soil fertility in the study area. Through this study, we hope to have a comprehensive understanding of the overall distribution of forest soil nutrients in the study area. It aims to help people understand the nutrient content of forest soil and the effect of human activities on its spatial variation and develop the southern hilly effectively degraded ecosystem restoration; the purpose of annual/seasonal crop cultivation and the development of more effective forestry management measures have important guiding significance, in hilly and mountainous regions of southern China.

## Samples and methods

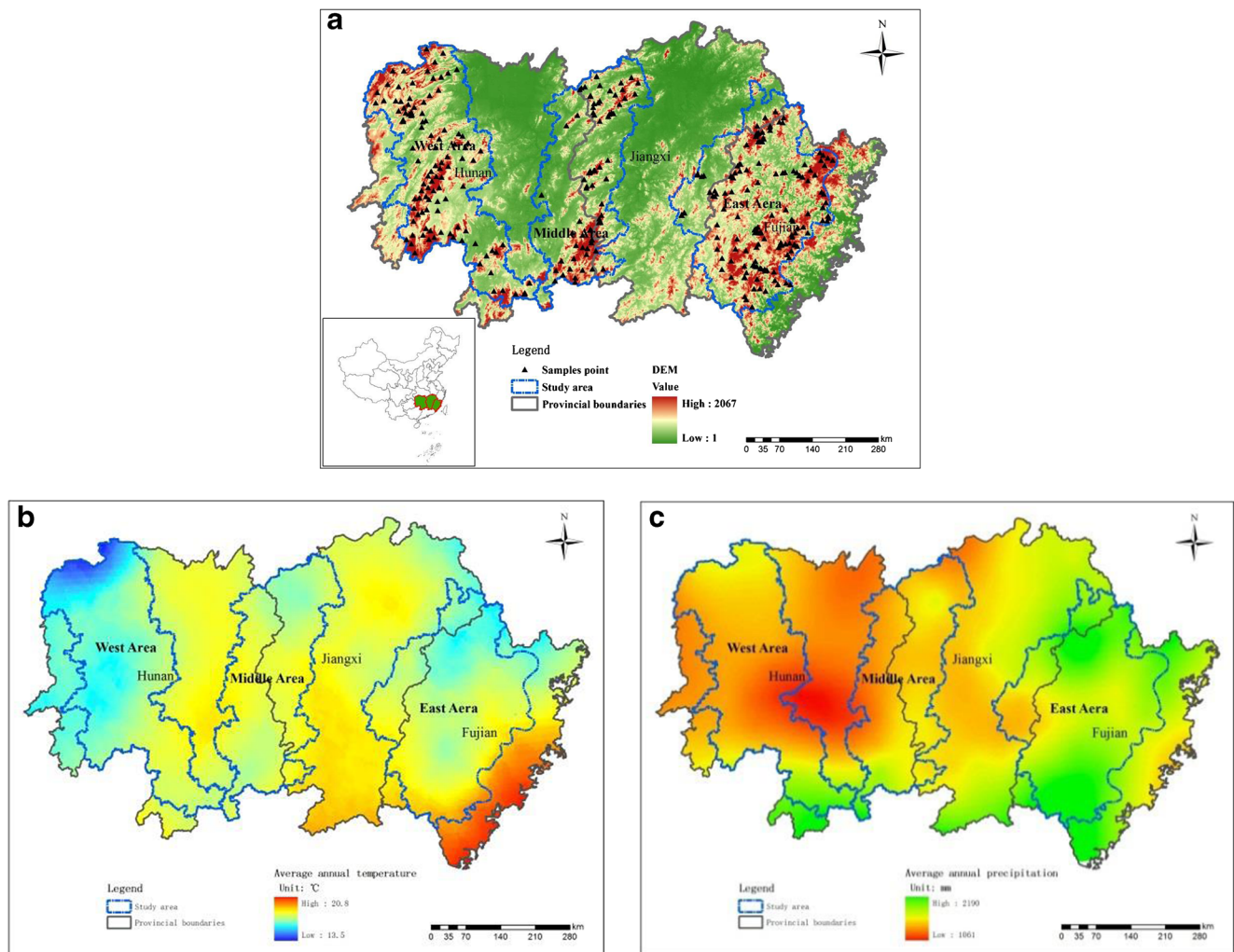
The proposed approach included four main, interdependent components: sample acquisition and analysis for the soil nutrients, geostatistics approaches for determining the soil nutrient quality and spatial variation, the influencing factors and their conclusions. The general flowchart is shown in Fig. 1.



**Fig. 1** General flowchart of the proposed approach (pH; SOM soil organic matter, STN total nitrogen, AP available phosphorus, AK available potassium)

## Study area

This study selected three provinces, Hunan, Jiangxi, and Fujian, as the research area. As the core area of the south hilly and mountainous areas, the research area consists of the mountainous area of western Hunan, the border of Hunan and Jiangxi, and Fujian and Jiangxi. The research area includes five major mountains: Wuling Mountain, Xufeng Mountain, Mufu Mountain, Luoxiao Mountain, and Wuyi Mountain (109.93°–118.54° E, 24.88°–30.00° N). This research defines the Fujian–Jiangxi mountainous area, the Hunan–Jiangxi mountainous area, and the west Hunan mountainous area as the eastern, central, and western regions, respectively, for clarity (Fig. 2a). Together,



**Fig. 2** a Study area and sampling locations in the investigated area of southern China. b Average annual temperature in 2013. c Average annual precipitation in 2013

these areas cover a total area of 26.3 km<sup>2</sup> with diverse terrains. This region features the alternating ridges and valleys, with an altitude variation from 90 to 2100 m. The hilly and mountainous area accounts for 82% of the area of the whole region. The region has a subtropical humid monsoon climate, with an annual average temperature of 13.5~20.8 °C (Fig. 2b), an annual average precipitation of 1061~2190 mm (Fig. 2c), an annual average sunshine duration of 1300~2100 h, and a frost-free period of 250~300 days. The soil shows a distinct zonal pattern and the vegetation also shows a zonal distribution. The eastern part of the research area is subtropical evergreen broad-leaved forest, mainly covered by coniferous forest and a broadleaf-coniferous mixed forest. The representative species include fir, pine, nanmu (Chinese *Lauraceae* species), sassafras, *Schima*, Chinese sweetgum, chinquapin, ring-cupped oak, and moso bamboo. The low-slope hilly land has mainly oil tea trees.

## Sampling

In our study, the principle of distribution points was based on the data of forest resources in Jiangxi province, Fujian province, and Hunan province. According to the type of forest, the area, accumulation, and composition of various types of forests, and their geographical distribution weights, they were distributed within the study area and combined with topographic maps for the layout of soil samples. Sample coordinates were obtained via the global positioning system. The samples were analyzed for their nutrient content. The forest soil samples were taken from the surface layer, at 0–20 cm in depth. At each sampling site, samples were collected from the field by means of a random sampling method. One thousand and thirty-four soil samples were collected in the districts. All samples were sealed in polyethylene bags. The spatial distribution of the sampling sites is shown in Fig. 2 a. At the same

time as sampling, handheld GPS was used to record information such as latitude, longitude, and altitude of each sampling point. Information on the sampling site, including the vegetation type, forest type, vegetation coverage, slope and aspect, human factors (such as fertilization, irrigation), and pH were measured and recorded.

### Sample preparation and analysis

The soil samples were air-dried and ground to pass through a 100- $\mu$ m mesh screen. The physical–chemical parameters of the soils (pH, SOM, STN, AP, and AK) were analyzed at the Center for Environmental Remediation Laboratory of the Institute of Geographic Sciences and Natural Resources Research at the Chinese Academy of Sciences, according to standard methods (Bao 2000). The precision and bias of the chemical analyses were less than 10%. All analyses were performed with the SPSS statistical package (v18.0) (SPSS Inc., Chicago, IL, USA).

### Comprehensive evaluation method of the soil nutrient content

Independent nutrient indexes for the soil cannot directly reflect the overall level of soil nutrients. To reflect the overall situation of the soil nutrients objectively, this study adopted the revised Nemerow index method to conduct a comprehensive quantitative evaluation on the soil nutrition contents (Sun et al. 1995). This study took the five nutrient factors (pH, SOM, STN, AP, and AK) as the basic parameters. By referring to the standard of the second national soil census and combining the actual data from the research area, the five basic parameters were divided separately into three levels according to their minimum, median, and maximum values for these factors (Table 1). The index of integrated fertility was obtained after parameter standardization. Then, the integrated fertility of the forest soil of different categories was compared. The following is the specific computation method:

**Standardization of parameters** The various nutrient factors were standardized in the following way to eliminate the dimensional differences and to obtain the index of fertility for each nutrient factor (Sun et al. 1995). The computing method

**Table 1** The grading standards of the soil quality assessment index

Nutrient index	$X_a$	$X_c$	$X_p$
SOM (g/kg)	10	20	30
STN (g/kg)	0.75	1.5	2.0
AP (mg/kg)	5	10	20
AK (mg/kg)	50	100	200
pH	4.5	5.5	6.5

for the sub-index of fertility  $P_i$  is as follows:

$$P_i = \begin{cases} X_i/X_{i\min} \\ 1 + (X_i - X_{i\min}) / (X_{i\text{mid}} - X_{i\min}) \\ 2 + (X_i - X_{i\max}) / (X_{i\max} - X_{i\text{mid}}) \\ 3 \end{cases} \quad (1)$$

In the above relationship,  $P_i$  represents the sub-index of fertility, i.e., the index of fertility for each soil property  $i$  ( $i = 1, 2, 3, 4, 5$ ),  $X_i$  is the measured value of the property  $i$ ,  $X_{i\min}$  and  $X_{i\max}$  are the upper and lower limits of the grading standard, respectively, and  $X_{i\text{mid}}$  is assigned to a value between the two. The grading of the soil properties ( $X_a, X_c, X_p$ ) mainly take into account the standards of the second national soil census and the local soil characteristics (National Soil Survey Office 2002). Referring to the research results (Que and Wu, 1994), the  $X_{i\min}$ ,  $X_{i\text{mid}}$ , and  $X_{i\max}$  for grading the pH value were set at 4.5, 5.5, and 6.5, respectively.

After standardization with this method, the  $P_i$  value was found to be within the range of 0–3. This leads to the following advantages. First, there is a strong comparability between the same parameters. Various soil properties at the same level have a close sub-index of fertility, suggesting they share a high level of comparability. When the measured value exceeds the upper limit, the sub-index of fertility no longer increases. This indicates that a higher soil property is not necessarily better for crops.

$$P = \sqrt{\frac{(\overline{P_i})^2 + (P_{i\min})^2}{2} \cdot \frac{(n-1)}{n}} \quad (2)$$

where  $P$  represents the index of integrated soil fertility, and  $\overline{P_i}$  is the average value of the sub-indexes of fertility for various soil properties.  $P_{i\min}$  is the minimum sub-index of fertility, and  $n$  is the number of soil properties. Table 2 details the grading standard for the integrated soil quality index  $P$ .

### Evaluation method for the spatial variability of soil nutrients

The semi-variation function is the most widely applied description tool for discerning spatial patterns, and its formula (Goovaerts 1998; Sun et al. 2002; Li et al. 2008) is as follows:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \quad (3)$$

**Table 2** The quality and grade standards of the soil nutrient quality

Quality levels	I	II	III	IV
Range	$P \geq 2$	$1.5 \leq P < 2$	$1 \leq P < 1.5$	$P < 1$
Evaluation index	Excellent	Good	Moderate	Poor



Above,  $\gamma(h)$  is the semi-variation function value,  $N(h)$  is the number of point pairs with the norm of vector  $h$  as the spacing,  $Z(x_i)$  is the measured value of the regionalized variable  $Z$  at  $x_i$ , and  $Z(x_i + h)$  is the value of the sampling point whose distance from  $x_i$  is equal to the norm of vector  $h$ . It is generally believed that the semi-variation function is meaningful only within 1/2 of the maximum interval (Western et al. 1998). In this research, all effective lag distances were set as 1/2 of the maximum sampling interval, except for special illustrations.

## Results and discussion

### Overall distribution of soil nutrient characteristics

In the whole research area (Table 3), the nutrient factors of the topsoil of the forest ecosystem showed significant differences. The value ranges of the various factors were as follows: organic matter 8.24–104.29 g/kg, total nitrogen 0.23–7.67 g/kg, available phosphorus 0.40–13.68 mg/kg, available potassium 30.86–361.12 mg/kg, and pH value 4.35–6.51. The overall soil sample was acidic, according to the grading standard for the nutrient indexes of the second national soil census (National Soil Survey Office 2002). Overall, the content of the soil-available potassium was also lower. Organic matter and the total nitrogen were abundant, but the available phosphorous and potassium were lacking. The forested areas of the red-soil hilly areas in south China suffer from serious soil and water loss. At the same time, the soil has a low degree of base saturation under acidic conditions, which has aggravated soil

leaching under the conditions of high temperature and heavy rains.

The unit of SOM is g/kg, STN is g/kg, AP is mg/kg, and AK is mg/kg.

According to the coefficient of variation (CV), the five soil nutrient factors could be ranked in decreasing order as follows: AP > SOM > AK > STN > pH. In the research area, the degree of variation of the soil nutrients in the eastern region was slightly higher as a whole, and the CVs of the STN, AP, and AK were the highest. This suggests a significant difference in the spatial distribution of soil nutrients in the eastern region. There, the soil nutrients in different spatial positions may also be under the significant influence of human factors such as fertilization and the planting system, while being affected by the soil parent materials, soil type, and climate.

If the data of soil nutrients had a normal distribution or lognormal distribution, it could be studied by semi-variance analysis. After the original data of samples was tested by the Kolmogorov–Smirnov test (K–S test), we could determine the parameters, which were listed in the Table 4. The data of pH and SOM here follow a normal distribution, and the data of STN, AP, and AK show a certain deflection effect, after logarithmic transformation, which also followed a normal distribution.

### Comprehensive assessment of soil nutrient

As shown in Table 5, this research divided the research area into four dimensions according to their geological position, altitude, forest types, and forest stand level. On the whole, there were differences between the sub-indexes of fertility,

**Table 3** Descriptive statistics characteristics of the soil nutrients in study area ( $N = 1034$ )

Area	Index	Minimum	Maximum	Mean value	Standard deviation	Coefficient of variation (%)	Sampling number
East	SOM	8.24	104.29	41.17	21.74	138.32	413
	STN	0.23	7.67	1.54	1.06	50.12	413
	AP	0.91	13.68	3.56	2.31	221.43	413
	AK	37.83	361.12	137.71	84.95	88.73	413
	pH	4.39	5.98	5.08	0.32	9.45	413
Middle	SOM	10.83	94.67	36.71	16.15	98.64	286
	STN	0.37	3.87	1.39	0.73	33.56	286
	AP	1.05	9.12	2.57	1.56	130.22	286
	AK	30.86	292.13	83.83	48.39	55.34	286
	pH	4.35	5.95	5.01	0.39	8.75	286
West	SOM	10.85	76.71	33.43	21.16	78.31	335
	STN	0.45	3.50	1.82	0.71	20.72	335
	AP	0.40	10.82	2.88	2.59	165.63	335
	AK	28.31	336.63	118.82	70.28	63.84	335
	pH	4.48	6.51	5.20	0.40	10.32	335

**Table 4** Normal distribution tests of soil nutrients (K–S test)

Area	Index	Skewness	Kurtosis	$K_{S1}$	$K_{S2}$	$A_{0.05}$
East	SOM	0.371	0.863	1.205	–	+
	STN	1.411	2.435	2.815	1.687	–o
	AP	1.623	3.278	3.846	2.035	–o
	AK	0.673	–1.402	1.935	0.982	–o
	pH	0.196	0.029	0.423	–	+
Middle	SOM	1.065	1.744	1.986	–	+
	STN	0.077	–0.635	1.513	0.735	–o
	AP	1.943	2.562	3.568	1.765	–o
	AK	1.446	2.106	2.417	1.552	–o
	pH	0.045	–0.113	0.356	–	+
West	SOM	1.105	0.425	1.346	–	+
	STN	1.816	3.782	2.689	1.292	–o
	AP	0.922	–0.841	3.012	1.525	–o
	AK	1.434	2.304	2.341	1.136	–o
	pH	–0.052	–0.393	0.792	–	+

Note:  $K_{S1}$  represents the normal statistics of K–S test without logarithmic transformation and  $K_{S2}$  represents the normal statistics of K–S test after logarithmic transformation.  $A_{0.05}$  means the confidence value is 0.05. “+,” “o,” and “–” represents the data with a normal distribution, lognormal distribution, and other distributions respectively under the confidence value of 0.05

which could be ranked as follows:  $P_{SOM} > P_{AK} > P_{STN} > P_{pH} > P_{AP}$ . The index of integrated fertility was within the scope of 0.91–1.51. Most of the sub-indexes of fertility were at grade III, showing a middle level. The index of the soil-integrated fertility was above 1.5 only for the medium altitude mountains, i.e., reaching grade II. In various systems classified according to their geological position, altitude, forest type, or stand level, the soil fertility showed significant

differences. Specifically, in all these classification systems, the organic matter always had the highest sub-index of fertility, ranging between 2 and 3. The Table 5 suggests the good quality of the SOM within the entire research area. The pH values showed no significant differences in the sub-index of fertility, which was within the medium level, with a range of 1.6–1.8. For the STN and AK, the sub-index of fertility fell mostly within the range of 1.5–2.0, suggesting a good fertility level. The soil AP had the poorest sub-index of fertility, ranging from 0.51 to 1.11 in different classification systems. This reflects the fact that the content of the soil AP in the entire research area is extremely poor. Artificial structural adjustment or the addition of phosphate fertilizer was required for the forest land, especially for economic forests. Moreover, the effectiveness of phosphate fertilizers should be improved to raise the productivity of forestland and its ecological and economic benefits.

From the geological position, the eastern region had the highest index of soil-integrated fertility, followed by the western region and the central region. The lowest index of fertility in the central region was attributed to the lowest sub-indexes of available phosphorous and potassium. At the three altitudes (hilly, low-mountain, and medium-mountain), the index of integrated fertility followed the pattern of medium-mountain altitude (1.51) > low-mountain altitude (1.21) > hilly altitude (1.07). In other words, as the altitude increased, the coefficient of integrated fertility also increased. The variation trend of the content of SOM and STN was mainly formed by a drop in the temperature and an increase in humidity associated with the increasing altitude. The favorable conditions created by these changes are conducive to the accumulation of SOM. In terms of the forest type, the coefficients of integrated fertility of the five forest types were within the range of 0.91–1.41 and

**Table 5** Soil nutrient quality grading of the different indices in the in study area

	Sampling number	$P_{SOM}$	$P_{STN}$	$P_{AP}$	$P_{AK}$	$P_{pH}$	$P$	Index level	
Geographic location	West area	141	2.55	1.61	0.94	1.94	1.61	1.24	III
	Middle area	168	2.54	1.33	0.51	1.53	1.79	0.95	IV
	East area	273	2.78	1.52	1.01	2.04	1.59	1.35	III
Elevations	Hill (< 500 m)	315	2.51	1.52	0.88	1.93	1.59	1.07	III
	Low mountain (500–1000)	144	2.79	1.89	0.83	1.71	1.69	1.21	III
	Middle mountain (1000–3500)	123	2.95	2.34	0.81	1.91	1.76	1.51	II
Forest types	Coniferous forest	189	2.46	1.83	0.63	1.63	1.62	0.91	IV
	Deciduous broadleaf forest	123	2.69	1.75	0.87	2.23	1.69	1.41	III
	Mixed broadleaf-conifer forest	84	2.61	1.81	0.96	1.76	1.54	1.22	III
	Bamboo	87	2.65	1.88	0.87	1.77	1.82	1.14	III
	Shrubbery	99	2.49	1.56	1.11	1.86	1.55	1.36	III
Forest stand	Plantation forests	387	2.35	1.72	0.86	1.82	1.64	1.02	IV
	Natural forests	195	2.73	1.88	0.84	1.97	1.67	1.33	III
Total	582	2.67	1.77	0.85	1.87	1.65	1.21	III	

Note:  $P$  is the index of integrated soil fertility

ranked as follows in a decreasing order: broad-leaved forest (1.41) > shrubbery (1.36) > broadleaf-coniferous mixed forest (1.22) > bamboo forest (1.14) > coniferous forest (0.91). The soil-integrated fertility followed the order of natural forest (1.33) > artificial forest (1.01). This suggests that in the macro-environment featuring acidic soil and a vulnerable ecosystem in southern China, the natural forest can better maintain its favorable soil properties. In conclusion, for the above results, we should be addressed in future forest management research and policies.

### Spatial variation and structural features of the soil

The best fitting models for the various nutrient factors of the forest soil in the southern hilly and mountainous areas all had a large coefficient of determination, suggesting the fitting model can better reflect the spatial features of the soil nutrients (Table 6). According to previous scholars' research methods (Sun et al. 2003; Hengl et al. 2004; Gao et al. 2013), a proper theoretical model was selected according to the results of parameter fitting (Fig. 3). The optimal fitting model for each soil nutrient factor in the eastern, central, and western region included the spherical model, Gaussian model, and exponential model, with the coefficient of determination ranging from 0.619 to 0.884. This suggests that these fitting models can properly reflect the spatial features of the soil nutrients. The variation function curves of the five nutrient factors show a smooth change, suggesting that the various ecological processes play a role of equal importance in affecting the changes in the soil nutrients on the whole (Trangmar et al. 1985; Vieira and Paz Gonzalez 2003; Reza et al. 2016).

According to Table 6, the scales for the spatial autocorrelation changes of the five nutrient factors were different and

the range of pH value in the three regions was quite small, being 40–70 km. The other four soil nutrients all had a large range. The scope of these ranges was 23–274 km. Under different scales, the five nutrient factors showed different spatial autocorrelation patterns. The comparison for the eastern, central, and western regions shows that the nugget-to-sill ratios were all less than 25%, indicating a strong correlation. The nugget-to-sill ratios of the other nutrient factors varied from 10 to 50% in the different regions, indicating a strong or medium correlation. When the nugget-to-sill ratio of nutrient factors is less than 25%, there is a strong spatial correlation. This suggests that random factors make little contribution to the spatial distribution of the soil nutrient factors and that the variation is mainly caused by such structural factors as the terrain, soil parent material, climate, and other natural factors. When the nugget-to-sill ratio is between 25 and 75%, there is a medium spatial correlation. This is because soil nutrient distribution results from the combined action of structural and random factors (Cambardella et al. 1994). For instance, random factors, such as fertilization, cultivation measurements, planting systems, and other human activities can weaken the spatial correlation in the soil nutrients and facilitate homogenization. Some other researchers had also found the moderate spatial dependence of soil properties (Zhang et al. 2008; Safari et al. 2013; Liu et al. 2015).

### Conclusions

The summary statistics for soil nutrients were shown that the soil in the research area is generally acidic, with a high content of organic matter and total nitrogen. However, the available phosphorus and potassium are lacking. Except for the pH

**Table 6** Best-fitted semi-variogram models of soil nutrients and the corresponding parameters

	Nutrition	Nugget ( $C_0$ )	Sill ( $C_0 + C$ )	Nugget/Sill (%)	Range (km)	Best model	$R^2$
East	SOM	105.1	474.4	22.15	51.07	Gaussian	0.789
	STN	0.338	1.571	21.51	74.30	Spherical	0.853
	AP	2.302	5.309	43.36	103.09	Exponential	0.727
	AK	2673	7184	37.21	45.19	Exponential	0.708
	pH	0.026	0.124	20.97	63.36	Gaussian	0.884
Middle	SOM	119.4	398.1	29.99	165.7	Gaussian	0.813
	STN	0.324	1.244	26.05	257.5	Gaussian	0.827
	AP	0.838	2.474	33.87	210.4	Exponential	0.775
	AK	291.5	2303	12.66	23.33	Spherical	0.619
	pH	0.026	0.161	16.15	42.62	Exponential	0.735
West	SOM	96.75	446.8	21.65	145.96	Exponential	0.627
	STN	0.492	4.809	10.23	274.92	Gaussian	0.834
	AP	1.973	6.407	30.79	50.45	Exponential	0.724
	AK	3550	7101	49.99	253.23	Exponential	0.662
	pH	0.0036	0.0408	8.82	67.37	Spherical	0.775

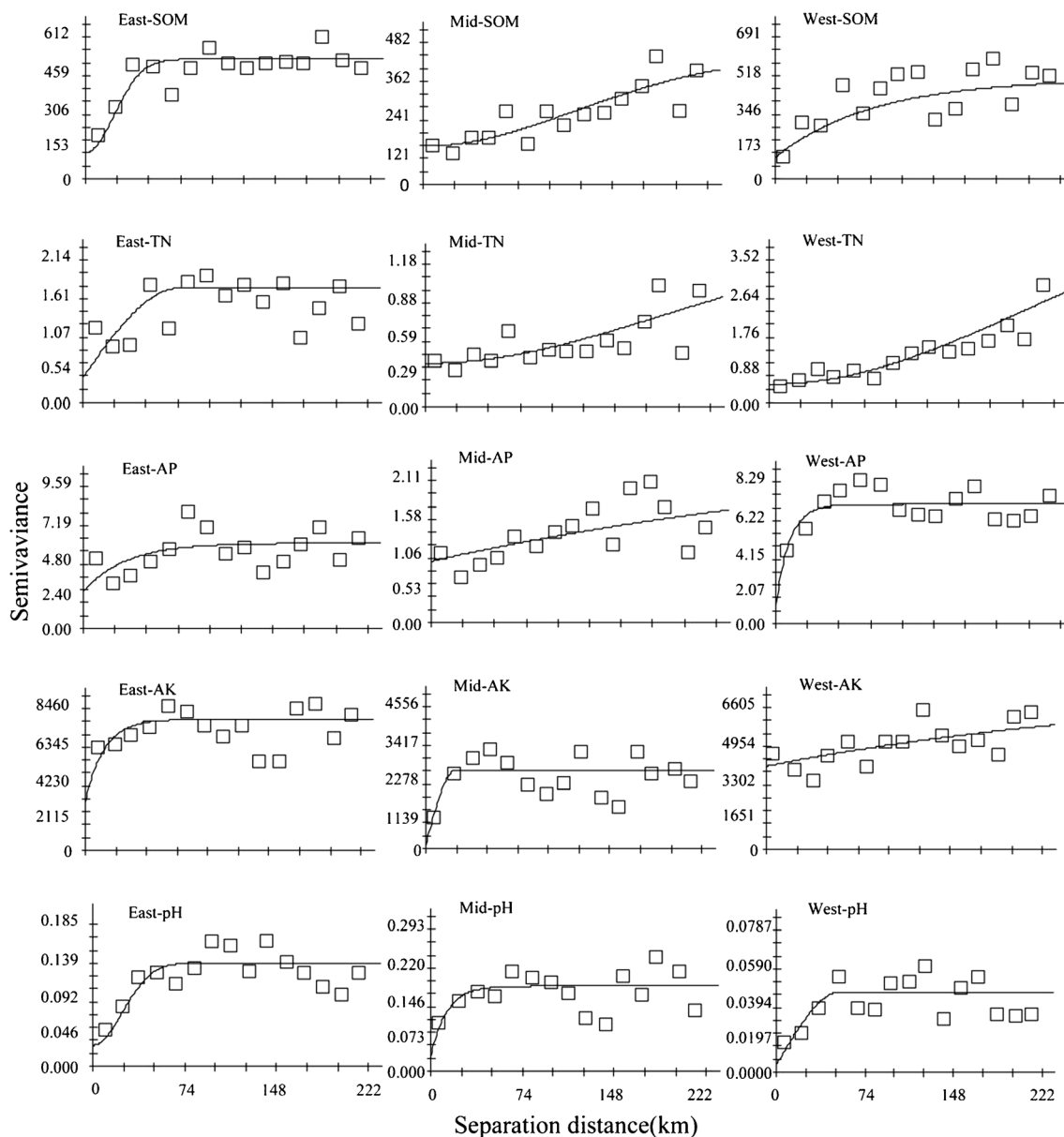


Fig. 3 Semi-variograms of the soil nutrients in the investigated area

value, which showed a weak variation, all other nutrient factors showed a medium or strong variation. According to the degree of variation, the five nutrient factors were ranked as follows: AP > SOM > AK > STN > pH. Differences exist in the soil nutrient status at different geological positions, altitude, forest types, and forest stand level. On the whole, there were differences between the sub-indexes of fertility, which could be ranked as follows:  $P_{SOM} > P_{AK} > P_{STN} > P_{pH} > P_{AP}$ . The comprehensive evaluation grade of forest soil fertility in the study area were at grade III, showing a middle level.

The geostatistical method based on GIS can better describe the spatial variation pattern of soil nutrients. The semi-variation functions for the five soil nutrient factors studied here show some spatial structure features, over a range of

23–274 km. In the eastern, central, and western regions, all the nugget-to-sill ratios of the pH value are less than 25%, indicating a strong spatial correlation. Other nutrient factors were found to have their own nugget-to-sill ratios in these regions, which ranged from 10 to 50%, suggesting a strong or medium correlation.

Geostatistics could well describe the spatial variability, and reflect the structure and randomness, correlation, and independence of soil nutrients. At the same time, it could reflect the variation characteristics of soil nutrient content in a certain range of the study area. In conclusion, it could be observed that the distribution of soil nutrients in the entire research area was the result of the combined action of soil-forming process, geographic location, elevations, vegetation type, year of the



forest, and the human activities affected the soil nutrients in the research area which are highly complicated. Changes in the spatial distribution of soil properties could exacerbate the vulnerability of the ecosystem and accelerate its deterioration. Therefore, based on this research area, we would develop more targeted research plans about soil nutrients of forest in the next time. Great emphasis should be placed on finding a balance between protecting and exploring the area.

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