Analysis of Spatial Variation Characteristics of Soil Nutrients and Evaluation of Soil Fertility in Small-scale Mountain Tea Gardens

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Abstract [**Objectives**] To elucidate the spatial variation characteristics and fertility status of soil nutrients in small-scale mountain tea gardens and to inform precise fertilization and nutrient management practices in these tea gardens. [**Methods**] Based on soil nutrient data collected from 72 sampling points in the tea garden in 2021, which covers an area of approximately 2.4 km^2, the spatial variation characteristics were analyzed using geostatistical methods. Spatial distribution maps of soil pH, total nitrogen, available phosphorus, and available potassium were generated employing the ordinary Kriging interpolation method in Surfer 23 software. Furthermore, a quantitative assessment of soil fertility was performed utilizing the fuzzy comprehensive evaluation method. [**Results**] The majority of the soil in the tea garden was acidic. The average values for pH, organic matter, total nitrogen, available phosphorus, and available potassium were 4.66, 14.4 g/kg, 0.9 g/kg, 6.2 mg/kg, and 78.1 mg/kg, respectively. The pH exhibited the lowest coefficient of variation at 12.85%, indicating low variability. The coefficients of variation for organic matter, total nitrogen, and available potassium ranged from 31.94% to 49.88%, reflecting moderate variability. In contrast, the coefficient of variation for available phosphorus was 243.41%, indicating high variability. The distribution of soil pH and available phosphorus in the study area was relatively uniform. In contrast, total nitrogen content exhibited a spatial pattern characterized by higher concentrations in the western region and lower concentrations in the eastern region. Organic matter content displayed a spatial distribution pattern with lower values centrally and higher values along the periphery. The distribution of available potassium content was marked by several pronounced "elevations" and "depressions", with notably lower levels observed in the northeastern region of the garden. Total nitrogen and organic matter were the most significant contributors to the integrated fertility index (I_{IFI}), each with a weight value of 0.29, whereas pH had the lowest weight value of 0.14. The proportions of tea garden soils categorized under I_{IFI} grades I to V were 0.26%, 69.55%, 25.89%, 4.30%, and 0.002 2%, respectively. [**Conclusions**] It is recommended that the application of phosphorus fertilizer should be reduced in the study area, whereas the use of potassium fertilizer should be increased in the northeastern region. Additionally, the incorporation of organic and nitrogen fertilizers is advised to improve the soil's capacity for water and nutrient retention.

Key words Tea garden, Soil nutrient, Spatial variation, Fertility evaluation

0 Introduction

Tea is a significant cash crop in China and plays a crucial role in the adjustment of the rural industrial structure as well as in rural revitalization. Chongqing is the principal tea-producing region in Southwest China and is recognized as an important origin of high-quality green tea in China. The 14th *Five-Year Plan for the Development of Agricultural Economic Crops in Chongqing* (2021 – 2025) explicitly outlines the establishment of a nationally recognized early-market, high-quality tea industry belt in the western region of Chongqing. Soil nutrients play a crucial role in influencing the growth of tea plants, as well as the quality and yield of tea leaves[1 – 2]. Nitrogen facilitates the development of tea plant roots and improves photosynthetic efficiency. Phosphorus and potassium are crucial for the structural formation of tea plants and contribute to an increased concentration of tea polyphenols. Soil pH influences the distribution and diversity of microbial communities in tea gardens, thereby directly impacting the flavor and quality of tea. Therefore, conducting soil fertility evaluation in tea gardens enables timely evaluation of soil fertility status and provides a foundation for diagnosing nutrient surpluses or deficiencies, thereby facilitating the implementation of scientific fertilization practices in tea cultivation[3]. Chongqing possesses a humid climate and favorable natural conditions, establishing it as a principal region for the production of high-quality tea. Nevertheless, its distinctive geographical features, soil parent material, and ecological climate contribute to pronounced spatial variability in soil nutrient content in tea gardens. The physical and chemical properties of the soil vary according to spatial location and terrain, leading to substantial differences in tea yield and quality across different areas in the same tea garden. Consequently, elucidating the spatial distribution and spatiotemporal variation of soil nutrients in tea gardens is critically important for the effective nutrient zoning and management of these plantations.

In recent years, the application of geostatistics, geographic information technology (GGIS), and mathematical statistical methods to investigate the spatiotemporal variation of soil nutrients and to assess soil fertility has remained a prominent research focus both domestically and internationally[4 – 6]. Suo Yanyan *et al.*[7] examined the distribution and variation characteristics of soil nutri-

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ents prior to planting and during the maturity stage of peanuts in the lime concretion black soil region, thereby providing a scientific foundation for fertilization management in peanut cultivation in this area. Wang Youqi *et al*.[8] focused on sandy field soil in Ningxia as their research subject and developed a soil nutrient and fertility quality evaluation system for sandy fields by integrating spatial variation characteristics with soil fertility index. Guo Yingxin *et al*.[9] investigated the spatiotemporal variation characteristics and regional distribution patterns of soil nutrients in tobacco-cultivated soils in the Erhai Basin, employing the fuzzy comprehensive evaluation method to quantitatively assess soil fertility. Chen *et al*.[10] employed the fuzzy comprehensive evaluation method to calculate the integrated soil fertility index of Jianli City, Hubei Province, and concluded that variations in planting systems, fertilization practices, and the reduction of acid rain were significant factors influencing changes in soil properties and soil fertility in the city. The aforementioned studies demonstrate that geostatistical and GIS methods have been extensively utilized to assess the spatial variability and fertility of soil nutrients in field crops, orchards, and tobacco leaf cultivation at large and medium scales[11-13]. However, their application in small-scale tea gardens remains relatively limited. Furthermore, there are no universally established standards for soil fertility evaluation methods, including principal component analysis, fuzzy mathematics, and grey relational degree, both domestically and internationally[14-16]. Therefore, it is essential to select appropriate evaluation methods according to the specific soil types. This study focused on the mountain tea gardens located in the western region of Chongqing. It employed geostatistical techniques and the fuzzy comprehensive evaluation method to analyze the spatial variability of various soil fertility indicators in the tea garden. Additionally, the study generated spatial distribution maps of nutrient levels and quantitatively assessed soil fertility. The findings aim to provide technical support for precise fertilization and efficient nutrient management in small-scale mountain tea gardens.

1 Materials and methods

1.1 Overview of the study area The study area is situated within the Yongchuan Tea Mountain and Bamboo Sea Ecological Tea Garden, Chongqing City (105°89′ – 105°90′ E, 29°38′ – 29°38′ N). This tea garden is located on the northern bank of the upper Yangtze River, in the western region of Chongqing. It encompasses an area of approximately 2.4 km^2 and is positioned at an altitude of 684.8 m. The region experiences a typical subtropical monsoon humid climate, characterized by an annual average temperature of 17.7 ℃, a maximum temperature of 42.1 ℃, a minimum temperature of –2.9 ℃, and an average annual precipitation of approximately 1 015 mm. The average total annual sunshine duration is around 1 218.7 h, and the frost-free period averages about 317 d. The climate is marked by warm winters, hot summers, four distinct seasons, and abundant precipitation. The tea tree variety cultivated is 'Fuding Dabai'. The soil in the tea garden primarily consists of typical paddy soil and red loam, with a soil layer thickness ranging from 30 to 100 cm and a pH between 5.2 and 6.7. The soil is rich in organic matter and exhibits relatively high fertility. Compound fertilizers are typically applied in middle March, late May, middle September, and late October each year.

1.2 Sample collection and determination In March 2021, soil samples were collected from the tea garden according to the planting conditions of the tea trees and the soil types. A total of 72 soil samples, taken from depths ranging between 0 and 30 cm, were obtained using a five-point sampling method (Fig. 1). Additionally, a GPS device was employed to record the precise location of each sampling point, including longitude, latitude, and altitude. At each sampling point, a composite soil sample weighing between 2.0 and 3.0 kg was collected. Subsequently, 1.0 kg of this soil sample was transported to the laboratory using the quartering method. Following air-drying, removal of impurities, grinding, and sieving, the samples were subjected to analysis and determination. Soil pH was measured using the glass electrode method with a soil-to-water ratio of 1 : 2.5[17]. Soil organic matter content was determined via the potassium dichromate volumetric method[17]. Total nitrogen content in the soil was assessed using the Kjeldahl method[17]. Available potassium content was quantified by flame photometry[17], while available phosphorus content was measured using the extraction-molybdenum antimony anti-colorimetric method, adjusted according to soil pH[17].

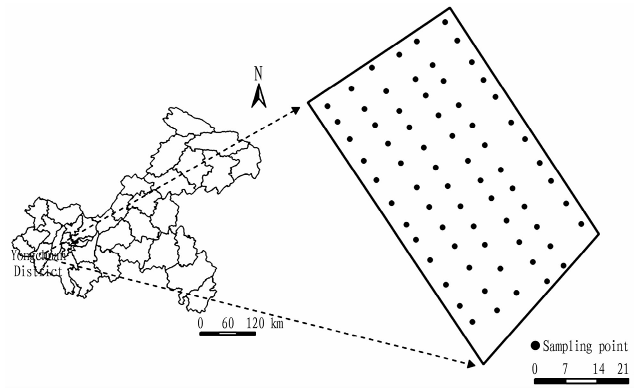


Fig. 1 Distribution of soil sampling points in the tea garden

1.3 Data statistical analysis Normality tests and correlation coefficient calculations were performed using SPSS 27.0. The optimal semivariance function and its parameters were determined with GS +9.0 software. Spatial interpolation and the generation of distribution maps for soil fertility indicators were conducted using Surfer 23, and the spatial distribution map for soil fertility classification was created using ArcGIS 10.8.

1.4 Evaluation methods for soil fertility in the tea garden

1.4.1 Membership degree of soil nutrient fertility evaluation indicators. The fuzzy comprehensive evaluation method was employed to quantify soil nutrient fertility. Five indicators, including pH, organic matter, total nitrogen, available phosphorus, and available potassium, were selected as evaluation factors for the integrated fertility index (I_{IFI}) of tea garden soil fertility. Membership degree is a fundamental concept in fuzzy logic. The membership function maps the values of various soil fertility indicators to a range between 0 and 1, thereby yielding the corresponding membership values. Membership functions are categorized into S-type and parabolic type. Specifically, available phosphorus and available potassium correspond to the S-type, whereas pH, organic matter, and total nitrogen correspond to the parabolic type[18]. The functional expressions are provided as follows.

S-type membership function:

$$f(x)=\begin{cases}0.1, & x\leqslant x_1\\ 0.1+0.9\ (x-x_1)/(x_2-x_1), & x_1<x<x_2\\ 1.0 & x\geqslant x_2\end{cases} \quad (1)$$

Parabolic membership function:

$$f(x)=\begin{cases}0.1, & x\leqslant x_1,\ x\geqslant x_4\\ 0.1+0.9\ (x-x_1)/(x_2-x_1), & x_1<x<x_2\\ 1.0, & x_2\leqslant x\leqslant x_3\\ 0.1-0.9\ (x-x_3)/(x_4-x_3) & x_3\leqslant x\leqslant x_4\end{cases} \quad (2)$$

In the formula, x represents the measured values of soil fertility indicators, while x_1, x_2, x_3, and x_4 denote the membership thresholds for each respective soil fertility indicator (Table 1).

1.4.2 Weight of integrated soil fertility evaluation indicators. The weight coefficient is a critical parameter in the evaluation of soil fertility, addressing the limitations of incomplete weighting inherent in traditional evaluation methods. Commonly employed calculation techniques include the entropy method, principal component analysis, and the correlation coefficient method. In this study, the correlation coefficient method was utilized to determine the weight coefficients. Initially, the correlation coefficients among the various indicators were computed to ascertain each indicator's contribution to the overall objective. Subsequently, appropriate weight values were assigned to each indicator based on these contributions.

1.4.3 Integrated fertility index (I_{IFI}). The I_{IFI} of soil can be determined by utilizing the membership degree value and the weight value. The I_{IFI} ranges between 0 and 1 ($0\leqslant I_{IFI}\leqslant 1$), and its calculation is expressed by the following formula:

$$IFI_i=\sum_{i=1}^{m}W_{ij}N_{ij}\ (i=1,2,\cdots,n;\ j=1,2,\cdots,m) \quad (3)$$

where W_{ij} denotes the weight value of the j-th indicator in the i-th sample; N_{ij} denotes the membership degree value of the j-th indicator in the i-th sample; n represents the total number of soil samples; and m represents the total number of soil fertility indicators.

Table 1 Membership thresholds for soil fertility indicators

Membership threshold	pH	Organic matter//g/kg	Total nitrogen//g/kg	Available phosphorus//mg/kg	Available potassium//mg/kg
x_1	5.0	6	0.50	3	30
x_2	5.5	10	0.75	40	200
x_3	7.0	25	1.25	–	–
x_4	7.5	40	2.00	–	–

1.4.4 Integrated soil fertility classification. According to the soil fertility classification standards recommended by the Second National Soil Census and based on the tea garden soil fertility classification method proposed by Lin Shaoxia *et al.* [19], this study categorized the soil fertility of the tea garden into five grades, as presented in Table 2.

Table 2 Classification standards for soil fertility in the tea garden

Fertility evaluation indicator	Fertility grade	Fertility level
$0.8<I_{IFI}\leqslant 1$	I	Excellent
$0.6<I_{IFI}\leqslant 0.8$	II	Good
$0.4<I_{IFI}\leqslant 0.6$	III	Average
$0.2<I_{IFI}\leqslant 0.4$	IV	Below average
$0<I_{IFI}\leqslant 0.2$	V	Bad

2 Results and analysis

2.1 Statistical analysis of soil fertility indicators in the tea garden As shown in Table 3, the average pH of the tea garden soil was 4.66, indicating acidic conditions. The coefficient of variation for pH was 12.85%, reflecting low variability. In contrast, the coefficients of variation for soil fertility indicators, including organic matter, total nitrogen, and available potassium, ranged from 31.94% to 49.88%, representing moderate variability. Notably, the coefficient of variation for soil available phosphorus was 243.41%, indicating strong variability. Skewness and kurtosis are commonly utilized statistical measures that describe the asymmetry and peakedness of data distributions, respectively. The distribution of available potassium, an indicator of soil fertility, exhibited negative skewness, indicating a left-skewed distribution. In contrast, the other fertility indicators demonstrated positive skewness, reflecting right-skewed distributions. The normal distribution of each indicator was assessed using the Kolmogorov – Smirnov (K – S) test. Organic matter conformed to a normal distribution. Total nitrogen, available phosphorus, and available potassium were subjected to logarithmic transformation to approximate a normal distribution, while pH was transformed using the Box – Cox method to achieve normality.

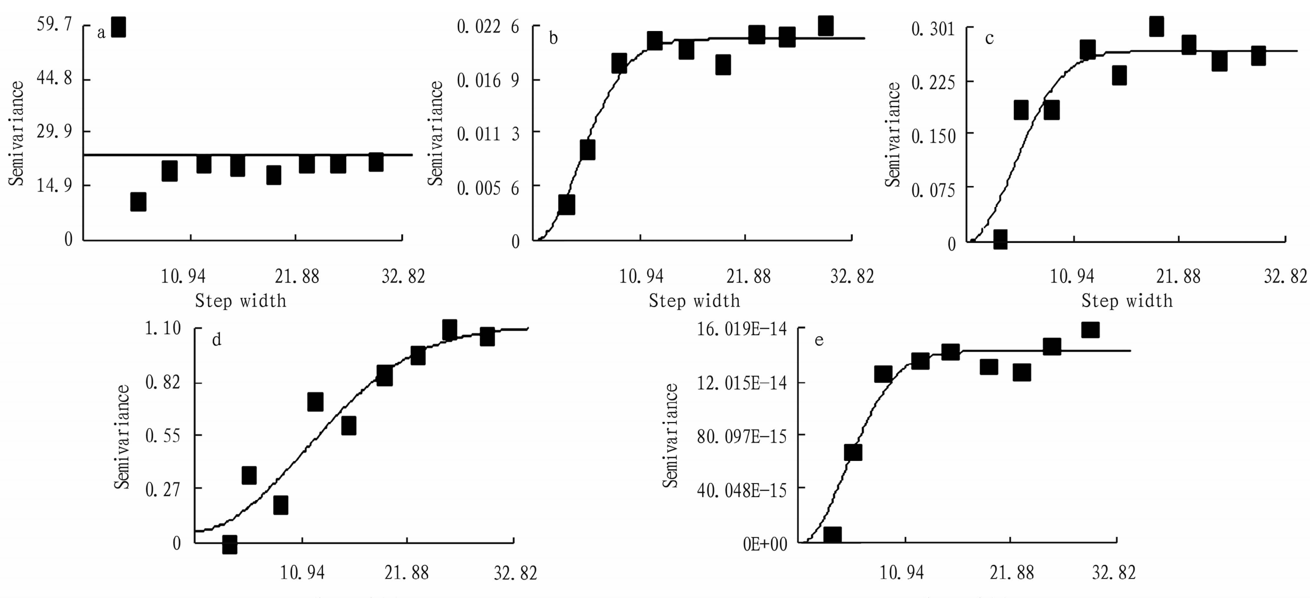
2.2 Spatial variation characteristics of soil fertility indicators in tea gardens Using GS + 9.0 software, model fitting was conducted for soil fertility indicators in the tea garden, resulting in the calculation of the optimal semivariance function and its parameters (Table 4 and Fig. 2). According to the principle that a higher coefficient of determination (R^2) and a lower residual sum of squares (RSS) signify a better model fit, Table 4 demonstrates that the optimal semivariance function for organic matter corresponds to the exponential model, whereas total nitrogen, available phosphorus, available potassium, and pH correspond to the Gaussian model. Among these, total nitrogen exhibited the highest coefficient of determination at 0.955, indicating the best model fit. Randomness and structure are two fundamental characteristics that describe the spatial variability of soil nutrients. Randomness pertains to the uncertainty and unpredictability in nutrient distribution, which is mainly influenced by human activities, biological processes, and inherent natural variability. In contrast, structure refers to the organized and patterned aspects of soil nutrient distribution, typically governed by factors such as topography, parent material, and vegetation type. Nugget-to-sill ratio indicates the extent of spatial autocorrelation in system variables. Cambardella *et al.* [20] categorized nugget-to-sill ratios into three groups: < 25%, 25% – 75%, and > 75%, corresponding to strong, moderate, and weak spatial autocorrelation, respectively. At the small-scale level, the nugget-to-sill ratio for total nitrogen, available phosphorus, available potassium, and pH in the tea garden were all below 25%, indicating that these fertility indicators are predominantly influenced by soil structural factors, including parent material, climate, and topography, and exhibit strong spatial autocorrelation. In contrast, the nugget-to-sill ratio for organic matter was 100%, demonstrating weak spatial autocorrelation, with its spatial variation being significantly affected by human factors.

Table 3 Descriptive statistics of soil fertility indicators in tea gardens

Fertility indicator	Sample size	Minimum value	Maximum value	Average value	Standard deviation	Skewness	Kurtosis	Coefficient of variation//%	*P* value for K – S test
pH	72	4.15	7.07	4.66	0.59	2.57	6.86	12.85	0.20
Organic matter	72	4.49	27.9	14.36	4.59	0.51	0.76	31.94	0.90
Total nitrogen	72	0.38	1.89	0.90	0.31	1.05	1.62	34.11	0.31
Available phosphorus	72	0.30	124.40	6.21	15.11	0.50	0.14	243.41	0.069
Available potassium	72	22.00	197.00	78.11	38.96	–0.038	–0.40	49.88	0.89

Table 4 Semivariance function model and parameters of soil fertility indicators in the tea garden

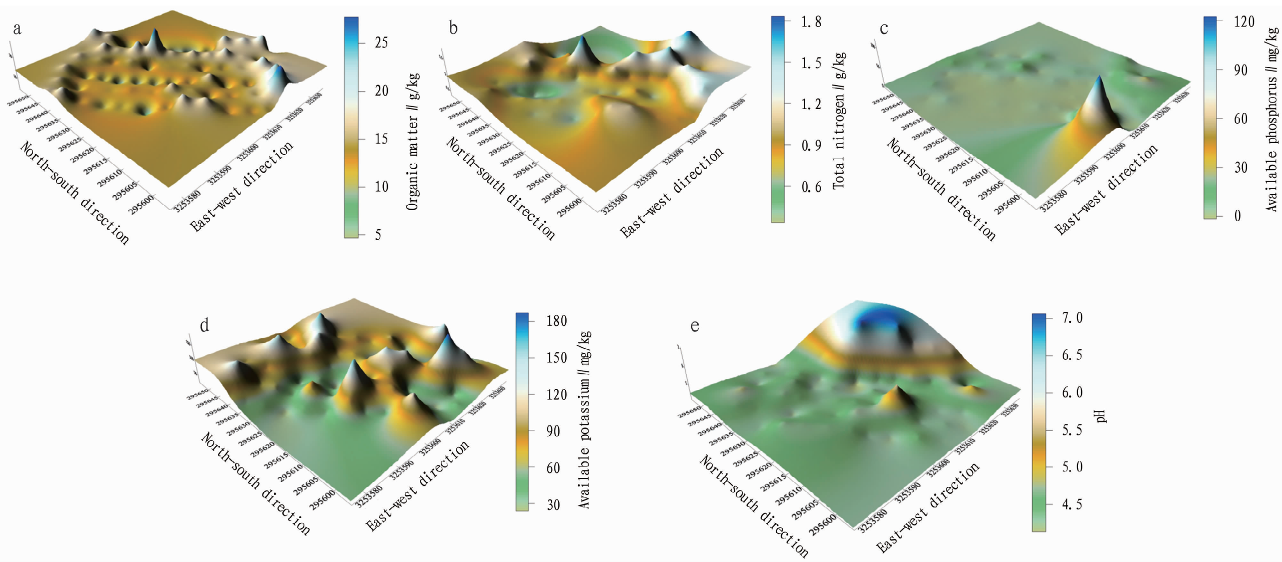
Fertility indicator	Theoretical model	Nugget (C_0)	Sill (C_0+C)	Nugget-to-sill ratio (C_0/C_0+C)//%	Range//m	Residual sum of squares (*RSS*)	Coefficient of determination (R^2)
pH	Gaussian model	1.00×10^{-16}	1.432×10^{-12}	0.069	12.176 3	1.438×10^{-27}	0.938
Organic matter	Exponential model	24.319 5	24.319 5	100.00	30.059 8	1 500	0.119
Total nitrogen	Gaussian model	0.000 01	0.021 1	0.047	11.777 9	1.534×10^{-5}	0.955
Available phosphorus	Gaussian model	0.000 1	0.266 2	0.038	12.003 1	0.010	0.851
Available potassium	Gaussian model	0.067	1.114	6.01	27.678 2	0.112	0.909



NOTE a. Organic matter; b. Total nitrogen; c. Available phosphorus; d. Available potassium; e. pH.

Fig. 2 Semivariance function of soil fertility indicators in the tea garden

2.3 Spatial distribution pattern of soil fertility indicators in the tea garden The spatial distribution patterns of soil fertility indicators in the tea garden effectively illustrate their spatial variability. Utilizing the optimal semivariance function model and corresponding parameters, spatial distribution maps of soil pH, total nitrogen, available phosphorus, and available potassium were generated through the ordinary Kriging interpolation method in Surfer 23 software. Given that organic matter exhibited no spatial autocorrelation, the inverse distance weighting method was employed for its interpolation analysis[21]. As illustrated in Fig. 3, the pH levels in the tea garden decreased progressively from the southwest to the northeast. Approximately 3/4 of the total area exhibited pH values below 5, indicating that the soil is predominantly acidic. The distribution of available phosphorus in the tea garden soil was relatively uniform, with only a small area in the northern region showing available phosphorus concentrations exceeding 90 mg/kg. Total nitrogen content demonstrated a distinct spatial pattern, with higher concentrations in the southwest (exceeding 1.6 g/kg) and lower concentrations in the northeast (below 0.6 g/kg), reflecting significant regional variability. The spatial distribution of soil organic matter content in the tea garden demonstrated a pattern characterized by lower values centrally and higher values along the periphery. The highest concentrations, observed at the northwest high-content points, exceeded 20 g/kg. The distribution of available potassium in tea garden soils exhibited distinct areas of "elevation" and "depression" at multiple locations, with relatively low available potassium content noted in the northeastern region of the garden. The results demonstrate that the spatial distribution of various fertility indicators in small-scale tea garden soil exhibits limited regularity. This finding suggests that soil properties in the tea garden are highly susceptible to influences from agricultural management practices, including fertilization and irrigation.



NOTE a. Organic matter; b. Total nitrogen; c. Available phosphorus; d. Available potassium; e. pH.

Fig. 3 Spatial distribution of soil fertility indicators in the tea garden

2.4 Comprehensive evaluation of soil fertility in the tea garden

2.4.1 Weight calculation of soil fertility indicators in the tea garden. Pearson correlation analysis of soil fertility indicators in the tea garden was performed using Origin 2021 software, with the results presented in Table 5. As indicated in Table 5, all soil fertility indicators demonstrated positive correlations with one another, except for organic matter and pH, as well as total nitrogen and pH, which exhibited negative correlations. Among the variables examined, organic matter demonstrated a highly significant correlation with total nitrogen, evidenced by a correlation coefficient of 0.79. In contrast, available phosphorus exhibited the weakest correlation with pH, with a correlation coefficient of merely 0.023.

Table 5 Correlation coefficients and weight values of soil fertility indicators in the tea garden

Indicator	Organic matter	Total nitrogen	Available phosphorus	Available potassium	pH
Organic matter	1.000				
Total nitrogen	0.790**	1.000			
Available phosphorus	0.120	0.170	1.000		
Available potassium	0.180	0.200	0.230*	1.000	
pH	−0.260*	−0.170	0.023	0.190	1.000
Average value	0.338	0.333	0.136	0.200	0.161
Weight coefficient	0.290	0.290	0.120	0.170	0.140

NOTE ** denotes a statistically significant correlation at the 0.01 level; * denotes a statistically significant correlation at the 0.05 level.

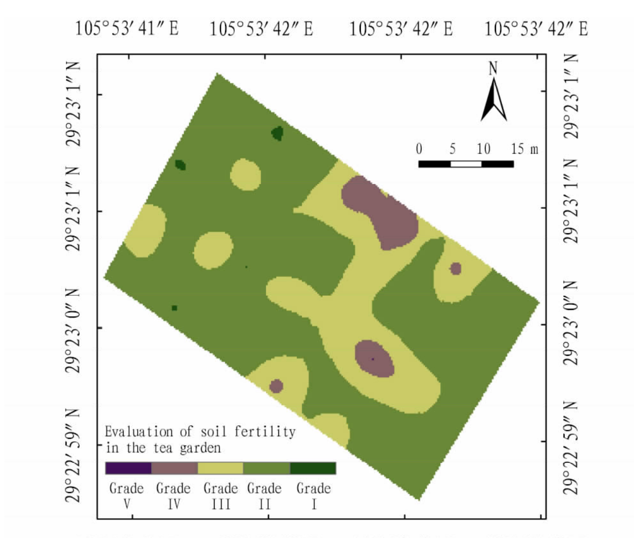


Fig. 4 Spatial distribution of soil fertility grades in the tea garden

Weight values are essential parameters for assessing soil fertility, and the correlation coefficient method was utilized to calculate the indicator weight[22]. As presented in Table 5, organic matter and total nitrogen had the highest weight coefficients, each at 0.29, whereas available phosphorus had the lowest weight coefficient.

2.4.2 Comprehensive evaluation of soil fertility in the tea garden. To quantitatively assess the soil fertility of the tea garden, the fuzzy comprehensive evaluation method was utilized to determine the I_{IFI} value. Within the evaluated regions, soils classified as grade II and grade III fertility constituted 69.55% and 25.89% of the total area, respectively. Soils categorized as grade I were scarce, comprising only 0.26% of the total area. To further elucidate the spatial variation in soil I_{IFI} distribution, Kriging interpolation was utilized to produce a spatial distribution map of soil classification (Fig. 4). As depicted in Fig. 4, the majority of tea garden soils were classified as grade II fertility. Grade I, representing high-quality soils, appeared sporadically in the northern region, whereas grade III and lower-quality soils were primarily distributed in patchy areas toward the northeast of the tea garden.

3 Discussion

Investigating the spatial variability of soil properties offers a scientific foundation for the precise management of nutrients in tea gardens[23]. This study, focusing on the soil characteristics and growth traits of tea plants in mountainous tea gardens, selected five soil nutrient indicators for analysis: pH, organic matter, total nitrogen, available phosphorus, and available potassium. Soil acidity significantly influences microbial activity as well as the decomposition of minerals and organic matter. The study area demonstrated generally low soil pH levels, which can be attributed primarily to the prolonged use of chemical fertilizers in the tea garden. Following the uptake of NH_4^+ from fertilizers by tea plants, the remaining acid anions combined with H^+ ions, resulting in soil acidification in the tea gardens. This observation aligns with findings reported in previous studies[24-27]. However, the spatial distribution of soil fertility revealed that the soil pH in the southwestern region of the tea garden was neutral. This phenomenon may be attributed to the topographical characteristics of the mountainous tea garden, as this area is characterized by low-lying terrain with poor drainage, making it susceptible to waterlogging. Evaporation of water contributes to the formation of saline-alkali patches on the soil surface, which elevates pH levels and adversely affects the enzymatic systems of tea tree roots. Besides, the soil structure in the tea garden deteriorates, thereby hindering root penetration. The installation of drip irrigation systems is therefore recommended to mitigate these issues. The coefficient of variation for available phosphorus in the soil of the study area was 243.41%, markedly exceeding that of other soil fertility indicators. This elevated variability may be attributed to the chemical characteristics of phosphorus fertilizers. Wang Jie[28] reported that the available phosphorus content in soil exhibits substantial variability, as soluble ions in fertilizers migrate under the influence of water, facilitating the movement of phosphate ions with water flow. He Junqi *et al.*[29] reported that organic matter, total nitrogen, available phosphorus, and available potassium demonstrated moderate spatial autocorrelation in farmland soils. Similarly, Zhao Yue *et al.*[30] identified that the spatial variation of these soil properties in lotus-cultivated soils was attributable to structural factors. Significant differences in spatial autocorrelation were observed among various indicators in the study area. Organic matter demonstrated a nugget-to-sill ratio of 100%, indicating that its variability is predominantly governed by random factors. Conversely, the spatial variation of total nitrogen, available phosphorus, and available potassium was influenced by structural factors. These findings suggest disparities in nutrient utilization efficiency between tea plants and other crops, which may be associated with tea garden management practices, including uneven fertilization and tillage disturbances. The spatial distribution patterns of organic matter, total nitrogen, available potassium, and available phosphorus in the tea garden were found to be inconsistent. Available phosphorus demonstrated a relatively uniform distribution, whereas the other three soil nutrient indicators exhibited irregular, patchy patterns. This variability is primarily attributed to traditional fertilization practices that do not consider the differing nutrient requirements of tea plants at various growth stages, leading to indiscriminate fertilization and irrigation and consequently significant spatial disparities in soil fertility. Additionally, the distinctive topography of Chongqing's hilly and mountainous terrain exacerbates soil erosion and promotes the redistribution of base ions, thereby intensifying the spatial heterogeneity of soil nutrients.

Soil fertility refers to a soil's ability to provide essential nutrients required for the growth of tea plants, thereby directly affecting both tea quality and yield[31]. Based on the I_{IFI} classification, the majority of soils in the tea garden were categorized as grade II fertility, signifying good soil quality. Nevertheless, soils located in the central and northeastern regions of the tea garden were classified as grades III and IV fertility, indicating an uneven distribution of nutrients. This disparity is likely attributable to the lack of soil testing and the absence of precision fertilization methods in the management of the tea garden. Wang Yanfei *et al.*[32] reported comparable findings in their investigation of soil fertility in Anxi tea garden. Their analysis of weighting values for soil fertility indicators identified soil organic matter content and total nitrogen as the principal factors constraining soil fertility. This outcome is largely attributed to the application of organic fertilizers, which markedly decreases soil bulk density, enhances porosity, and facilitates the formation of soil aggregates. Xu Yan *et al.*[33] reported that soil organic matter in the tea garden contributes to maintaining stable soil fertility and prevents the excessive growth of tea plants. Total nitrogen facilitates the mineralization and decomposition of organic nitrogen, resulting in the release of ammonium and nitrate forms of nitrogen that are available for plant uptake, thereby enhancing the soil's nitrogen supply capacity. Furthermore, Xu Yawen *et al.*[34] demonstrated that prolonged omission of nitrogen fertilization in the tea garden leads to soil fertility depletion, which directly diminishes metabolic processes in tea plants associated with quality. Wu Hao *et al.*[35] propose that the appropriate application of nitrogen fertilizer enhances the competitive advantage of tea plants over other crops in terms of photosynthesis and physiological processes. Additionally, total nitrogen content is closely associated with organic matter. Song Yang[36] observed that variations in soil total nitrogen primarily depend on the relative rates of organic matter decomposition and accumulation. Consequently, considering the soil fertility characteristics of mountain tea gardens, it is advisable to reduce phosphorus fertilizer application, increase potassium fertilizer application in the northeastern region, and concurrently enhance the use of organic and nitrogen fertilizers to improve the water and nutrient retention capacity of tea garden soils.

4 Conclusions

(i) Soils in mountain tea gardens generally display acidic properties, with moderate variability observed in organic matter, total nitrogen, and available potassium, whereas available phosphorus demonstrates high variability. The Gaussian semivariance model best fits pH, total nitrogen, available phosphorus, and available potassium, while the exponential model is most appropriate for organic matter.

(ii) The spatial variability of total nitrogen, available phosphorus, available potassium, and pH in the study area is predominantly governed by natural factors, whereas organic matter content is chiefly influenced by human activities. Soil nutrients in tea gardens display non-uniform spatial distribution, and soil physicochemical properties are substantially regulated by agricultural management practices, including fertilization and irrigation.

(iii) Among the indicators of soil fertility in the tea garden, organic matter and total nitrogen possess the highest weight values and contribute most substantially to the I_{IFI}, whereas available phosphorus exhibits the lowest weight value. The soils in the study area are predominantly classified as grade II and grade III fertility, with soils of grade II fertility encompassing 69.55% of the total region. Soils of grade III fertility are primarily located in the central and northeastern areas, constituting 25.89% of the region.

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