Status and influential factors of soil nutrients and acidification in Chinese tea plantations: A meta-analysis

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Abstract. The knowledge of the status and influential factors of soil nutrients including soil organic matter (SOM), nitrogen (N), potassium (K) and phosphorus (P), and acidification is the basis for sustainable management of tea plantations and thus the sustainability of the tea industry. However, a national-level study addressing this topic is lacking. Thereby, we assessed the status, spatial variations, and influential factors of soil nutrients and acidification in China's tea plantations based on 1,843 datasets collected from 379 published articles. The results showed that only 40.9% of the observed tea plantations meet the standards of high-quality tea plantations. Most tea plantations were facing soil acidification, nutrient deficiencies and imbalance. Furthermore, the status of soil nutrients and pH varied among cultivation zones due to the impacts of location, climate, and soil type. Specifically, tea plantations in the southern zone showed the lowest concentrations of soil available N and K and total K, but the highest stoichiometric ratios of soil nutrients ($P<0.05$). Management practices (e.g., rotational cycle and fertilization strategies) also significantly shaped the status of soil nutrients and pH. Therefore, applying organic fertilizer, extending the duration of the cultivation cycle, and planting shading trees were recommended to improve soil nutrient availability and balance, and to mitigate soil acidification. Specifically, it is recommended to apply K fertilizer to tea plantations in the southern zone and/or at high altitudes.

1 Introduction

Tea plants (*Camellia sinensis* (L.) O. Kuntze) are widely cultivated as an important economic crop in many countries such as China, Kenya, India, Sri Lanka, etc. (FAO and CAAS, 2021). Globally, the cultivation area and yield of tea have increased annually to meet the growing demand (FAO, 2022). China is the largest tea grower, producer and consumer at the globe (FAO and CAAS, 2021), and its cultivation area, including Taiwan (CAEY, 2023), grows fast, expanding from 1.1 million hectares in 2000 to 3.4 million hectares in 2022 (NBS, 2024). The expanding tea cultivation area occupies other land uses (Li et al., 2011; Zhu et al., 2017; Wu et al., 2020), together with monoculture and the intensive and/or improper use of

chemical fertilizer (Yan et al., 2018), soils in Chinese tea plantations are degrading, such as soil acidification and nutrients imbalance (Yang et al., 2023), which may influence the productivity and quality of tea and cause ecological and environmental problems. Therefore, assessing the status of soil nutrients and acidification, and identifying the key influential

35 factors are crucial for soil management in tea plantations, and vital to tea production and environmental protection.

The concentrations and availability of soil organic matter (SOM), nitrogen (N), potassium (K), phosphorus (P), as well as pH, are important indicators of the health and fertility level of the soil to support plant growth (Zhu et al., 2021). The stoichiometric ratios of carbon (C), N, P and K reflect the restrictions, overloads and imbalances in soil nutrients (Su et al., 2019), determining nutrient availability for plants and soil microorganisms and further affecting ecosystem functions (Zheng

40 et al., 2021). Although local and regional status of soil nutrients have been widely investigated (Hua and Li, 2018; Yan et al., 2018; Zhang and Shu, 2021), knowledge concerning the status and spatial variation of soil nutrients and the influential factors in tea plantations at the national level is lacking. Soil pH affects many physical, chemical and biological soil properties and processes, influencing plant growth and biomass yield (Neina, 2019). As an important aspect of soil degradation, soil acidification has been widely reported across various ecosystems and regions, such as cropping systems

45 (Zhu et al., 2018) and tobacco plantations in China (Zhang et al., 2016), 21 land use types in Britain (Malik et al., 2018), and global terrestrial ecosystems (Chen et al., 2023). Soil acidification increases the leaching loss of cationic nutrients and exacerbates the imbalance of soil nutrients (Zhang et al., 2016), and also causes losses of soil inorganic carbon (Raza et al., 2021). Soil acidification in tea plantations gains specific attention because of the special property of tea plant which prefers acidic soil for growth and in turn acidifies soil (Yan et al, 2018). Yan et al. (2020) have reported the status and variation of

50 soil acidification in China's tea plantations based on 2,058 datasets collected from literature covering 225 tea-planting counties in 19 provinces in mainland China, and analyzed its historical change trend (between the 1980s and 2000s). Zhang et al. (2022) have reported on the soil pH in China's tea-planting provinces and the variations in altitudes and tea varieties based on data collected from 122 articles. However, little information about what and how influential factors affect soil pH in tea plantations at a national level is available.

55 The status of soil nutrients (Zheng et al., 2012) and pH (Yan et al., 2020) vary spatially and is strongly influenced by environmental factors, such as location (e.g., longitude and latitude), topography (e.g., elevation), soil conditions (e.g., soil type) and climate (e.g., temperature and precipitation) (Chen et al., 2022). To begin with, location and topography determine the spatial distribution of hydrological, climatic, and pedological properties, and thus likely to alter the concentrations and distributions of soil nutrients (Shao et al., 2022). For instance, Wang et al. (2018) have demonstrated that soil total nitrogen

60 (TN) and organic carbon (SOC) are positively correlated with elevation in non-karst soils. Meanwhile, the physiochemical conditions of soil, such as texture, bulk density, pH and nutrient concentrations vary markedly with soil types, and determine the status of soil nutrients (Di et al., 2020). Ge et al. (2019) have reported that the concentrations and ratios of soil C, N and P were significantly affected by clay content of soil (Baker et al., 1998). Besides, climatic factors not only affect the growth and distribution of vegetation (Shao et al., 2022) but also the mineralization and immobilization of organic materials (Xin et

65 al., 2016), suggesting that climate factors are key drivers of the concentrations and stoichiometric ratios of soil nutrients.

Together, the status of soil nutrients and pH may depend on environmental conditions. However, the status of soil nutrients and pH in tea plantations at a national scale and key drivers remains unknown.

Agronomic management practices can alter the status of soil nutrients and pH in artificial ecosystems (Ronnenberg and Wesche, 2011). On the one hand, extensive disturbance of surface soil and biomass harvesting in agroecosystems accelerate the decomposition of SOC and soil degradation, and therefore agroecosystems are generally considered to have lower SOC (Martín et al., 2016), N and P storage than natural ecosystems (Zhu et al., 2021). However, Fan and Han (2020) have reported that tea plantations have higher soil TN than forests and a 100-year-old tea plantation holds higher SOC than forest. On the other hand, fertilizer application can replenish soil nutrients, but may also cause imbalances in soil nutrients and soil acidification, as well as other environmental problems depending on fertilization strategies (Vitousek et al., 2009). Generally, organic fertilizer can improve crop productivity, as well as increasing concentrations of soil nutrients, resisting soil acidification (Shi et al., 2019), and reducing nutrient runoff losses (Yan et al., 2023). Inorganic fertilizers can efficiently improve the concentrations of available macro-nutrients, but they may also cause soil acidification and imbalance of soil nutrients (Jin et al., 2023). Particularly, excessive N fertilization is recognized as the major cause of serious soil acidification in China's tea plantations (Yan et al., 2020). Consequently, the combined application of organic and inorganic fertilizers is considered the best way to balance soil nutrients (Quan et al., 2020), and the knowledge regarding the effects of management practices on the status of soil nutrients in tea plantations is the basis for sustainably managing tea plantations.

Therefore, to obtain the knowledge regarding the effects of environmental factors and management practices on the status of soil nutrients and pH, this study assessed the status of soil nutrients and pH in China's tea plantations. We aimed to answer the following three questions: 1) What is the status of soil nutrients and pH in China's tea plantations? 2) How do geological and climatic factors, and management practices influence the concentrations and stoichiometric ratios of soil nutrients and soil pH? 3) What measures can be taken to address the possible soil problems? Our findings could provide valuable references for the sustainable management of tea plantations.

2 Methodology

2.1 Study area

The study area encompasses all 20 tea-planting provinces in China (Figure 1). These provinces were divided into four cultivation zones: southwestern zone, southern zone, south Yangtze zone and north Yangtze zone (Zhang et al., 2017), based on tea types, soil types and climate (FAO and CAAS, 2021; Wang et al., 2023).
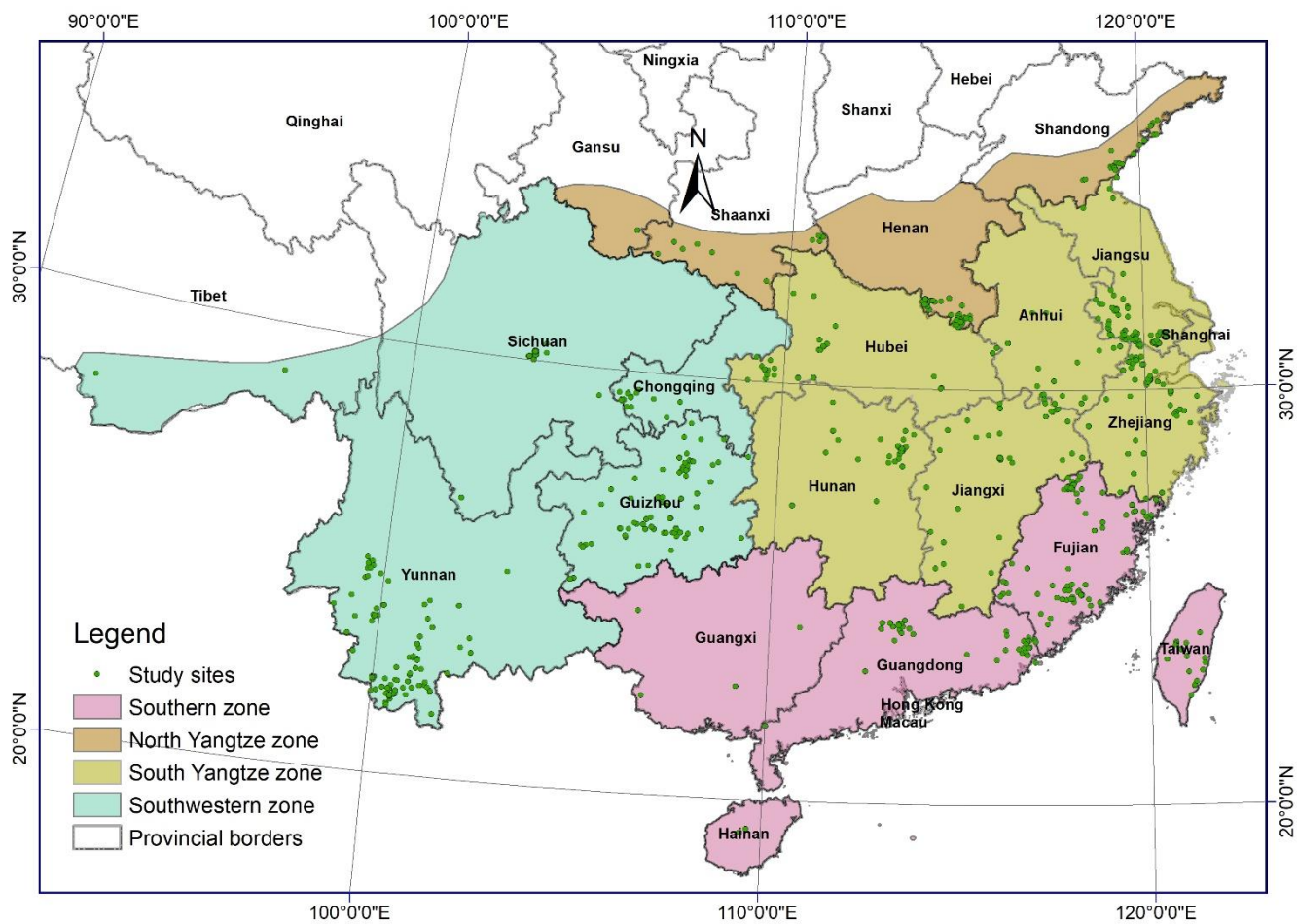
Figure 1. Tea cultivation zones and provinces in China and the spatial distribution of study sites.

2.2 Data collection and compilation, and assumptions

Articles published from January 2000 to May 2023 were searched and collected using keywords 'stoichiometry', 'soil fertility', 'soil nutrient' or 'soil organic matter' plus 'tea plantation' or 'tea garden' through China National Knowledge and Web of Science. Collected articles were filtered based on the following criteria: (1) experiments were conducted in the field, and (2) the soil depth was indicated and thicker than 10cm in the literature. After filtration, 379 published articles met the criteria and were selected for data collection. In total, 1,843 datasets were collected and compiled into the database. The database included the concentrations and stoichiometric ratios of soil nutrients: TN, total phosphorus (TP), total potassium (TK), available nitrogen (AN), available phosphorus (AP), available potassium (AK), pH, SOC, SOM and the ratios of C:N, C:P, N:P, C:K, N:K and P:K. Other information regarding soil classification, sampling depth, age of tea plantation, cultivation zone, longitude, latitude, elevation, mean annual precipitation (MAP), mean annual temperature (MAT), and

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105   fertilization strategy was also collected and recorded in the database. Soil classifications referred to the Classification and Codes for Chinese Soil (GB/T 17296-2009) to ensure consistency and comparability with the literature as most studies where we collected data from used the Chinese soil classification system. Translating soil types between different soil classification systems may cause uncertainty due to differences in scientific basis, classification principles and hierarchy, etc. (Table S1). The characteristics of representative soil classifications in tea cultivation zones are illustrated in Table 1. The

110   central longitude and latitude of the administrative district of the study area were adopted if the exact locations of the sampling sites were not reported. Then, all units were unified to ensure consistency among studies.

    In this study, a soil depth of 0–30 cm was used to explore and compare the concentrations and stoichiometric ratios of soil nutrients; however, the sampling depths varied among the published articles. Under this circumstance, certain assumptions and data processing methods were applied to standardize the soil depths. In some articles, soil depths were 0–30

115   cm or thicker, but they were divided into several layers, for example, sampled soils were divided into layers of 0–10 cm, 10–20 cm and 20–30 cm or 0–20 cm and 20–40 cm. In these cases, the average values of all soil layers were considered equivalent to those in the 0–30 cm soil layer. In other articles, the soil depths for sampling were less than 0–30 cm, e.g., 0–20 cm. In these cases, the stoichiometry of soil nutrients in the 0–20 cm soil layer was assumed to be same as that in the 0–30 cm soil layer.

120 **2.3 Data processing and analysis**

    Calculations were conducted for articles that reported only partial information about soil nutrients. Conversion between SOM and SOC was performed using a constant of 1.724 to divide SOM or multiply SOC (Fang et al., 2012). The stoichiometric ratios of soil nutrients were expressed in mass ratios of SOC, TN, TP and TK. Mass ratios are commonly used in the literature where we collected data from and other meta-analyses of soil nutrients (Shi et al., 2016). For studies that

125   only reported the concentrations of soil nutrients or calculated stoichiometric ratios based on molar data, the ratios of C:N, C:P, N:P, C:K, N:K and P:K were calculated and adjusted by multiplying the molar masses of the elements before analysis to ensure consistency and comparability among studies.

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Table 1. Main characteristics of representative soil classifications in tea cultivation areas.

Soil classification	Classification characteristics	Parent material	Formation processes	Main distribution area
Red earth (Ferralsols)	Ferrallitic acidic soil, with a red-brown or orange-red illuvial layer and mottles and iron-manganese nodules in the lower part of the.	Mainly weathered products of Quaternary red clay, Tertiary red sandstone, granite, phyllite, limestone, basalt.	The combined bio accumulation and interaction between desilication and ferruginous-aluminous weathering processes.	Hilly regions in the south of the Yangtze River, and part of Sichuan, Guizhou and southern Tibet.
Brown earth (Luvisols)	Soils developed under warm temperate humid forests and dry forests, and soil layers that show varied shades of brown.	Primarily weathered products of medium and acidic igneous rocks, as well as other non-limestone sediments.	Processes of leaching, illuviation, and strong biological accumulation.	Humid region of eastern China, northern Anhui and western Hubei.
Laterite soil (Latosols)	Strongly ferruginous acidic soil developed under tropical rainforests or monsoon forests, with a high degree of weathering.	Multiple parent material, mainly weathered Basalt, shallow marine sediments, and granite.	Intensive aluminum enrichment and high biological enrichment.	Hainan Island, Leizhou Peninsula, Xishuangbanna, and southern Taiwan
Lateritic red earth (Latosols)	Transitional soil with some properties of red soil and latosol, developed under subtropical evergreen broad-leaved forests. Thick soil layers, heavier texture.	Multiple parent materials.	Slightly weaker weathering and leaching compared to latosol, and is red in color.	Southern Yunnan, southern Guangxi, southern Guangdong, southeastern Fujian, and southern Taiwan
Paddy soil (Anthrosols)	A type of anthropogenic soil formed due to long-term rice cultivation.	Multiple parent materials.	Mainly formed from long-term paddy cultivation and water management practices.	Widely distributed in China, mainly in rice-growing areas.
Purplish soil (Lithosols)	Soil formed from Jurassic and Cretaceous purple sandstone and shale. Rich in calcium, magnesium, potassium, sodium, iron, manganese, and other elements, and has high fertility.	Purple-red sandstone and shale from the Jurassic and Cretaceous periods.	Frequent weathering and erosion.	Sichuan Basin and the Three Gorges area of the Yangtze River.
Yellow earth (Ferralsols)	Ferrallitic acidic soil developed under subtropical evergreen broad-leaved forests, characterized by moist soil layers and yellow or wax-yellow illuvial layers in the middle part of the profile.	Multiple parent materials, mainly granite, sandstone and weathered products of Quaternary red clay and limestone.	Combined alumina enrichment and the hydration of iron oxides.	Mainly in Guizhou and Sichuan provinces.
Yellow-brown earth (Luvisols)	Weakly ferruginous, clayey, and acidic soil developed under subtropical deciduous broad-leaved forests mixed with evergreen broad-leaved forests.	Multiple parent materials.	Combined eluviation, clayization and weak alumina enrichment.	South of the Yellow River and the north of the Yangtze River.

Cited from Zhu et al. (2019).

140   Statistical analyses were conducted using SPSS software ver. 23 (SPSS Inc., Chicago, IL, United States of America). One-way ANOVA was performed to assess differences in the stoichiometry of soil nutrients and pH among tea cultivation zones, fertilizer strategies, and soil classifications. Subsequently, post-hoc multiple comparisons between two groups were conducted using the Tukey HSD method. Correlations between the stoichiometry of soil nutrients and pH, geological and climatic factors, and age of tea plantations were analyzed to explore the factors influencing soil nutrients status and

145 acidification. The correlations between soil nutrients and pH were analyzed and visualized using OriginPro 2024 software (OriginLab Corporation, Northampton, MA, United States of America). The effect strengths of longitude, latitude, elevation, MAT, MAP, and age of tea plantations on soil nutrients and pH were compared using the standardized beta coefficients from regression analyses. Additionally, multi-way ANOVA was performed to compare the effects of fertilizer strategies and soil classifications. The significances of all statistical tests were set up at the level of 0.05.

150 **2.4 Classification of tea plantations**

      Tea plantations were classified into four levels based on the concentrations of soil nutrients (Table 2), in accordance with the Chinese Standards of Environmental Requirement for Growing Area of Tea (NY/T 853-2004) and the soil nutrition diagnostic indicators of high-quality tea plantations (Zhang and Shu, 2021).

Table 2. Soil nutrient classification standards for tea plantations.

Indicator	High-quality tea plantation	Level I	Level II	Level III
pH	4.5–5.5	-	-	-
SOM (g·kg^{-1})	≥20	>15	10–15	<10
TN (g·kg^{-1})	≥1.5	>1.0	0.8–1.0	<0.8
TP (g·kg^{-1})	≥1	>0.6	0.4–0.6	<0.4
TK (g·kg^{-1})	≥10	>10	5–10	<5
AN (mg·kg^{-1})	≥100	>100	50–100	<50
AP (mg·kg^{-1})	≥20	>10	5–10	<5
AK (mg·kg^{-1})	≥100	>120	80–120	<80

155 **3 Results**

**3.1 Status and variations of soil nutrients and pH**

      At the national level, the average concentrations of all soil nutrients, except for TP, were higher than the standards for soil nutrients in high-quality tea plantations (Tables 2–3). However, the concentrations of soil nutrients, especially for available nutrients (AN, AP, and AK), varied greatly among tea plantations. The status of soil nutrients in 40.9% of the

observed tea plantations met the standards for high-quality tea plantations, but more than 20% of tea plantations were classified as level Ⅲ tea plantations due to deficiencies in soil nutrients and unsuitable soil pH. Importantly, 46.5% and 32.0% of observed tea plantations showed deficiencies in soil AK and TP, respectively, and the pH of 52.9% of the soil samples fell outside the optimal soil pH for tea growth (4.5–5.5). Notably, the stoichiometric ratios of soil nutrients in China's tea plantations varied widely, especially for the ratios of C:N, C:P and C:K (Table 3 and Figures 5–6), indicating that some of China's tea plantations were facing a serious imbalance of soil nutrients. We also observed that the concentrations of available N, P and K in some tea plantations were very high (Figure 3).

Table 3. Concentrations and stoichiometric ratios of soil nutrients in Chinese tea plantations.

Indicator	n	Range	Mean	Std. Deviation (%)	Distribution frequency (%)			
					High-quality tea plantation	Level I	Level II	Level III
pH	1610	3.0–8.4	4.7	0.7	47.1	-	-	-
AN (mg·kg⁻¹)	1147	0.8–649.7	118.1	81.2	51.1	51.1	31.7	17.3
AP (mg·kg⁻¹)	1561	0.1–713.6	40.5	77.2	40.3	59.3	17.3	23.5
AK (mg·kg⁻¹)	1368	0.2–1,011.8	105.0	89.9	40.0	29.9	23.6	46.5
TN (g·kg⁻¹)	1167	0.01–20.5	1.5	1.3	35.5	68.0	11.9	20.1
TP (g·kg⁻¹)	506	0.1–5.4	0.7	0.6	15.6	39.3	28.7	32.0
TK (g·kg⁻¹)	427	0.1–79.4	14.1	11.5	60.9	60.9	19.2	19.9
SOM (g·kg⁻¹)	1843	0.6–159.6	27.6	20.5	60.0	77.5	13.9	8.5
Average percentage	-	-	-	-	40.9	52.8	19.8	21.4
C:N	1164	0.1–286.7	15.44	21.8	-	-	-	-
C:P	506	1.6–573.4	41.9	43.1	-	-	-	-
N:P	484	0.1–34.3	2.9	2.9	-	-	-	-
C:K	427	0.1–485	13.5	68.2	-	-	-	-
N:K	402	0.01–8.8	4.0	1.2	-	-	-	-
P:K	347	0.004–4.	0.2	0.5	-	-	-	-

Note: n is the number of observations.
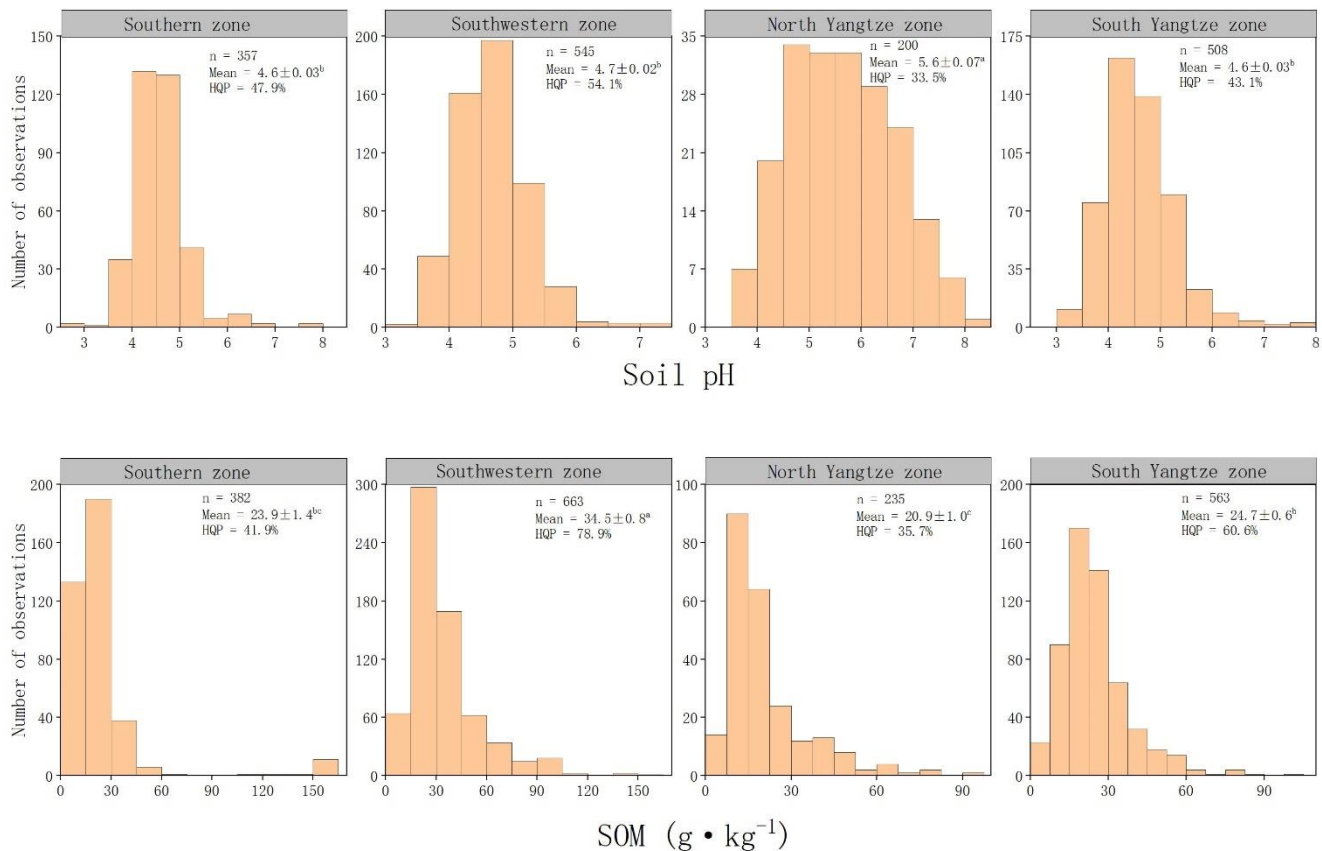
Figure 2. Frequency distribution of soil pH and SOM in tea plantations in each cultivation zone. n is the number of observations; HQP represents the percentage of high-quality tea plantations; letters on values indicate significant differences among cultivation zones at the 0.05 level.
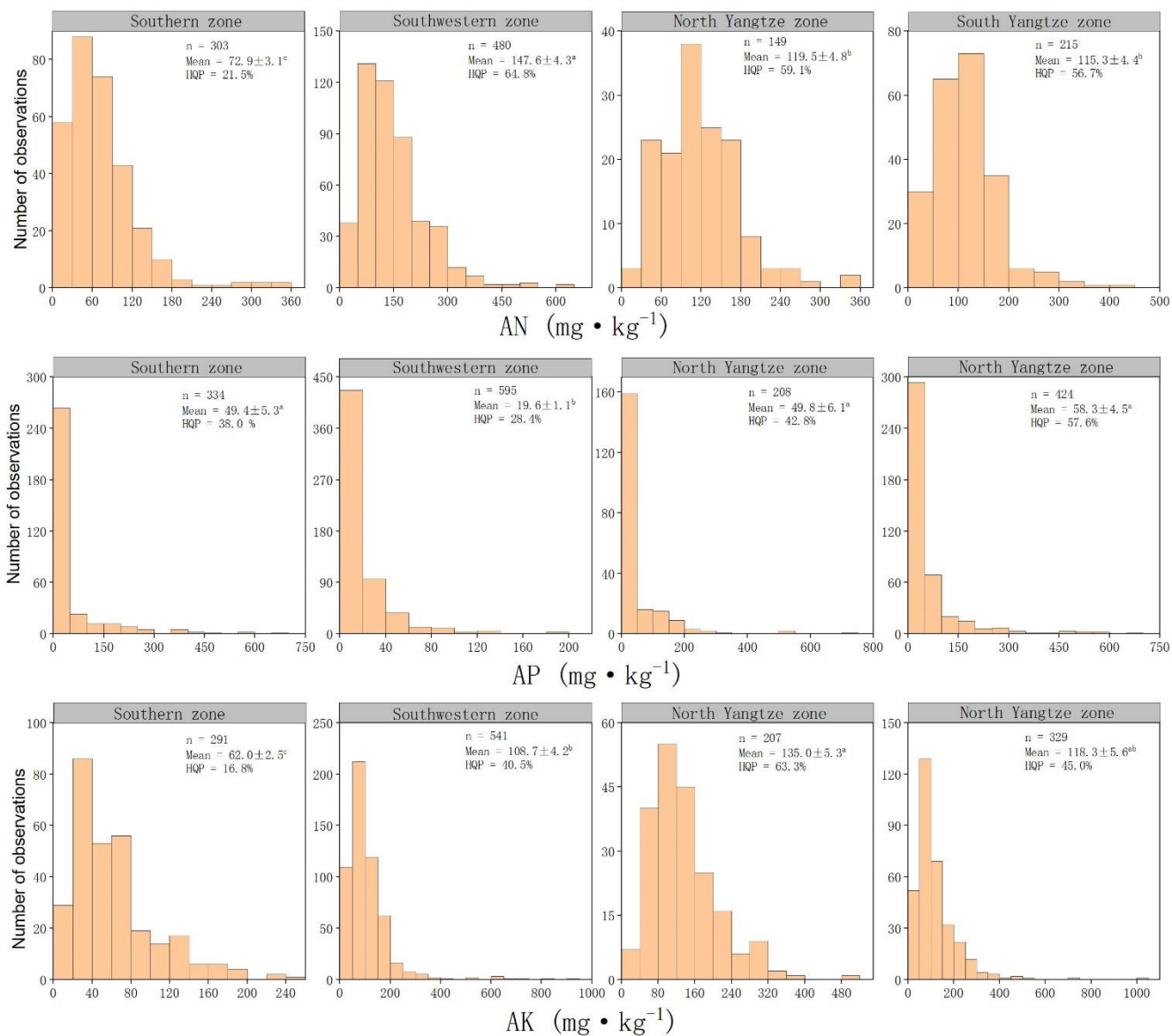
Figure 3. Frequency distribution of soil AN, AP and AK in tea plantations in each cultivation zone. n is the number of observations; HQP represents the percentage of high-quality tea plantations; letters on values indicate significant differences among cultivation zones at the 0.05 level.
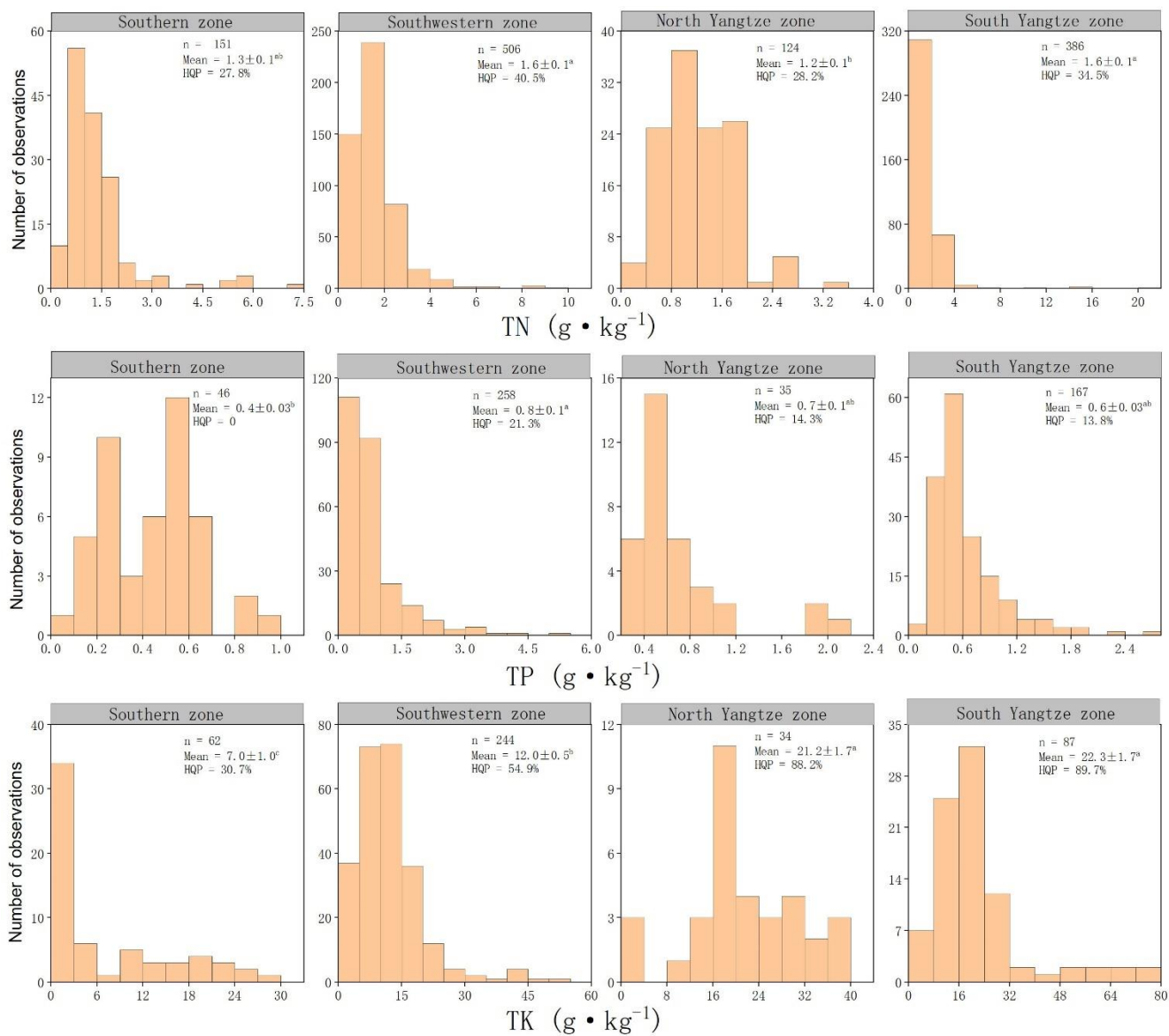
Figure 4. Frequency distribution of soil TN, TP and TK in tea plantations in each cultivation zone. n is the number of observations; HQP represents the percentage of high-quality tea plantations; letters on values indicate significant differences among cultivation zones at the 0.05 level.
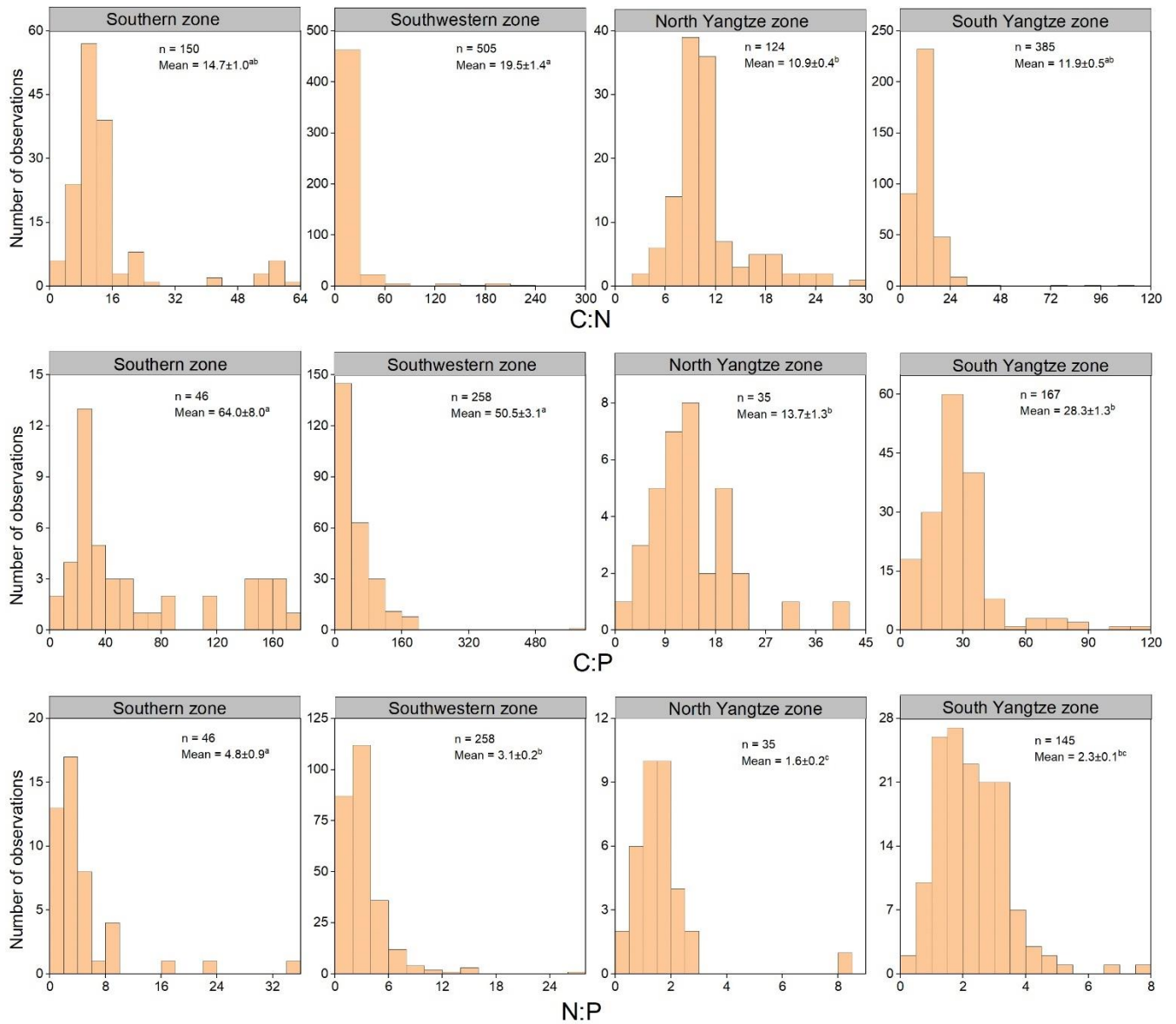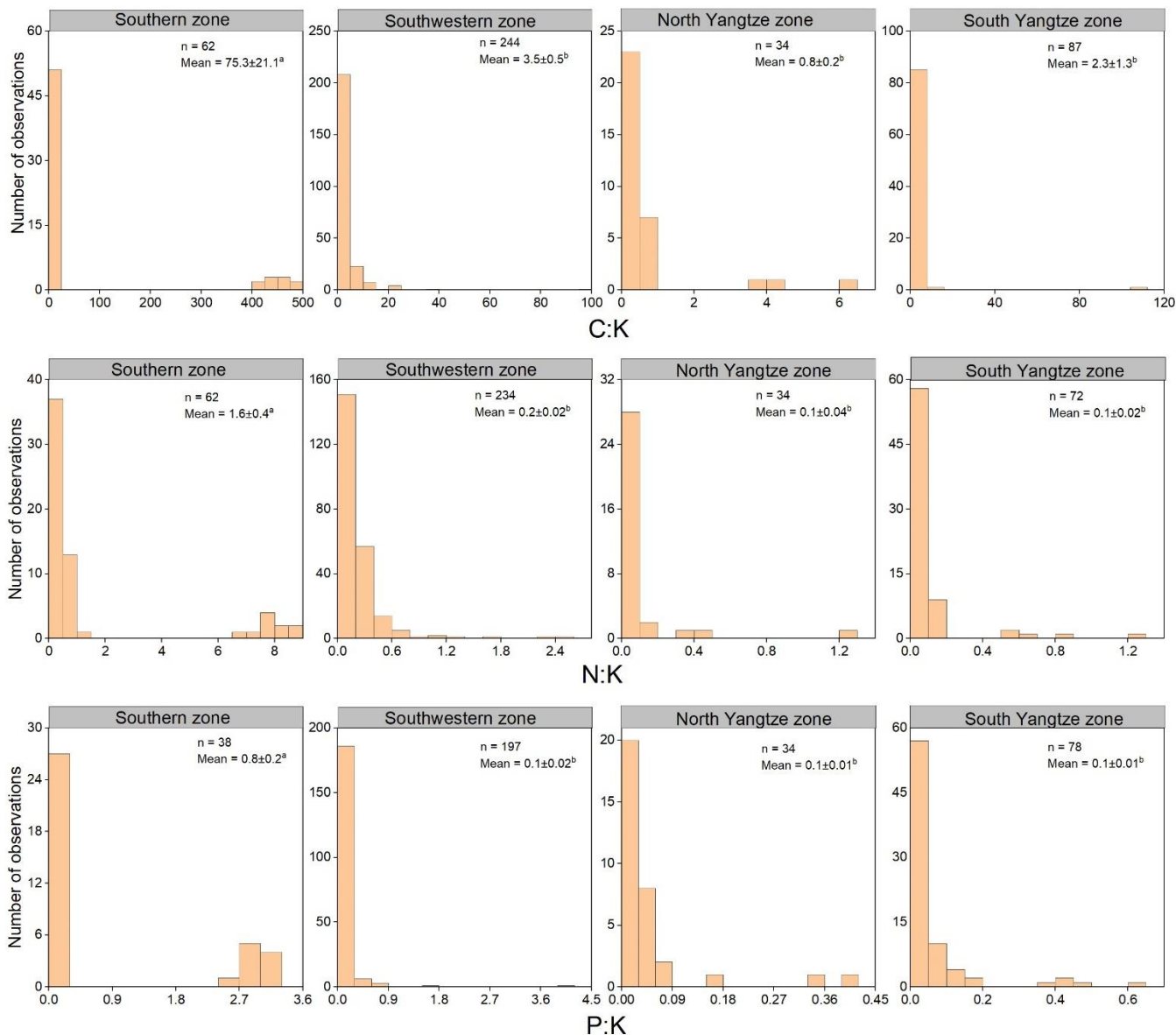
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Figure 5. Frequency distribution of the ratios of C:N, C:P and N:P in tea plantations in each cultivation zone. n is the number of observations; letters on values indicate significant differences among cultivation zones at the 0.05 level.

Figure 6. Frequency distribution of the ratios of C:K, N:K and P:K in tea plantations in each cultivation zone. n is the number of observations; letters on values indicate significant differences among cultivation zones at the 0.05 level.

Spatially, the ecological stoichiometry of soil nutrients and pH varied markedly among cultivation zones (Figures 2–6). Specifically, tea plantations in the southwestern zone had the highest concentrations of soil AN and SOM, while tea plantations in the southern zone showed the lowest concentrations of soil AN, AK and TK ($P<0.05$). The soil pH of tea plantations in the north Yangtze zone was significantly higher than in other zones ($P<0.05$) (Figure 2). In terms of the percentage of high-quality tea plantations, the south Yangtze zone showed the highest percentage (50.1%), while the southern zone had the lowest percentage (28.1%) due to low concentrations of AN, AK, TK and the extremely low

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concentration of TP (Figures 3–4). Less than half of tea plantations in the southwestern (47.9%) and north Yangtze (45.6%) zones met the standards for high-quality tea plantations. Stoichiometric ratios, except for C:N and C:P, of soil nutrients in the southern zone were significantly higher than these in other cultivation zones. Furthermore, concentrations of SOM, TP, TK, AN and AK, as well as ratios of C:N, C:P, N:P and P:K varied widely among tea plantations in the southwestern zone, while concentrations of soil AN, AP, AK, TN and TK varied widely among tea plantations in the south Yangtze zones, and concentrations of SOM and AP, and ratios of N:P, C:K, N:K and P:K varied markedly among tea plantations in southern zones.

3.2 Patterns of soil ecological stoichiometry and pH

Table 4 illustrates the correlations of pH, SOM, the concentrations and stoichiometric ratios of soil nutrients against the geographic and climatic factors. The concentrations of soil nutrients, pH and SOM, and the ratios of C:N and C:P significantly decreased from west to east ($P<0.05$), but the concentration of AP and the ratios of C:K, N:K and P:K significantly increased from west to east ($P<0.05$), while the ratio of N:P varied slightly along the longitude gradient ($P>0.05$). Meanwhile, the concentrations of AN, AP, AK, TP and TK, and pH increased gradually with latitudes, while the concentration of SOM and the ratios of C:N, C:P and N:P decreased with latitudes ($P<0.05$). However, ratios of C:K, N:K and P:K varied slightly from south to north ($P>0.05$). Correspondingly, concentrations of AN, AK, TN, SOM, and pH, the ratios of C:P, N:P, C:K, and N:K increased with the elevation ($P<0.05$), but the concentrations of AP and TK decreased with the elevation ($P<0.05$). Also, the TP concentration and the ratios of C:N and P:K varied slightly with the elevation ($P>0.05$). Concentrations of AN, AK, and TK, and pH significantly decreased ($P<0.05$) with MAP and MAT. The change in MAP had an insignificant influence on the concentration of TP and all stoichiometric ratios of soil nutrients ($P>0.05$). The concentration of AP and the ratios of C:K, N:K and P:K were positively correlated with MAT ($P<0.05$), but TP and the ratios of C:N, C:P and N:P were slightly ($P>0.05$) correlated with MAT.

Addition, the status of soil nutrients and pH varied among soil classifications (Tables 5–6). Compared with other soil classifications, brown earth had significantly higher pH, and higher concentrations of AP, AK and TP ($P<0.05$). The concentrations of AN and SOM, and the ratios of C:P and N:P in Laterite soil were significantly higher than those in other soil classifications ($P<0.05$). The TN concentration in yellow-brown earth and the ratio of C:N in yellow earth were significantly higher than those in other soil classifications.

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225 **Table 4. Pearson correlations of geological and climatic factors and the age of tea plantations with soil pH and the concentrations and stoichiometric ratios of soil nutrients.**

Variable	Longitude	Latitude	Elevation	MAP	MAT	Age of tea plantations
pH	-**	+***	+***	-***	-***	-*
AN	-***	+**	+***	-***	-**	+***
AP	+***	+***	-***	+***	+***	ns
AK	-***	+***	+**	-**	-***	ns
TN	-**	ns	+***	+*	-**	ns
TP	-*	+*	ns	ns	ns	ns
TK	-***	+***	-***	-**	-**	ns
SOM	-***	-***	+***	+*	-***	+***
C:N	-**	-**	ns	ns	ns	+**
C:P	-***	-***	+***	ns	ns	+**
N:P	ns	-***	+***	ns	ns	ns
C:K	+***	ns	+**	ns	+**	ns
N:K	+***	ns	+**	ns	+**	ns
P:K	+***	ns	ns	ns	+*	ns

Note: MAP is the mean annual precipitation; MAT is the mean annual temperature; -, negative correlation; +, positive correlation; *, correlation is significant at the 0.05 level; **, correlation is significant at the 0.01 level; ***, correlation is significant at the 0.001 level; ns, correlation is not statistically significant.

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Table 5. The variations of concentrations of soil nutrients among soil classifications.

Soil classifications	AN (mg·kg^{-1})	AP (mg·kg^{-1})	AK (mg·kg^{-1})	TN (g·kg^{-1})	TP (g·kg^{-1})	TK (g·kg^{-1})*	SOM (g·kg^{-1})
Red earth	142.3±12.0[b]	38.5±5.2 [b]	100.5±7.8 [abc]	1.4±0.1 [ab]	0.7±0.1 [ab]	12.8±1.5	33.8±2.3 [ab]
Brown earth	123.9±14.4[b]	83.98±14.2 [a]	192.4±40.3 [a]	1.0±0.1 [b]	1.3±0.3 [a]	18.3	16.7±2.1 [c]
Laterite soil	263.1±48.2 [a]	41.5±9.3 [b]	103.3±13.6 [abc]	1.2±0.1 [ab]	0.2±0.1 [b]	6.6±0.8	48.1±6.4 [a]
Lateritic red earth	108.5±36.0[b]	11.2±3.0 [b]	50.4±14.2 [c]	1.4±0.4 [ab]	0.8±0.7 [ab]	6.4±0.2	31.1±4.5 [bc]
Paddy soil	136.6±13.2[b]	29.1±3.1 [b]	79.1±2.3 [bc]	1.7±0.3 [ab]	0.7±0.1 [ab]	17.2±3.6	23.4±4.4 [bc]
Purplish soil	107.5±15.0[b]	22.1±5.2 [b]	60.5±8.9 [c]	1.5±0.1 [ab]	1.0±0.5 [ab]	12.5±2.7	26.3±2.3 [bc]
Yellow earth	157.2±6.6 [ab]	16.2±3.0 [b]	123.1±8.2 [abc]	1.4±0.1 [ab]	0.6±0.1 [ab]	14.8±0.9	30.0±1.2 [bc]
Yellow-brown earth	105.7±8.0[b]	25.2±3.0 [b]	168.6±16.6 [ab]	1.9±0.2 [a]	0.8±0.1 [ab]	6.8±2.9	27.1±1.6 [bc]

Note: letters on values indicate significant differences among soil types at the 0.05 level; *, post hoc tests were not performed because one group had fewer than two cases.

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Table 6. The variations of pH and stoichiometric ratios of soil nutrients among soil classifications.

Soil classifications	pH	C:N	C:P	N:P	C:K[*]	N:K[*]	P:K[*]
Red earth	4.6±0.1[c]	13.0±1.1 [b]	35.0±3.6 [b]	4.3±0.8 [b]	5.2±2.9	0.25±0.04	0.11±0.03
Brown earth	5.7±0.2 [a]	11.2±2.1 [b]	13.6±7.8 [c]	0.9±0.4 [c]	0.37	0.02	0.1
Laterite soil	4.8±0.1[bc]	9.9±1.1 [b]	104.1±36.1 [a]	9.3±2.9 [a]	2.0±0.5	0.19±0.03	0.03±0.01
Lateritic red earth	4.4±0.1[c]	12.4±2.0 [b]	40.3±22.3 [b]	3.6±2.5 [bc]	2.6±1.6	0.18±0.08	0.13±0.11
Paddy soil	4.8±0.1[bc]	11.2±1.7 [b]	31.5±5.5 [bc]	2.8±0.6 [bc]	1.8±0.7	0.15±0.06	0.05±0.01
Purplish soil	4.7±0.2[c]	11.3±0.9 [b]	29.9±8.4[c]	2.8±0.9 [bc]	1.8±0.6	0.16±0.06	0.08±0.03
Yellow earth	4.7±0.1[c]	27.1±4.0 [a]	56.1 ±4.6 [b]	3.1±0.3 [bc]	2.0±0.6	0.14±0.03	0.09±0.02
Yellow-brown earth	5.5±0.1 [ab]	10.1±0.5 [b]	33.6±5.9 [bc]	3.6±0.6 [bc]	3.5±0.8	0.4±0.15	0.16±0.06

Note: letters on values indicate significant differences among soil types at the 0.05 level; *, post hoc tests were not performed because one group had fewer than two cases.

3.3 Influences of management on ecological stoichiometry

Management practices significantly altered the status of soil nutrients and pH in tea plantations. Specifically, the age of tea plantations (or rotational cycle duration) positively affected the concentrations of AN and SOM, and the ratios of C:N and C:P, but negatively influenced soil pH ($P<0.05$) (Table 4). Regarding the influence of fertilization strategies on the status of soil nutrients and pH in tea plantations (Tables 7–8), the concentrations of AN, AK, TN, TP and SOM, pH, and the ratio of N:P were relatively higher when applying organic fertilizer compared to other fertilization strategies. Using chemical or compound fertilizer alone was beneficial for improving the concentration of AP but the combined application of chemical and compound fertilizer reduced soil pH. Besides, a combination of organic fertilizer with chemical and/or compound fertilizer also lowered soil pH and the concentrations of some nutrients.

Table 7. The influence of fertilization strategies on the status of soil nutrients.

Fertilization modes	AN (mg·kg^{-1})	AP (mg·kg^{-1})	AK (mg·kg^{-1})	TN (g·kg^{-1})	TP (g·kg^{-1})	TK (g·kg^{-1})[*]	SOM (g·kg^{-1})
Chemical fertilizer	122.4±10.4[b]	81.8±25.8[a]	129.6±12.2[ab]	1.7±0.2[ab]	0.48±0.06[ab]	16.6±1.4	27.5±2.7[ab]
Compound fertilizer	75.7±15.8[c]	67.6±30.2[a]	116.3±19.4[b]	1.1±0.1[ab]	0.35±0.06[b]	12.0±2.7	16.7±2.5[b]
Organic fertilizer	159.2±14.3[a]	22.2±6.1[c]	142.3±16.0[a]	1.7±0.1[a]	0.64±0.10[a]	17.2±2.0	39.6±3.3[a]
No fertilizer	142.1±11.3[a]	65.4±19.6[a]	122.4±8.3[b]	1.5±0.1[ab]	0.45±0.04[ab]	10.0±1.7	43.4±4.4[a]
Organic fertilizer + Chemical fertilizer	173.5±54.4[a]	42.7±20.5[b]	85.5±41.9[c]	1.1±0.2[ab]	0.41±0.06[ab]	22.5±1.8	25.2±2.5[ab]
Organic fertilizer + Compound fertilizer	82.0±26.1[c]	20.1±11.0[c]	87.3±20.4[c]	1.1±0.2[ab]	0.50±0.08[ab]	4.4	31.9±4.0[ab]
Chemical fertilizer + Compound fertilizer	116.3±24.8[b]	25.1±8.9[c]	128.3±23.9[ab]	1.2±0.1[ab]	0.54±0.05[ab]	7.6±3.2	26.7±2.7[ab]
Organic fertilizer + Chemical fertilizer + Compound fertilizer	109.2±25.2[b]	29.3±4.8[bc]	107.3±29.8[bc]	0.9±0.2[b]	0.56±0.01[ab]	15.4±0.3	31.4±2.3[ab]

Note: letters on values indicate significant differences among fertilizer application modes at the 0.05 level; *, post hoc tests were not performed because one group had fewer than two cases.

Table 8. The influence of fertilization strategies on the pH and stoichiometric ratios of soil nutrients.

Fertilization modes	pH	C:N	C:P	N:P	C:K[*]	N:K[*]	P:K[*]
Chemical fertilizer	4.4±0.1[bc]	10.8±0.8[b]	28.6±3.0[b]	3.7±0.7[a]	0.8±0.2	0.10±0.01	0.03±0.01
Compound fertilizer	4.9±0.2[ab]	13.0±2.2[b]	45.7±9.7[ab]	3.7±0.8[a]	1.6±0.4	0.12±0.02	0.04±0.01
Organic fertilizer	5.0±0.1[a]	12.7±0.7[b]	47.4±4.9[ab]	3.8±0.4[a]	1.3±0.2	0.11±0.02	0.04±0.01
No fertilizer	4.6±0.1[abc]	16.0±1.6[b]	74.6±12.1[a]	3.0±0.2[ab]	10.3±5.3	0.33±0.13	0.11±0.04
Organic fertilizer + Chemical fertilizer	4.3±0.1[c]	17.0±1.6[ab]	31.4±2.6[b]	2.2±0.4[ab]	0.6±0.3	0.16	0.02±0.01
Organic fertilizer + Compound fertilizer	4.2±0.04[c]	13.4±1.0[b]	33.1±11.8[b]	2.5±1.1[ab]	4.2	0.35	0.06
Chemical fertilizer + Compound fertilizer	4.4±0.1[c]	10.9±1.2[b]	26.9±6.6[b]	2.1±0.3[ab]	5.5±2.0	0.45±0.20	0.18±0.08
Organic fertilizer + Chemical fertilizer + Compound fertilizer	4.1±0.1[c]	26.5±4.7[a]	27.6± 0.9[b]	1.2±0.1[b]	0.9±0.1	0.04±0.01	0.03±0.01

Note: letters on values indicate significant differences among fertilizer application modes at the 0.05 level; *, post hoc tests were not performed because one group had fewer than two cases.

3.4 Key drivers of the status of soil nutrients and pH

Among the influential factors including longitude, latitude, elevation, MAP, MAT, and the age of tea plantations, longitude exerted the strongest influence on the concentrations of AP, AK, and the ratios of C:N and P:K, while elevation had the strongest effects on the concentrations of TN, TP, SOM, and the ratios of C:P and C:K. The MAP and the age of tea plantations had the strongest influence on the ratio of N:K and the concentration of AN, respectively (Table 9). The comparison between soil classification and fertilizer strategy showed that the fertilizer strategy had a stronger influence on

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soil pH, the concentrations of AN, AP, TN, SOM, and the ratios of C:N, C:P and N:P than soil classification, whereas soil classification had stronger influences on the concentration of TK, and the ratios of C:K, N:K and P:K (Table 10).

Table 9. The standardized beta coefficients of regression analyses.

Influential factors	pH	AN	AP	AK	TN	TP	TK	SOM	C:N	C:P	N:P	C:K	N:K	P:K
Longitude (°E)	0.16	0.13	0.53**	0.49*	0.66***	0.72***	-0.23	0.44***	-0.28*	0.28	-0.06	0.54	0.28	0.91*
Latitude (°N)	0.02	-0.07	-0.18	-0.24	0.001	0.13	-0.001	-0.09	-0.20	0.26	-0.22	0.07	-0.01	0.06
Elevation (m)	0.32*	0.35**	0.06	0.17	0.68***	0.81***	-0.71	0.80***	0.07	1.01***	0.05	0.96*	0.56	0.88*
MAP (mm)	-0.52***	-0.02	-0.03	-0.19	0.19*	0.30*	-0.47	0.10	-0.21*	0.03	0.26	0.67*	0.66*	0.56
MAT (°C)	0.05	-0.02	0.06	0.14	-0.07	0.24	-0.01	0.06	0.08	0.34*	-0.21	0.05	-0.15	-0.02
Age (yr)	0.37***	0.72***	0.03	-0.14	0.18*	-0.28*	-0.12	0.30***	0.15	0.13	-0.01	0.01	-0.10	-0.06

Note: MAP is mean annual precipitation, and MAT is mean annual temperature. Age is the age of tea plantation. *, correlation is significant at the 0.05 level; **, correlation is significant at the 0.01 level; ***, correlation is significant at the 0.001 level; ns, correlation is not statistically significant.

Table 10. The effect strengths (expressed as %SS, the percentage of sum of squares) of soil classifications and fertilizer strategies on soil nutrients and pH.

Influential factors	pH	AN	AP	AK	TN	TP	TK	SOM	C:N	C:P	N:P	C:K	N:K	P:K
Soil classification	17.0*	15.5***	5.4	3.8	6.9	1.7	45.5***	17.1***	4.7	5.8	3.8	43.6**	37.9***	39.8***
Fertilizer strategy	31.1**	25.0***	25.7*	6.5	19.8*	8.9	13.8	22.1**	58.7***	27.2*	23.6*	9.7	24.3**	23.3**

Note: *, correlation is significant at the 0.05 level; **, correlation is significant at the 0.01 level; ***, correlation is significant at the 0.001 level; ns, correlation is not statistically significant.

4 Discussions

4.1 Implications of soil ecological stoichiometry and pH

The results of this study indicated that Chinese tea plantations were experiencing soil nutrient deficiencies and imbalances, particularly in terms of TN, TP and AK. The soil C:N ratio (16.5) in tea plantations was lower than the optimal C:N ratio (25) required for soil microbial decomposition of organic matter (Zhang et al., 2019). The soil C:P (41.9) and N:P (2.9) ratios in tea plantations were lower than these in global terrestrial ecosystems (110.9 and 7.9) (Xu et al., 2013). This could accelerate the decomposition of SOM and the mineralization and release of N and P (Wang et al., 2024). The ratios of C:K, N:K and P:K in the present research were higher than these in previous studies (Wang et al., 2024), suggesting that tea plantations in China were restricted by K nutrients. The deficiency and imbalance of soil nutrients would restrict the growth of tea plants, increase the risk of disease infestation, and affect the activities of soil microorganisms (Amtmann et al., 2008), ultimately influencing the yield and quality of tea (Li, et al., 2017). It may also reduce the resilience of the tea plantation ecosystem to global change (Zheng et al., 2021). The possible reasons for soil nutrient deficiencies and imbalances may

include biomass harvest, mechanical disturbance of surface soil, and improper fertilization. Besides, high concentrations of available nutrients and extreme stoichiometric ratios of soil nutrients in certain parts of tea plantations suggest potential over-fertilization, which can lead to resource waste, environmental pollution, and downstream eutrophication. Strategies such as applying organic fertilizer and K fertilizer should be considered to improve the levels of TN, TP and AK and nutrient balance. Organic fertilizer can enhance the soil nutrient balance and reduce environmental pollution by releasing nutrients slowly (Shaji et al., 2021). However, most tea plantations had a high level of SOM, even higher than that (in 0–20 cm soil layer) in China's terrestrial ecosystems (21.1 g·kg^{-1}), forests (24.7 g·kg^{-1}) and croplands (19.2 g·kg^{-1}) (Pan et al., 2021), but lower than that in global terrestrial ecosystems (98.6 g·kg^{-1}) (Xu et al., 2013). This indicates that soils in tea plantations can store a significant amount of organic carbon and act as a carbon pool.

Chinese tea plantations were also experiencing soil acidification. The average soil pH of tea plantations across China was 4.74, ranging from 2.97 to 8.38, which was slightly higher than the national average of 4.68, with a range of 3.96–5.48, as reported in Yan et al. (2020). This could be due to measures taken to address soil acidification, the encroachment of more tea plantations onto other land uses with higher base pH (Chen et al., 2018; Zhu et al., 2017), or the difference on soil parent materials and soil formation processes (Table 1). Soils developed from limestone and river alluvium, which are widely distributed in north and south Yangtze zones, often exhibit high pH (>7) (Geodata, 2024; Zhao et al., 2019), while stronger weathering and aluminous accumulation processes often lead to more acidic soils (Table 1). We also observed that a few tea plantations, mostly in the north Yangtze zone, had soil pH higher than 6.0. However, tea requires acidic soil for growth, and high soil pH can affect tea growth (Yan et al., 2018). To ensure tea productivity, the soil may need to be pretreated with special materials, such as aluminum sulfate (Fung et al., 2008), which could increase the investment in tea cultivation and potentially harm local ecosystems or increase the risk of environmental contamination, thus posing a burden on the sustainable development of the tea industry. Although the soil pH was still within the lower band of the optimal soil pH for tea growth, many tea plantations had a soil pH lower than 4.5, particularly in the southern and south Yangtze zones (Figure 2). Furthermore, only 47.1% of soil samples in the present study had a pH in the interval of 4.5–5.5, while 40.8% and 10.1% of the soil samples had pH levels lower than 4.5 and 4.0. Low pH increases the leaching loss of cationic nutrients such as K, Na, Ca, and Mg (Zhang et al., 2016) and inorganic carbon (Raza et al., 2021), thereby inhibiting tea growth and reducing yield and quality and increases greenhouse gas emissions (Fung et al., 2008), thus restricting the sustainable development of the tea industry in China and contribute to global climate change.

4.2 Factors influencing ecological stoichiometry

The status of soil nutrients and pH in China's tea plantations varied among cultivation zones (Figures 2–6) and closely related to geographic and climatic factors (Table 4). At the national level, longitude, latitude and elevation were the key factors affecting the status of soil nutrients and pH. This may be because geological positions influence the climate gradient and parent material, which in turn determine soil development (Tsozué et al., 2019), and eventually influence the status of soil nutrients and pH (Li et al., 2023). The significant correlations between the concentration of soil nutrients and MAP and

MAT, as well as the significant variation in soil nutrient concentrations among soil classifications (Tables 5–6) also confirmed this.

320   Soil management strategies also influence the status of soil nutrients and pH. The age of tea plantations significantly influenced soil pH, the concentrations of AN and SOM, and the ratios of C:N and C:P. Tea is an aluminum (Al)-accumulating plant, and increased Al-accumulation (Wang et al., 2010) over plantation years, associated with the application of N fertilizer, might be the main reason for the decrease in soil pH. The application of N fertilizer, mainly NH+-N fertilizer, can accelerate soil acidification (Yan et al., 2018). Low pH restricts microbial activities and thus decreases SOC

325   decomposition (Zheng et al., 2020), and consequently increase SOM (Figure 7), thus beneficial for SOC sequestration. Fertilizer application was another factor strongly influencing the status of soil nutrients and pH. The comparison among fertilizer strategies indicated that the application of organic fertilizer was beneficial for improving the levels of soil nutrients and pH, especially for the improvements in AK and TK (Tables 7–8). As Figure 7 illustrates, soil AN and TN are positively correlated with SOM and TP but negatively correlated with TK. Therefore, the application of N fertilizer might be beneficial

330   for SOC sequestration but produce a negative effect on the nutrient balance between N and K.

        Additionally, the effectiveness of influential factors varied. Among geological factors, elevation had a stronger influence on soil nutrients and pH, which could be due to its stronger control over local climate, thereby affecting the formation process and weathering of soil. Meanwhile, fertilizer strategies directly shaped the levels and balance of soil nutrients and pH at a relatively rapid pace, and thus exerted stronger influence on soil nutrients and pH than soil

335   classification. However, it is worth noting that soil classification has a more significant influence on TK because K primarily comes from the soil itself, and the application of K fertilizer is not common in tea plantations.
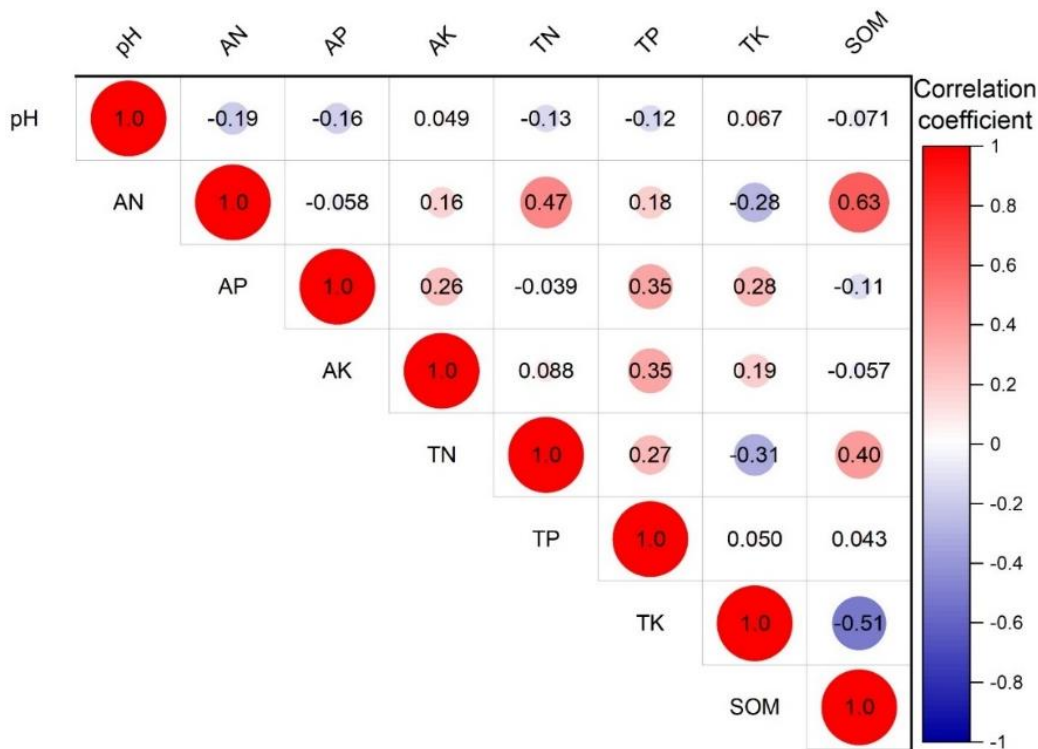
Figure 7. Correlations (Pearson's r) between pH, SOM and soil nutrients in Chinese tea plantations.

4.3 Recommendations

Based on the results and discussions above, some recommendations were made for the improvement of the status of soil nutrients and pH in Chinese tea plantations. First, soil K concentrations were low in tea plantations and showed a decreasing trend from west to east and from north to south, similar to the findings of Geng et al. (2020), and were negatively affected by elevation. The application of K fertilizer is recommended for tea plantations, especially in southern regions and at high altitudes. Additionally, fertilization strategies should be based on local geological and climatic conditions, as they are influential factors of soil nutrients. Second, it is recommended to adjust fertilizer strategies, such as using less chemical fertilizer or replacing it with organic fertilizer, to tackle soil acidification, nutrient deficiencies and imbalances. Third, as Table 4 illustrates, high temperatures harm the accumulation of soil nutrients and contribute to soil acidification. Cultivating shading trees in tea plantations, especially in the southern zone and at low elevations, is recommended to alleviate heat damage (Wu et al., 2015) and improve the activities, number and richness of soil microorganisms (Wang et al., 2019), thereby, benefiting soil nutrient balance and mitigating soil acidification. Fourth, the status of soil nutrients and pH should be assessed before converting other land uses to tea plantations to ensure the suitability of tea cultivation and proper soil management planning, so as to reduce the risk of environmental pollution. Finally, extending the cultivation duration of tea plantations is also recommended for SOC sequestration, as Wang et al. (2010) have indicated that the soil acidification rate

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decreases with tea cultivation time, and Wang et al. (2023) have indicated the great potential of SOC sequestration in tea
355 plantations. This could contribute to achieving carbon neutrality in the tea industry and mitigating global warming.

4.4 Limitations, uncertainties and future outlooks

It is difficult to accurately evaluate the status of soil nutrients and pH in tea plantations covering all soil types, tea
plantation ages, geological, meteorological and management varieties and existing periods across the whole country due to
the large and increasing tea cultivation area in China. In this study, only a few soil types and fertilizer strategies were
360 compared because of data deficiency, and the study period spanned a decade. However, the amount and method of fertilizer
application also influence soil physiochemical and biological characteristics (Xie et al., 2019; Liu et al., 2024). Furthermore,
more ecological management practices, such as intercropping, poultry raising, and applying biochar or microbial fertilizers,
have been introduced to tea plantation management (Duan et al., 2024; Liang et al., 2023). The comparison among a limited
number of soil types and management strategies may restrict the application of the findings in this study. In this case, more
365 efforts should be made to explore the effect of varied and combined management strategies on the soil physiochemical
properties, either through experiments or meta-analysis, to support the sustainable development of tea industry. Besides, the
extended study period may exacerbate the unavoidable uncertainties arising from differences and variations in climate, soil
texture, nutritional condition, and management practice among regions and provinces during this period, leading to
uncertainties caused by legacy effects.

370 The data sources, methods of data collection, and the uneven distribution of data for each soil nutrient and cultivation
zone in this study will also introduce uncertainties. As stated in Section 2.2, soil data were collected from published literature.
Varied research methods among studies may lead to uncertainties. Moreover, the imprecise longitude and latitude of the
study sites, extracted based on the name of the study area from the Baidu Map, will cause uncertainty. In addition, MAT and
MAP were adopted as climatic factors influencing soil nutrients and pH. However, the annual averages of MAT and MAP
375 cannot reflect soil temperature and moisture, nor the distribution of temperature and precipitation throughout the year. The
status of soil nutrients and pH may be influenced by the evenness of precipitation distribution, precipitation in growing
seasons, or the occurrence of extreme climate events. Therefore, the influence of climate factors on soil nutrients and pH
requires further investigation. As illustrated in Table 3 and Figures 1–6, the numbers of observations for soil nutrients and
cultivation zones were uneven, with more attention focusing on available nutrients and pH, and concentrating in the
380 southwestern zone. Less attention has been paid to nutrient balance and other cultivation zones. This may affect the
comprehensiveness of the assessment of the status of soil nutrients and acidification, and the accuracy of comparisons among
cultivation zones, thus requiring wider coverage of soil nutrients and cultivation areas in future research.

In addition to soil pH and nutrients of N, P, K, many mineral elements are also important for the healthy growth of tea
plants and thus the productivity and quality of tea (Han et al., 2011). Future research should pay more attention to other
385 medium and micronutrients in tea plantation soils. Moreover, a more accurate assessment of tea plantation soil nutrients

should involve an in-depth investigation of the mechanisms and interactions between influential factors to guide the development of sustainable managerial strategies.

As suggested in section 4.3 and the literature, organic management strategies, such as intercropping and applying organic fertilizer or biochar, are often recommended as effective ways to improve soil fertility, buffer soil acidification (Xie et al., 2021), and increase profits. However, organic management strategies are not always environmentally and economically sustainable. For example, Mohamad et al. (2014) have pointed out that applying manure in olive plantations results in higher costs and environmental impacts when assessed from a life cycle perspective, possibly due to higher energy or labour consumption required for transport and application (Rahmah et al., 2022). De Keyser et al. (2024) have also pointed out that mineral fertilizer plays an important role in the fertilizer mix. Therefore, the viability of soil management innovations should be comprehensively assessed from both environmental and economic aspects in a life cycle approach to evaluate whether the benefits of these practices outweigh the associated impacts and costs.

5 Conclusions

In this study, we assessed the status and spatial variations of soil nutrients and pH in Chinese tea plantations and analyzed the relationships between these soil characteristics and influential factors, including soil classification, management practices, and climatic and geographic factors using data collected from literature. The results indicated that less than 45% of the observed tea plantations could meet the standards for high-quality tea plantations, and more than 20% of tea plantations were facing soil nutrient deficiencies, especially in TN, TP and AK. A significant portion of tea plantations was also facing soil acidification. The status of soil nutrients and pH varied among cultivation zones due to the influence of geographic and climatic factors. Additionally, management practices, including the age of tea plantations and fertilization strategies, had significant influences on the status of soil nutrients and pH. Based on the results, recommendations such as applying K fertilizer in southern and high-altitude tea plantations, adjusting fertilization strategies, extending the cultivation duration of tea plantations, and planting shading trees were proposed to mitigate soil acidification and to improve the concentrations and balance of soil nutrients and SOC sequestration ability in Chinese tea plantations. Furthermore, more efforts should be made to cover a broader range of soil nutrients and cultivation areas in the assessment and to explore the mechanisms and interactions between influential factors.

Author contributions

Conceptualization, funding acquisition, Data collection, analyses, writing and revision: DW. Conceptualization, writing and revision, funding acquisition: WY. Writing and revision, funding acquisition: BL. Writing and revision: FL, JH, ZW, RC,YZ.

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