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Spatial Heterogeneity of Selected Soil Nutrients Related to *Torreya grandis* cv. *Merrillii* Plantation in Southeastern China

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ABSTRACT

Chinese *Torreya grandis* (*Torreya grandis* cv. *Merrillii*) is a unique economic tree species in China. Intensive management related to application of chemical fertilizer and herbicides caused serious soil quality degradation of Chinese *Torreya grandis* plantations. Totally, 120 soil samples were collected from the main disbtributed areas of Chinese *Torreya grandis* in Southeastern China. In this area, soil pH values varied from 3.68 to 6.78, with a median value of 4.91, implying a trend of acidification. The average concentrations of organic matter, available nitrogen, available phosphorus and available potassium were 27.52 g kg^{-1}, 135.77 mg kg^{-1}, 15.12 mg kg^{-1}, and 153.43 mg kg^{-1}, respectively. The results of spatial analysis revealed that target variables had clear spatial patterns. The soil fertility was relevantly high in most of the study area, with soil nutrient imbalances existing. The stand age had a large effect on soil properties, which were also mainly influenced by human activities. Therefore, it is necessary to change the fertilization method for a sustainable management of *Torreya grandis* plantation.

KEYWORDS

Torreya grandis cv. *Merrillii*; soil nutrients; geostatistics; Moran's I; evaluation for soil fertility

1 Introduction

Soil provides essential nutrients for plant growth, also makes a vital contribution to human life activities and the balance of the ecosystem [1]. Therefore, soil quality directly affects the biological diversity and the quality of crops. Improper human management measures such as over-application of fertilizer have led to the uneven distribution of soil nutrients at different regional scales, thus causing degradation of soil quality [2]. Soil degradation could cause a series of changes in crop growth, such as affecting the growth process of crops, which is mainly reflected by the crop yield decrease due to uneven distribution of nutrients. Soil fertility is the core foundation and essential characteristics of soil quality, which is closely related to soil nutrients, and has a strong impact on crop yield, fertilizer input, cultivation methods and natural environment [3]. Soil fertility directly affects crop growth, yield and quality of agricultural products [4]. Scientific and reasonable soil fertility assessment is the key to manage soil changes in the field, which is of great significance to guide the fertilization of farmland, maintain soil health and improve

environmental quality [3–5]. Moreover, it is conducive to the optimization and sustainable development of agricultural ecosystem [4,6].

Different environmental conditions, management measures and fertilizer requirements of crops can affect the distribution of soil nutrients, while uneven distribution of soil nutrients will significantly affect the growth of crops. In order to achieve the high yield of crops, it is often necessary to test the soil nutrient status, usually including the determination of organic matter (OM), pH, total nitrogen (TN), available phosphorus (AP), available potassium (AK), etc., which then could be used to guide the fertilization and a series of management measures [7]. Soil OM can promote soil physical and chemical properties while providing the necessary nutrients for crop growth and the suitable environment. pH can affect the effectiveness of nutrient elements in soil. Soil nitrogen levels can reflect crop yield and quality. Available phosphorus (AP) and available potassium (AK) can be absorbed by plants directly. Uneven distribution of nutrients will hinder the synthesis of crop and energy, decrease the yield, lead to frequent occurrence of diseases and insect pests, etc. Therefore, it is of importance to understand the distribution pattern of soil nutrients to provide effective measures for soil improvement [1].

Economic forest industry can bring ecological benefit, economic benefit and social benefit to agricultural development. Harvesting and utilization of economic forests is less ecologically destructive than timber harvesting and can therefore be an important component of sustainable forest management for their ecosystem services [8,9]. Economic forest have the potential to alleviate poverty and protect nature in many protected areas around the world because of the renewable ability, which can increase rural income while reducing the impact on forest structure [8,10,11]. Currently, effective spatial auto-correlation methods such as geostatistics and Moran's I are popular in revealing the spatial patterns of environmental variables [12]. In recent decades, most of the research on the spatial heterogeneity of soil nutrients has focused on farmland and grasslands [13], but few in-depth analyses are carried out on nutrient distribution patterns and evaluation of integrated soil fertility of economic forests. Fu et al. [14] studied the spatial heterogeneity of nutrients in grassland soils in Ireland which provided the basis for a variable rate fertilization model. Ma et al. [15] revealed the spatial variability of soil nutrients in the grasslands along the Kunes River in Xinjiang, China, indicating that the improvement of soil organic matter in the region through changes in land use and agricultural practices will benefit grassland protection.

Torreya grandis cv. *Merrillii*, an evergreen plant of the *Taxus* family, is an excellent species which is artificially bred from *Torreya grandis Fortune ex Lindley*. *Torreya grandis* is a unique economic forest species in China. *Torreya grandis* has extremely high nutritional and medicinal values, which is of great significance to human health (disease prevention and improvement of immunity). Moreover, *Torreya* nut has special fragrance and excellent taste, which is a favorite nut snack in Chinese daily life [16]. Up to date, few studies has been carried out to study the spatial distribution of soil nutrients in the *Torreya grandis* plantation. The main objectives were: (1) to clarify the spatial distribution of soil nutrients in a typical *Torreya grandis* region; (2) to discuss spatial heterogeneity and evaluation of integrated soil fertility in the *Torreya grandis* region; (3) to explore the improvement measures for soil nutrients imbalance and provide a scientific basis for site-specific fertilization.

2 Material and Methods

2.1 Study Site and Sample Collection

The study was conducted in Zhejiang Province of China (118°01′~123°10′E and 27°06′~31°11′N) (Fig. 1), which has a subtropical monsoon climate, with a mean temperature of 16.5°C, an average annual rainfall of 1490 mm and sunshine duration of 1774 h. Parent soil rocks mainly include rhyolite, tuff and rhyolite tuff, and the soil types are mainly red soil, yellow soil and yellow-red soil [17,18]. *Torreya grandis* generally grows in the alpine environment of 200–800 m above sea level, especially in the ecologically warm, humid environment with less sunshine [19]. The total planting area of *Torreya* in

Zhejiang Province has reached 48,000 ha with the annual output of 6000 t, accounting for 94% of the total national output [20]. The research samples are selected from the typical *Torreya grandis* production areas in the cities of Zhuji, Shengzhou, Keqiao and Dongyang in the Kuaiji Mountains of Zhejiang Province. *Torreya grandis* plantations in this area account for 65% of the total province's area and 80% of its output [21,22].

In 2019, 120 soil samples were collected from the *Torreya grandis* plantation including different stand age which is divided into four categories (0–10 years, 10–30 years, 30–100 years and above 100 years, respectively), using a grid of 1.0 km × 1.0 km and accurate positioning was recorded by a hand-held GPS. At the selected sample points, the surface soil samples (0~20 cm) of 5 sub-sample points were gathered and distributed according to the shape of "plum blossom" within a radius of 10 m. The samples were evenly mixed to form a soil sample with a weight of about 1 kg. At the same time, information such as site conditions, household management and *Torreya grandis* yield of *Torreya grandis* plantation was recorded.
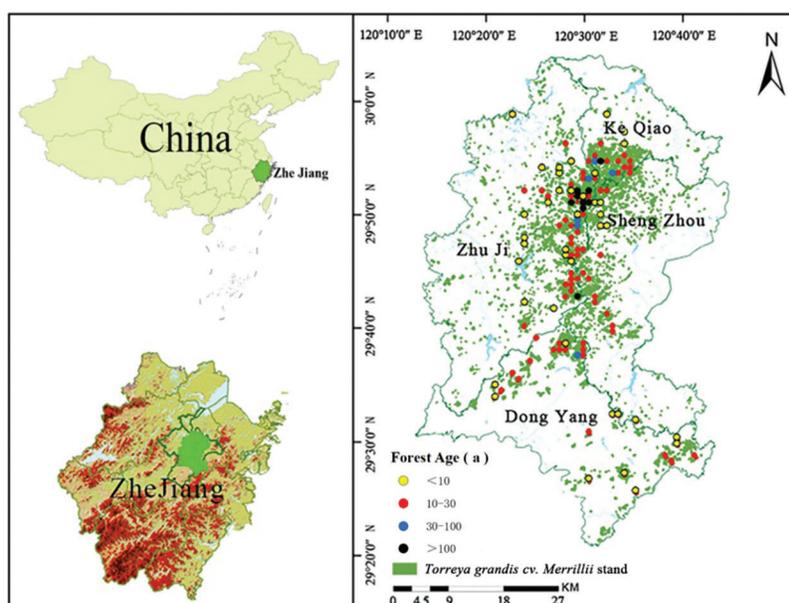
Figure 1: Soil sampling distribution map

2.2 Soil Chemical Analysis

Soil samples were pretreated following Bao's [22]. Soil pH was measured with a ratio of 1:2.5 (soil: water). Potassium dichromate oxidation method was used to determine SOM. The alkali-hydrolyzed diffusion method, Olsen method and ammonium acetate leaching-flame photometric method were taken to measure AN, AP and AK, respectively [23].

2.3 Geostatistical Analysis

The semi-variogram is popularly applied in studying spatial patterns of environmental variables, which could be found in detail in relevant references [24–28]. Moran's I index can systematically reveal the spatial autocorrelation of research variables, which usually includes global and local Moran's I [29]. Detailed description could be found in previous references [25,30,31].

2.4 Soil Fertility Evaluation Method

Based on previous research results, the above mentioned elements were selected to represent soil fertility quality, We used the membership function method to normalize the indicators, and converted each indicator

into a dimensionless value from 0.1 to 1 [32]. Due to the different effect curves of plants, the membership function is divided into S-shaped and parabolic. Combining previous studies and the fertility characteristics of forest soil [16], value of each index in the type function is shown in Table 1.

Table 1: Value of breaking point of soil indicators in parabola- and S-type membership function

Breaking point	pH (Parabolic type)	OM (g kg^{-1}) (S-type)	AN (mg kg^{-1}) (S-type)	AP (mg kg^{-1}) (S-type)	AK (mg kg^{-1}) (S-type)
x_1	4.5	10	50	2.5	50
x_2	6.5	50	150	10	100
x_3	7.5	–	–	–	–
x_4	8.5	–	–	–	–

In this study, only pH belongs to the parabolic type, and the other four indexes belong to the sigmoidal function, and the formula is as follows:

Parabolic:

$$W_i = \begin{cases} 0.9(x - x_3)/(x_4 - x_3) + 0.1 & x_3 < x \le x_4 \\ 1.0 & x_2 < x \le x_3 \\ 0.9(x - x_1)/(x_2 - x_1) + 0.1 & x_1 < x \le x_2 \\ 0.1 & x < x_1 \ or \ x > x_4 \end{cases} \quad . \tag{1}$$

Type S:

$$W_i = \begin{cases} 1.0 & x \ge x_2 \\ 0.9(x - x_1)/(x_2 - x_1) + 0.1 & x_1 \le x < x_2 \\ 0.1 & x < x_1 \end{cases} \tag{2}$$

where Wi is the membership degree of the index; x is the measured value of the index; x_1, x_2, x_3 and x_4 are the classified levels of the indicator.

The weight of soil evaluation index is determined by factor analysis method. The proportion of the common factor variance of each evaluation index is the weighted value [33]. After evaluating each index, the single-factor evaluation result needs to be converted into a comprehensive soil fertility evaluation result. The method of additive synthesis is applied to obtain the comprehensive fertility evaluation index of soil by weighting and summing the membership value of each index. The formula is as follows:

$$IFI = \sum_{i=1}^{n} WiNi \tag{3}$$

where IFI is the integrated soil fertility evaluation; W_i is the same as above; N_i is the weight value of the *i-th* soil fertility index.

2.5 Statistical Analysis

This paper uses Kolmogorov-Smirnov (K-S) to test the normality of the data set. K-S$p > 0.05$ means that the data conforms to the normal distribution, and the data that does not conform to the normality needs to be logarithmically transformed [34,35]. The analysis of variance (ANOVA) was used to test effects of forest ages on soil pH, OM, AN, AP and AK in *Torreya grandis* plantations. Duncan's multiple range test method was used for multiple comparison when a significant effect was detected ($\alpha = 0.05$). SPSS

(version 25.0, SPSS Inc., Chicago, IL, USA) and R software (version 3.3.3) were used for statistical analysis and normal distribution test on the data. The Geoda software (Gamma Design Software, Plainwell, Michigan) was used to analyze and identify spatial clusters and outliers and calculate spatial autocorrelation coefficients. All soil physical and chemical index spatial distribution maps were based on ArcGIS 10.2 software (ESRI, Redlands, CA, USA).

3 Results

3.1 Descriptive Analysis of Soil Nutrients in Torreya grandis Plantation

As shown in Table 2, pH values of *Torreya grandis* plantation in the study area ranged from 3.68 to 6.81, with an average value of 4.91. The average values of SOM, AN, AP and AK in the study area were 27.52, 135.77, 15.12 and 153.42 mg kg^{-1}, respectively. Only the pH value was moderately variable, while the other four nutrient elements showed a high variation.

Table 2: Descriptive statistical analysis for soil nutrients in main plantations of *Torreya grandis* cv. *Merrillii*

	Min.	Median	Max.	Mean	S.D.	CV (%)	Skewnes	Kurtosis	K-Sp
pH	3.68	4.86	6.78	4.92	0.63	12.44	0.68	1.07	0.456
OM (g kg^{-1})	1.66	26.38	93.36	27.52	21.39	76.80	0.82	0.43	0.153
AN (mg kg^{-1})	23.50	116.50	471.75	135.77	94.23	68.63	1.45 (0.008)	2.04 (−0.467)	0.004 (0.947)
AP (mg kg^{-1})	0.91	5.83	62.28	15.12	17.79	118.11	1.44 (0.243)	0.45 (−1.252)	0.000 (0.087)
AK (mg kg^{-1})	12.00	106.00	509.00	153.42	116.50	75.93	1.13 (−0.070)	0.42 (−0.521)	0.001 (0.054)

Note: The significance levels of skewness, kurtosis and K-S test after logarithmic conversion are shown in brackets. Min.: Minimum, Max.: Maximum, S.D.: Standard Deviation, CV: Coefficient of Variation.

3.2 Spatial Clustering and Outlier Analysis of Soil Fertility Indexes

The global Moran's I values of soil pH, OM, AN, AP and AK were 0.14, 0.24, 0.20, 0.29, 0.23, respectively, indicating a significantly positive autocorrelation ($P < 0.05$). The local Moran's I indicated that the high-value-clusters of soil pH were mainly distributed in Zhuji City, while the low-value-cluster areas were mainly distributed in Keqiao City (Fig. 2). The spatial autocorrelation distributions of soil OM, AN, AP and AK are relatively similar. High-value areas located in the cities of Keqiao and Shengzhou, and low-value located in the city of Zhuji City and Dongyang.

3.3 The Spatial Distribution Characteristics of Soil Nutrients in the Torreya grandis Plantation

Currently, there are few studies on *Torreya grandis* soil, and there is no corresponding soil nutrient grading standards to measure the soil nutrient status of *Torreya*. In this study, soil pH, OM, AN, AP and AK were classified into four levels based on the classification standards of nutrients commonly used in Zhejiang Forestry [36]. Through ordinary Kriging interpolation method, the spatial distribution maps of soil elements in the main producing areas of *Torreya grandis* were obtained. The low soil pH areas were mainly distributed in the city of Keqiao and Shengzhou, and the high-value areas were observed in the city of Zhuji and Dongyang (Fig. 3). Generally speaking, the pH value of the soil in most areas was low, and the soil acidification in the city of Keqiao and Shengzhou was particularly serious.

The spatial distribution patterns of soil OM, AN, AP and AK had certain similarities. The high-value areas mainly located in the city Keqiao and Shengzhou, a few were in the eastern part of Zhuji City, and the low-value areas were mainly distributed in the eastern part of the city of Zhuji City, and Dongyang City.
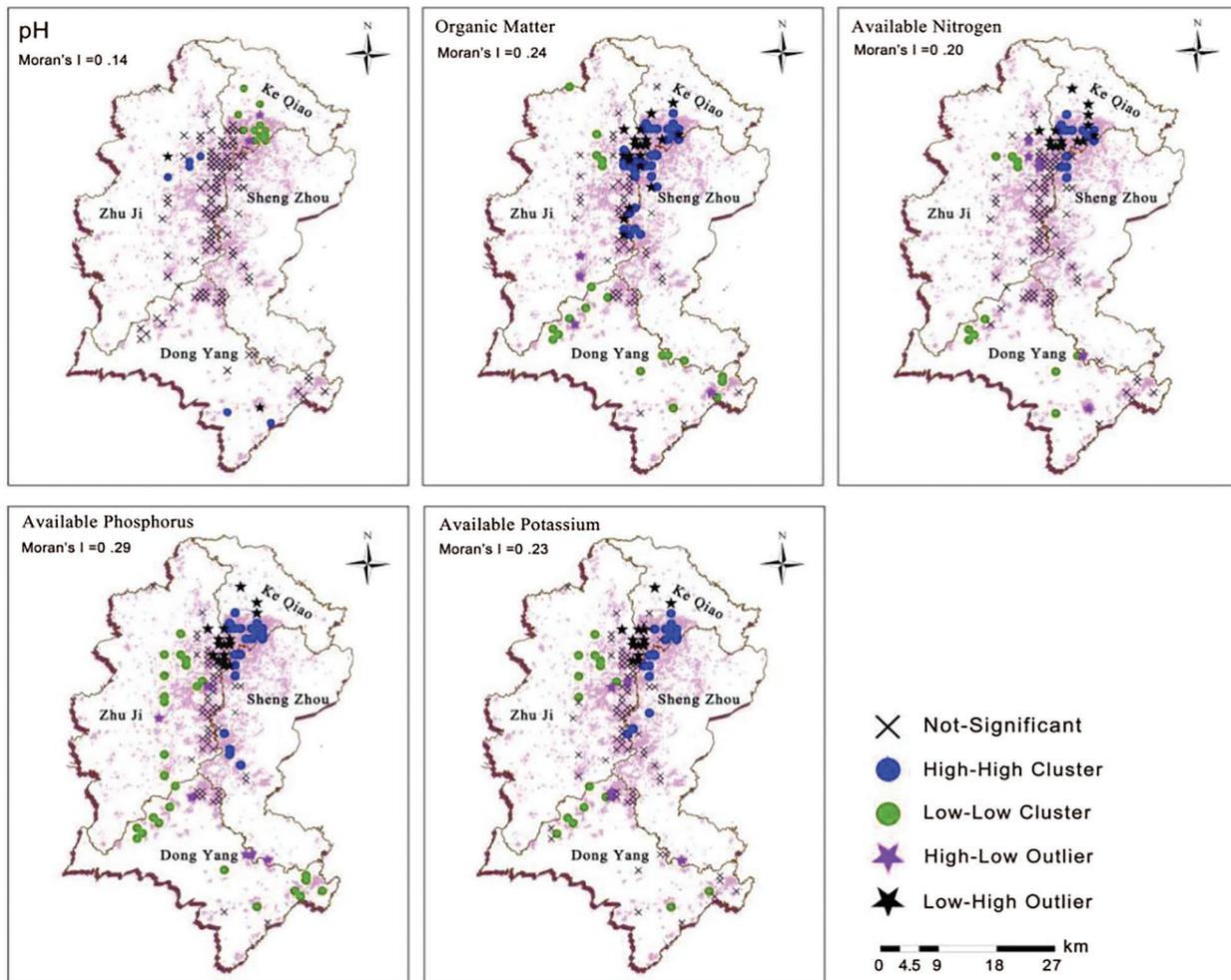
Figure 2: Local indicators of spatial association for soil nutrients in main plantations of *Torreya grandis* cv. *Merrillii*

3.4 The Soil Nutrients under Different Stand Ages

According to the actual forest age in this region, the forest age was divided into young-aged (<10 years), middle-aged (10–30 years), mature (30–100 years) and over-mature *Torreya grandis* (>100 years) groups. The soil pH tended to decrease with the growth of the forest age, and the difference in soil pH between young-aged and over-mature groups was significant (Fig. 4). With the growth of the forest age, the content of soil OM, AN and AP were gradually increasing, and there were also significant differences between the young forest (<10 years) and the ancient *Torreya gradis* forest (>100 years) in these indicators.

3.5 Evaluation of Integrated Soil Fertility in the Main Plantation of Torreya grandis

Through factor analysis, the common factor variance value and weight value of each evaluation index were obtained (Table 3). There is little difference in the weights assigned to each variable. The weights assigned to pH and organic matter were higher (0.215 and 0.209), and the weights of AN, AP and AK were 0.185, 0.194 and 0.197, respectively.
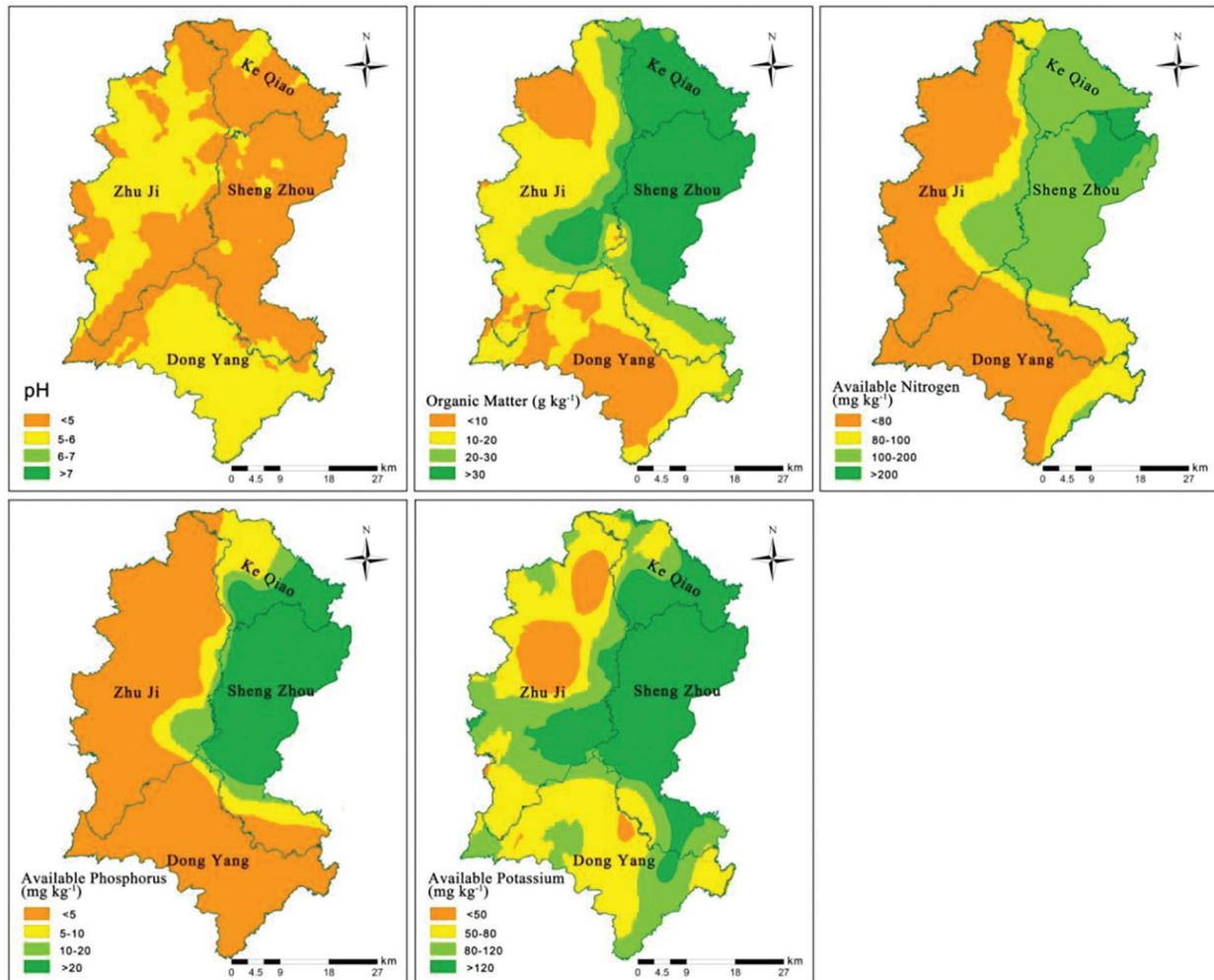
Figure 3: Spatial distribution maps of soil nutrients in plantations of *Torreya grandis*

The soil fertility index of the study area was calculated according to the comprehensive soil fertility evaluation method (IFI), and the spatial distribution map of soil fertility was drawn by the Kriging interpolation method (Fig. 5). In this study area, 61% of the soil fertility is of medium to high quality (IFI > 0.47), and 39% of the area has a relatively low level of soil fertility. High-fertility soils were mainly found in the cities of Keqiao and Shengzhou, some in the eastern part of Zhuji City, and low-fertility soils were mainly concentrated in the city of Zhuji and Dongyang.

4 Discussion

The selected study area is the main *Torreya grandis* plantation in China. According to the classification standard of Zhejiang forestry soil [37], the concentrations of soil OM, AN, AP and AK in the study area were relatively high. Based on field investigation, local forest farmers applied a large amount of compound fertilizers (N:P_2O_5:K_2O = 15:15:15 or 17:17:17) and herbicides. The average application amount of compound fertilizer was 5.28 kg plant^{-1}, and the highest application amount was 30 kg plant^{-1}. The average application amount of organic fertilizer was 15.54 kg plant^{-1}, and the highest application amount was 50 kg plant^{-1}. Herbicide application was usually 5 to 6 times a year, at least 1 to 2 times a year. Although fertilizer application could improve the overall soil nutrients, excessive nitrogen and

phosphorus addition would affect the yield and quality of *Torreya grandis*, leading to the deciduous leaf and *Torreya grandis* nut loss [37]. In other economic plantations (pecan, bamboo and tea) in China, non-scientific fertilizer ratio also led to soil nutrient imbalance [37–39].
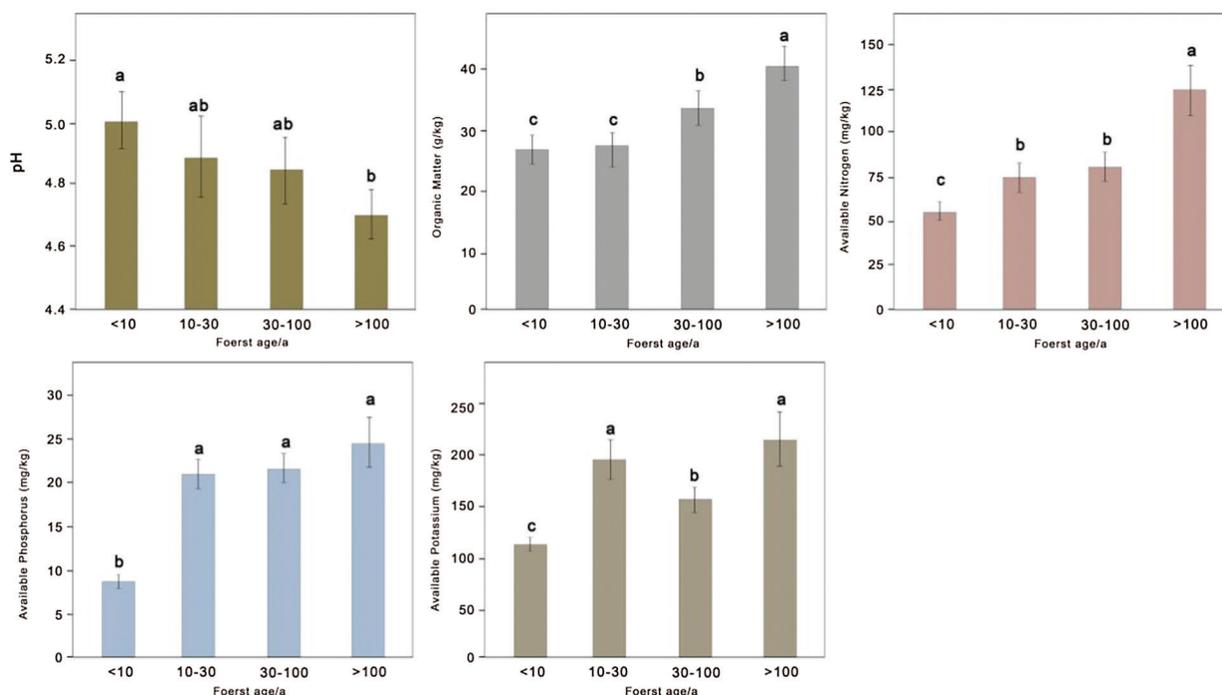
Figure 4: Effects of forest ages on soil pH, OM, AN, AP and AK in *Torreya grandis* plantations
Note: Different letters indicate significant differences ($P < 0.05$).

Table 3: Estimated communality and weight value of indexes of soil fertility

	pH	OM (g kg^{-1})	AN (mg kg^{-1})	AP (mg kg^{-1})	AK (mg kg^{-1})
Communality	0.990	0.961	0.848	0.892	0.903
Weights	0.215	0.209	0.185	0.194	0.197

Soil pH values had direct effects on other chemical properties of the soil [40], thus affecting the growth of *Torreya grandis*. However, excessive acidity in soils can lead to reduced yields and quality [30,31]. The pH values in soil of the study area could be affected by factors such as parent rock formation and anthropogenic fertilization, especially the long-term use of chemical fertilizer leads to soil serious acidification. The spatial distribution of soil pH in the study area was obvious, and the soil acidification in Keqiao district and Shengzhou city was relatively serious. Wang and Maleki et al. [41,42] reported that the use of lime and soil conditioners was efficient to improve the acidification of hickory plantation soil. Although the variation of soil acidity in the study area was small, excessive acidification was not conducive to improving the yield and quality of *Torreya grandis*, and local forest farmers should be guided to carry out scientific management for *Torreya grandis* plantation [36].

Figure 5: Soil fertility level distribution map of *Torreya grandis* cv. *Merrillii*

The spatial heterogeneity of soil nutrients was mainly brought by the difference of fertilization modes in different regions and the lacking standardized and unified scientific management measures [42–44]. The spatial distribution of soil nutrients and properties can be influenced by human factors mainly including soil management like fertilization and irrigation and natural factors mainly including soil formation, climate and topography factors [45]. Ecological factors can enhance the spatial correlation of soil nutrient variables, while human activities would weaken the spatial correlation and develop towards homogenization [46,47]. The spatial distribution patterns of soil OM, AN, AP and AK in the study area had certain similarities, as these variables were jointly affected by ecological factors (topography, soil type, parent material, climate, etc.) and human management (fertilization, irrigation, etc.) [16]. However, the natural climate and geographical conditions of the four regions were similar, and the terrain was mainly hilly in this study. Therefore, the difference of anthropogenic management was the main factor leading to the difference of soil nutrients in this study area. *Torreya grandis* has a wide range of stand age, and human management such as fertilization will accumulate over time. The eastern part of Zhuji is an early planting area of *Torreya grandis*, and long-term intensive management results in the enrichment of soil nutrients [48]. Keqiao district and Shengzhou city had higher soil nutrient content in the study area, which may be because the average application amount of compound fertilizer was the highest in Keqiao district (15.1 kg/plant), and the average application amount of organic fertilizer was the highest in Shengzhou city (25 kg/plant). For soil fertility quality, further acidification of the soil is not conducive to achieving the goal of sustainable development. With the increase of plantation management years, the site condition is basically stable, and the accumulation rate of organic matter is gradually greater than the decomposition rate. Coupled with the application of organic fertilizer and other management measures, the content of soil OM and AN gradually increased [49]. Meanwhile, the AP was enriched in the soil [50]. Potassium with strong mobility in the soil was easily affected by soil erosion, leaching and runoff loss [41]. According to field surveys, in recent years, forest farmers in various regions have used a large number of compound fertilizers to achieve the increasing yield. The average application amount of

compound fertilizer in Keqiao district and Shengzhou City was 7.83 kg/plant, the highest was 30 kg/plant, and the application amount in some areas of Zhuji city reached 25 kg/plant. Although the soil nutrient of the *Torreya grandis* plantation has been significantly improved, the pursuit of high yields without paying attention to the fertilizer efficiency would not only waste fertilizers, but also lead to fruit quality and yield decrease [44,50,51]. The level of soil fertility is not only determined by soil nutrients and crop absorption capacity, but also affected by the coordination degree of various factors. Therefore, according to the actual status of the soil fertility of the *Torreya grandis* plantation, the fertilization application based on soil testing should be used to formulate the fertilization structure and dosage to meet the actual production needs, and ultimately realize the sustainable development of the *Torreya grandis* industry.

The regional-scale variation of soil nutrients in economic forests (such as *Torreya grandis*) is important information to guide specific precision management measures in the plantations [18,52,53]. Our results revealed that the spatial variation of soil nutrients was clear, especially the soil pH values. Most of the study area had low pH, indicating the problem of soil acidification in the plantation. Qian et al. [36] had shown that too low soil pH affected the growth and development of *Torreya grandis*, leading to reduced yield and poor quality. Appropriate lime application can increase soil pH [25]. Necessary lime application is needed for Chinese *Torreya grandis* growth. The Chinese *Torreya grandis* nut is very famous in China as it has high nutritional, medicinal and economic values [19,41]. How to enhance its yield is concerned by local farmers, which is strongly related to economic profit. In this study, due to intensive management such as non-uniformed fertilizer application in Chinese *Torreya grandis* plantations, nutrients imbalance was found. Therefore, to avoid negative environmental issues caused by intensive management, natural and ecological application combined with manure fertilizer usage are strongly needed in the plantation management.

5 Conclusions

In this study, soil nutrients maps of Chinese *Torreya grandis* plantation indicated that the low-value of OM, AN, AP and AK were mainly distributed in the cities Zhuji and Dongyang and the high-value were mainly distributed in Keqiao and Shengzhou, while the spatial distribution pattern of pH was the opposite. The comprehensive soil fertility index indicated that the soil in Keqiao and Shengzhou was fertile, while in the Zhuji and Dongyang was barren. In summary, we concluded that the soil acidification and nutrient imbalance in the main production areas of *Torreya grandis* plantation were serious. It is recommended to use soil conditioners to improve acidified soil, and adopt methods such as "stabilizing nitrogen, reducing phosphorus and controlling potassium" for the *Torreya grandis* plantation. This information can further be used for site-specific fertilizer management of Chinese *Torreya grandis* plantations.

Authorship: The authors confirm contribution to the paper as follows: study conception and design: Zhao K. L., Wu J. S.; data collection: Zhang Y., Dong J. Q.; analysis and interpretation of results: Ye T., Zhang Y., Wang M.; draft manuscript preparation: Bai L. L. All authors reviewed the results and approved the final version of the manuscript.

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