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 study addressing this topic at a national level 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 could 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 locations, climate, and soil types. 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 rotational cycle duration of cultivation, and planting shading trees were recommended to improve soil nutrient availability and balance and mitigate soil acidification. Specifically, applying K fertilizer to tea plantations in the southern zone and/or at high altitudes was recommended.

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 and producer at the globe (FAO and CAAS, 2021). 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 is degrading, such as soil acidification and nutrients imbalance (Yang et al., 2023), which might 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 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) and pH are important indicators indicating 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 restriction, overload and imbalance of soil nutrients (Su et al., 2019), which determines nutrient availability for plants and soil microorganisms and further influences the functioning of ecosystems (Zheng et al., 2021). However, previous studies assessing the status of soil nutrients primarily focused on local (Hua and Li, 2018) or regional scales (Zhang and Shu, 2021), the 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 soil physical, chemical and biological properties and processes influencing plant growth and biomass yield (Neina, 2019). As an important aspect of soil degradation, soil acidification has been widely studied and reported across a variety of ecosystems and regions, such as cropping systems (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 enlarges the imbalance of soil nutrients (Zhang et al., 2016), and also causes soil inorganic carbon loss (Raza et al., 2021). Soil acidification in tea plantations gains specific attention because of the special property of tea which prefers acidic soil for growth and in turn acidifies soil (Yan et al, 2018). Yan et al. (2020) reported the status and variation of soil acidification in China’s tea plantations based on 2058 datasets collected from literature covering 225 tea-planting counties in 19 provinces (without Taiwan) in China, analyzed its historical change trend (between the 1980s and 2000s) and compared it to other ecosystems. Zhang et al. (2022) reported the soil pH in China's tea-planting provinces (without Taiwan and Gansu) 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.

The status of soil nutrients (Zheng et al., 2012) and pH (Yan et al., 2020) varied spatially and was 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 influence the concentrations and distributions of soil nutrients (Shao et al., 2022). For example, Wang et al. (2018) demonstrated that soil total nitrogen (TN) and organic carbon (SOC) were positively correlated with elevation in non-karst soils. Meanwhile, the physiochemical conditions of soil; for example, texture, bulk density, pH and contents of nutrients, are closely related to soil types, influencing microbial activities and vegetation productivity, and consequently the status of soil nutrients (Di et al., 2020). Ge et al. (2019) reported that the contents and ratios of soil C, N and P were significantly affected by clay content, which was closely related to soil types (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 al., 2016); therefore, possibly control the concentrations and stoichiometric ratios of soil nutrients. Together, the status of soil nutrients and pH may depend on environmental conditions. However, what and how environmental factors determine the status of soil nutrients and pH in tea plantations at a national scale remains unknown.

Agronomic management practices, such as tillage, fertilization, cultivation period and biomass harvesting, change 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 degrading, 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) reported that tea plantations had higher soil TN than forests and a 100-year-old tea plantation held higher SOC than forest. On the other hand, fertilizer application can replenish some soil nutrient loss, but may also cause an imbalance of soil nutrients and soil acidification, and other environmental problems depending on fertilization strategies (Vitousek et al., 2009). Organic fertilizer can improve crop productivity while increasing concentrations of soil nutrients (e.g., total C, N, P) and resisting soil acidification (Shi et al., 2019), as well as reducing nutrient runoff losses (Yan et al., 2023). Inorganic fertilizers can efficiently improve the concentrations of available nutrients (e.g., available P and K), but may cause soil acidification (Jin et al., 2023). Over N fertilization was recognized as the major cause of serious soil acidification in China's tea plantations (Yan et al., 2020). The combined application of organic fertilizer and inorganic fertilizer was considered the best way to improve the concentrations of soil nutrients (Quan et al., 2020). Briefly, 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 strengthen the national and local soil assessments and predictions and to support the employment of effective strategies for maintaining or improving soil fertility in tea plantations and environmental protection, this study assessed the status of soil nutrients and pH in China's tea plantations, compared the differences among cultivation zones, and analyzed the influential factors including geological (longitude, latitude, elevation, soil classification) and climatic (mean annual temperature and precipitation) factors, and management practices (stand age and fertilization strategies). Based on the assessments and analyses, 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? and 3) what measurements can be done to tackle 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 includes all 20 tea-planting provinces in China (Figure 1). They 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).

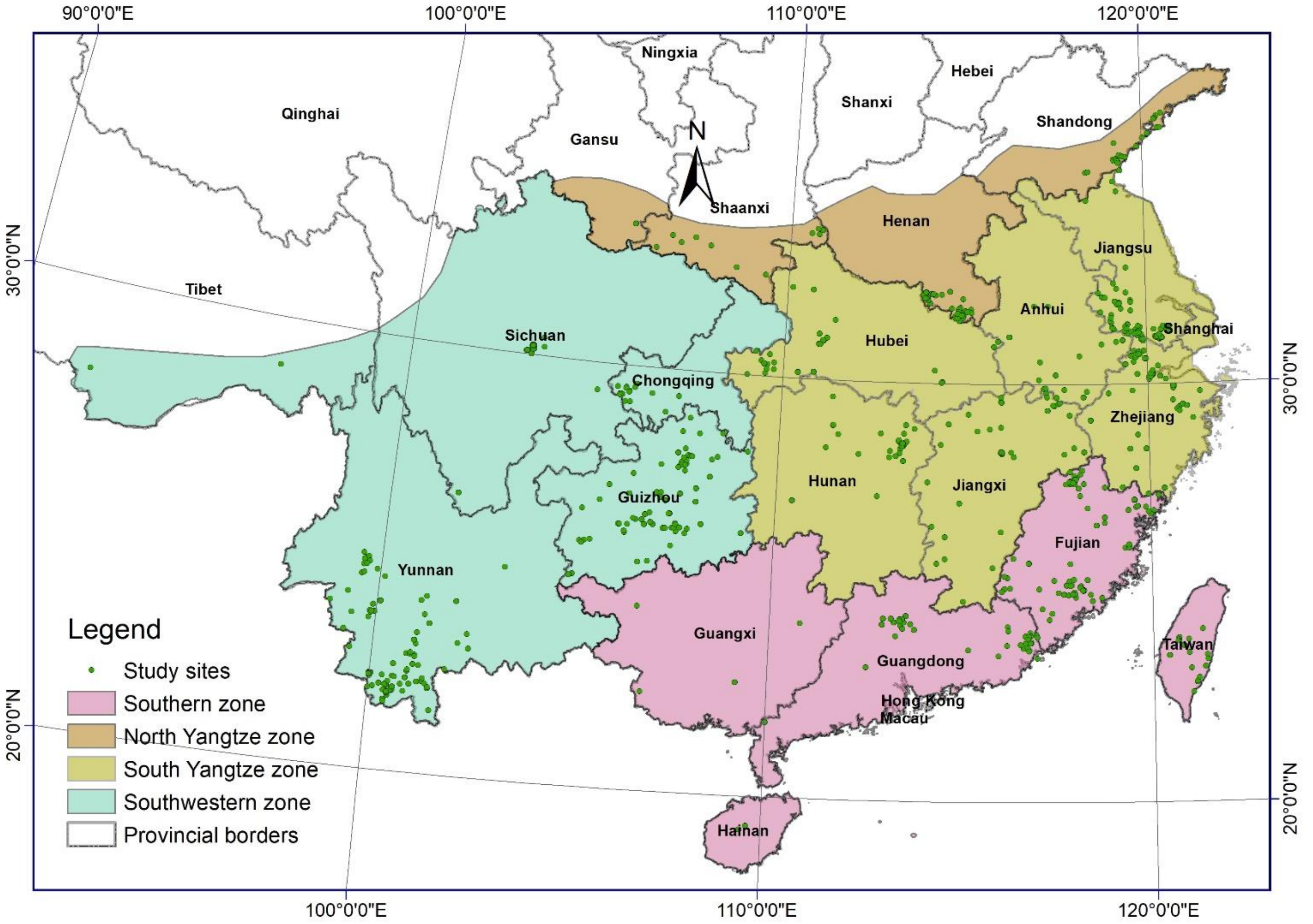

Figure 1. Tea cultivation zones and provinces in China and the spatial distribution of study sites.

2.2 Data collection and compilation, and assumptions

Journal articles published between 2000 and May 2023 were searched and collected using the searching 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 using the criteria: (1) experiments were conducted in the field and within the boundary of China, and (2) soil depth was indicated and thicker than 10cm in the literature. After filtration, 379 published articles met the criteria and were viewed for data collection. In total, 1843 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 concerning soil classifications, sampling depth, stand age of tea plantations, cultivation zone, longitude, latitude, elevation, mean annual precipitation

(MAP), mean annual temperature (MAT), and fertilization strategies were also collected and recorded in the database. Soil classifications were referred to the Classification and Codes for Chinese Soil (GB/T 17296-2009) for consistency and comparability with literature because most studies where we collected data used the Chinese soil classification system, and it was challenging to translate soil types between different soil classification systems due to their difference in scientific basis, classification principles and hierarchy, etc. (Table 1). The 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.

Table 1. A brief comparison of Chinese and international soil classification systems (Shi et al., 2004; Gerasimova, 2010; Wang et al., 2020)

Feature	Chinese soil classification system	American soil classification system	WRB (World Reference Base) soil classification system
Classification Principles	Based on the geographical distribution, genesis, and soil properties	Based on diagnostic horizons and properties, emphasizing soil temperature, moisture, and other classification indicators	Based on modern soil classification concepts, including Soil Taxonomy, the legend for the FAO Soil Map of the World 1988, the Référentiel Pédologique, and Russian concepts
Classification Hierarchy	Includes levels such as soil classes and soil types	Includes orders, suborders, great groups, subgroups, families, and series	Includes two levels: Reference Soil Groups and qualifiers
Naming Basis	Considers the genesis and characteristics of the soil	Based on soil properties and clear criteria for classification units	Combines diagnostic criteria and soil characteristics
International Applicability	Focuses on soil types and distributions specific to China	Used as the primary or secondary classification by more than 80 countries worldwide	Aimed at providing a unified classification and naming standard for global soil types
Scientific Basis	Combines China's soil science research achievements and field survey data	Developed by the U.S. Department of Agriculture (USDA) with the participation of more than 1,500 pedologists worldwide	Based on the work carried out by FAO, ISRIC World Soils, and the Universities of Leuven and Wageningen
Updates and Revisions	Regularly revised to reflect developments in scientific research and survey techniques	Regularly updated, with the latest version being the 12th edition in 2014	Regularly updated, with the latest version being the 4th edition in 2014
International Cooperation	Mainly based on the research achievements of Chinese experts	Accepted by many countries, especially in Latin America and Asia	Coordinated by IUSS, it is the result of international cooperation

In this study, a soil depth of 0–30 cm was utilized to explore and compare the concentrations and stoichiometric ratios of soil nutrients, but sampling depths varied among the published articles. Under this circumstance, some assumptions and processing were applied to unify the soil depths. In some articles, soil depths were 0–30 cm or thicker than 0–30 cm but 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 regarded as the same as that in the soil layer of 0–30 cm. In other articles, soil depths for sampling were thinner than 0–30 cm, e.g., 0–20 cm. In these cases, the stoichiometry of soil nutrients in the soil layer of 0–20 cm was assumed to be the same as that in the soil layer of 0–30 cm.

2.3 Data processing and analysis

Some calculations were conducted for the articles that only reported partial information about soil nutrients. Conversion between SOM and SOC was performed using a constant of 1.724 to divide SOM or multiple SOC (Fang et al., 2012). For the studies only reporting the concentrations of soil nutrients, the ratios of C:N, C:P, N:P, C:K, N:K and P:K were calculated and transformed before analysis to ensure consistency and comparability among studies. The stoichiometric ratios of soils were expressed in mass ratios of SOC, TN, TP and TK. Mass ratios were commonly used in literature where we collected data from and other meta-analyses of soil nutrients (Shi et al., 2016).

Statistical analyses were conducted using SPSS software ver. 23 (SPSS Inc., Chicago, IL, United States of America). One-way ANOVA was performed to assess the differences in the stoichiometry of soil nutrients and pH among tea cultivation zones, fertilizer strategies, and soil classifications. Then, post-hoc multiple comparisons between two groups were performed with the Tukey HSD method. Correlations between the stoichiometry of soil nutrients, soil pH, and geological and climatic factors and stand ages of tea plantations, as well as the interactions among soil nutrients and pH, were analyzed to explore the factors influencing the status of soil nutrients and acidification. The significances of all statistical tests were set up at the level of 0.05.

2.4 Classification of tea plantations

Tea plantations were classified into four levels based on the concentrations of soil nutrients (Table 2) according to 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 ($g \cdot kg^{-1}$)	≥20	>15	10–15	<10
TN ($g \cdot kg^{-1}$)	≥1.5	>1.0	0.8–1.0	<0.8
TP ($g \cdot kg^{-1}$)	≥1	>0.6	0.4–0.6	<0.4
TK ($g \cdot kg^{-1}$)	≥10	>10	5–10	<5
AN ($mg \cdot kg^{-1}$)	≥100	>100	50–100	<50
AP ($mg \cdot kg^{-1}$)	≥20	>10	5–10	<5
AK ($mg \cdot kg^{-1}$)	≥100	>120	80–120	<80

3 Results

3.1 Status and variations of soil nutrients and pH

The number of observations reporting the concentrations and stoichiometric ratios of soil nutrients and pH in Chinese tea plantations are summarized in Table 3. The frequency distributions of soil nutrients and pH in each cultivation zone are illustrated in Figure 2–6. At the national level, the average concentrations of all soil nutrients, except for TP, were higher than the standards of soil nutrients in high-quality tea plantations (Table 2–3). However, the concentrations of soil nutrients showed great variations, especially for available nutrients (AN, AP, and AK). The status of soil nutrients in 40.9% of the observed tea plantations could meet the standards of high-quality tea plantations, but more than 20% of tea plantations were classified as level Ⅲ tea plantations because of the deficiency of soil nutrients and unsuitable soil pH. Importantly, 46.5% and 32.0% of observed tea plantations showed a deficiency in soil AK and TP, and the pH of 52.9% of the soil samples were located out of the range of the optimal soil pH for tea growth (4.5–5.5). It was worth noting that the stoichiometric ratios of soil nutrients in China's tea plantations varied in wide ranges, especially for the ratios of C:N, C:P and C:K (Table 3 and Figure 5–6), indicating some of China's tea plantations was facing 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	0.2–1011.8	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	1165	0.1–1244.8	16.5	42.1	-	-	-	-
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.

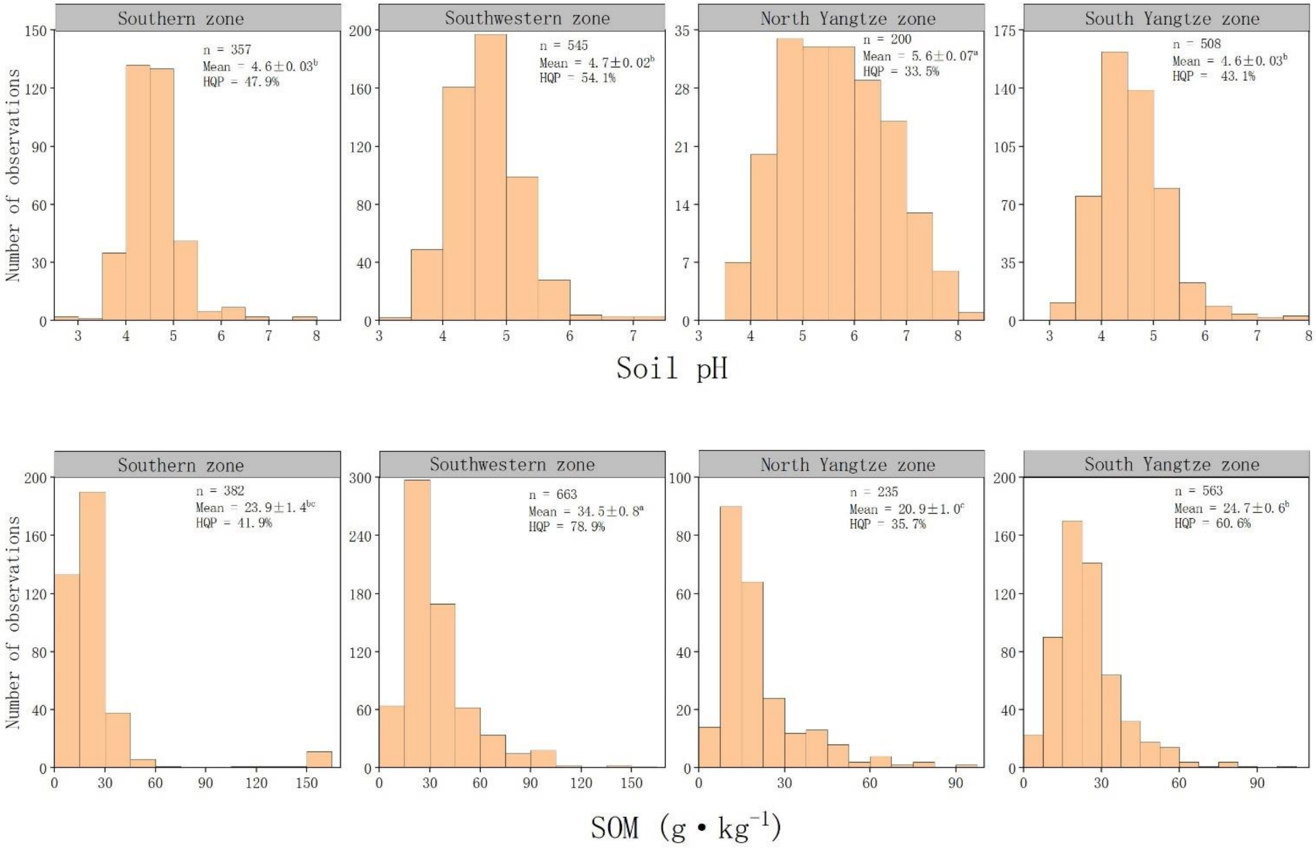

Figure 2. Frequency distribution of soil pH and SOM in tea plantations in each cultivation zone. n is the number of observations; HQP represents the percentage of high-quality tea plantations; letters on values indicate significant differences among cultivation zones at the 0.05 level.

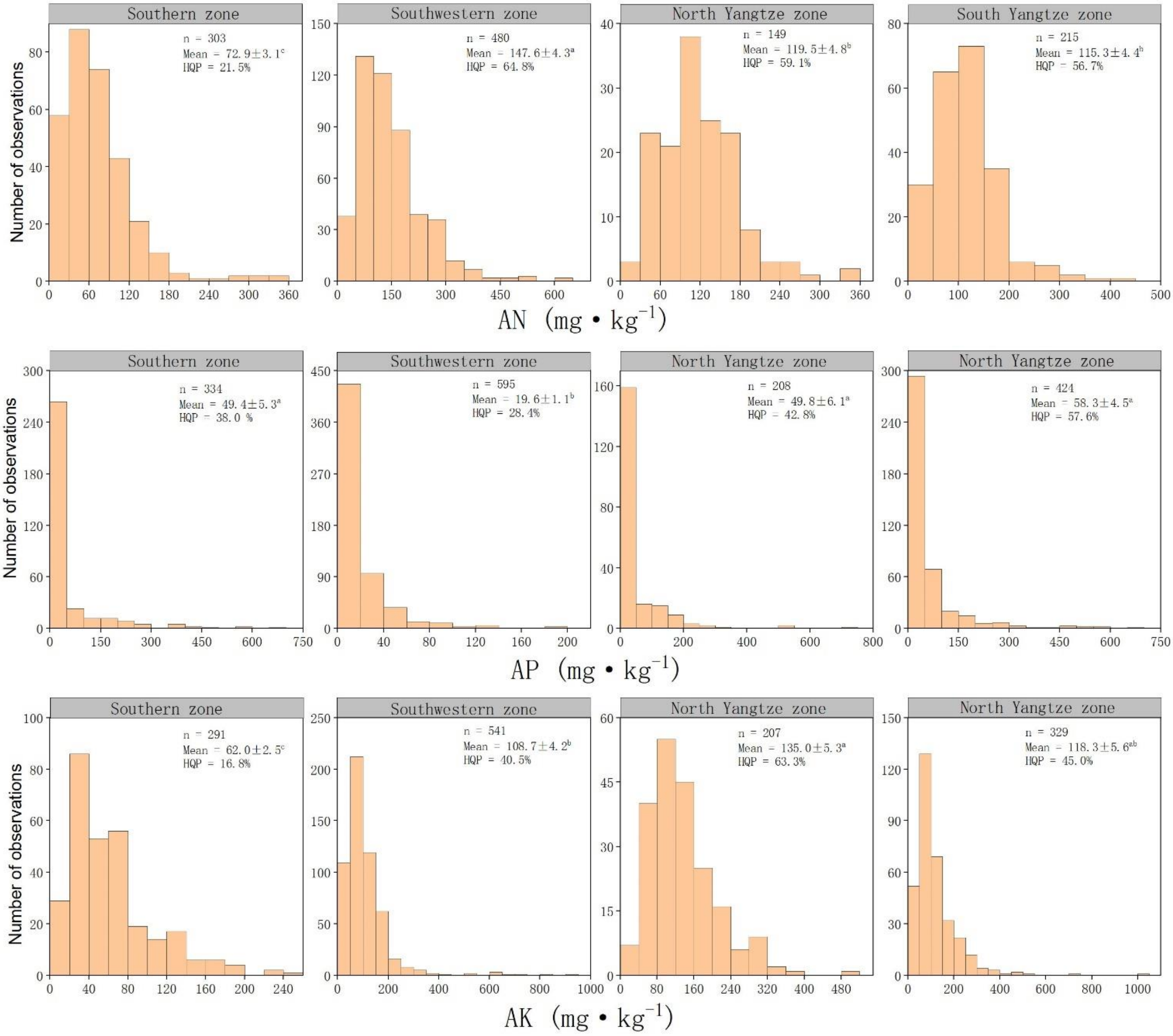

Figure 3. Frequency distribution of soil AN, AP and AK in tea plantations in each cultivation zone. n is the number of observations; HQP represents the percentage of high-quality tea plantations; letters on values indicate significant differences among cultivation zones at the 0.05 level.

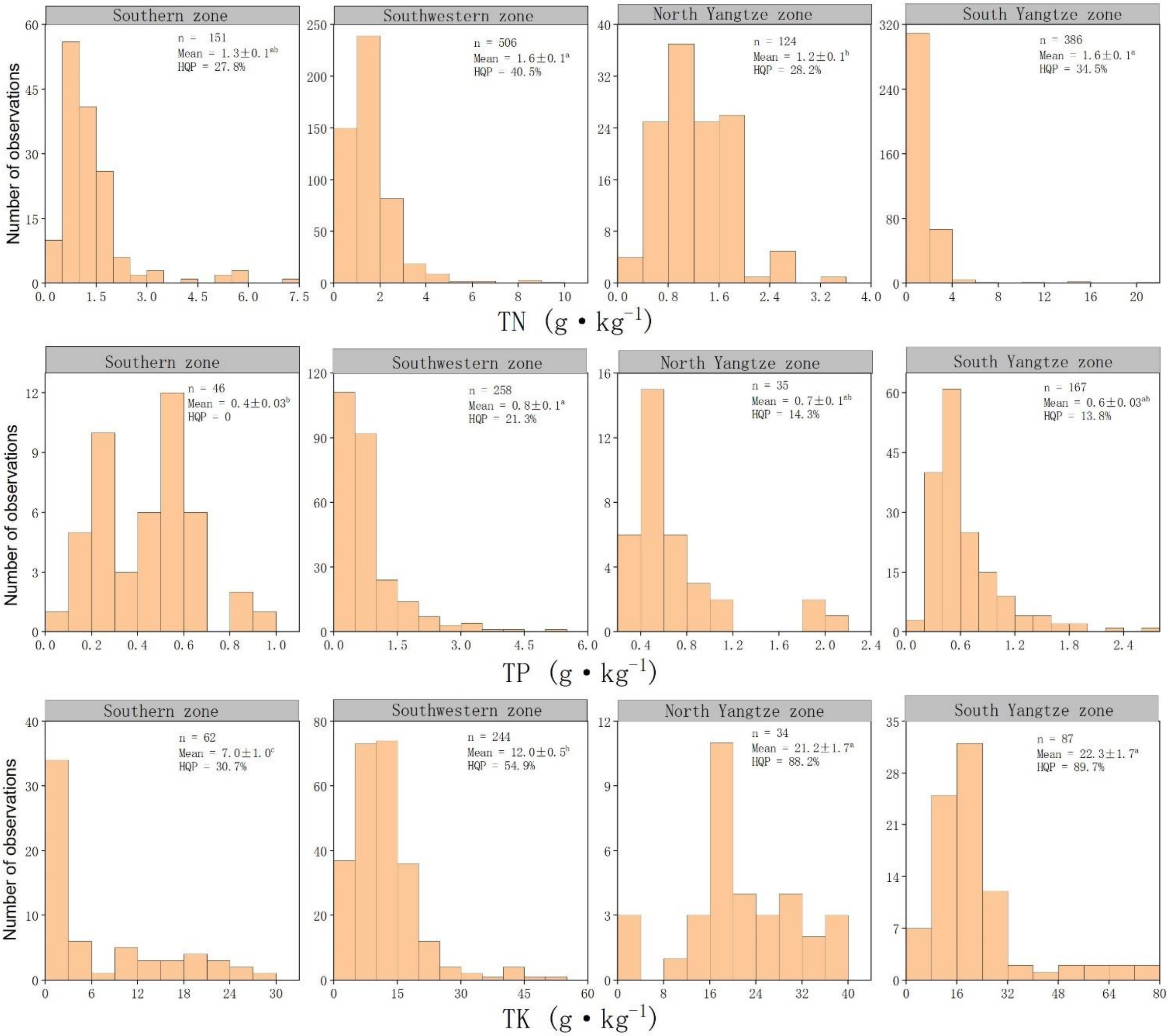

Figure 4. Frequency distribution of soil TN, TP and TK in tea plantations in each cultivation zone. n is the number of observations; HQP represents the percentage of high-quality tea plantations; letters on values indicate significant differences among cultivation zones at the 0.05 level.

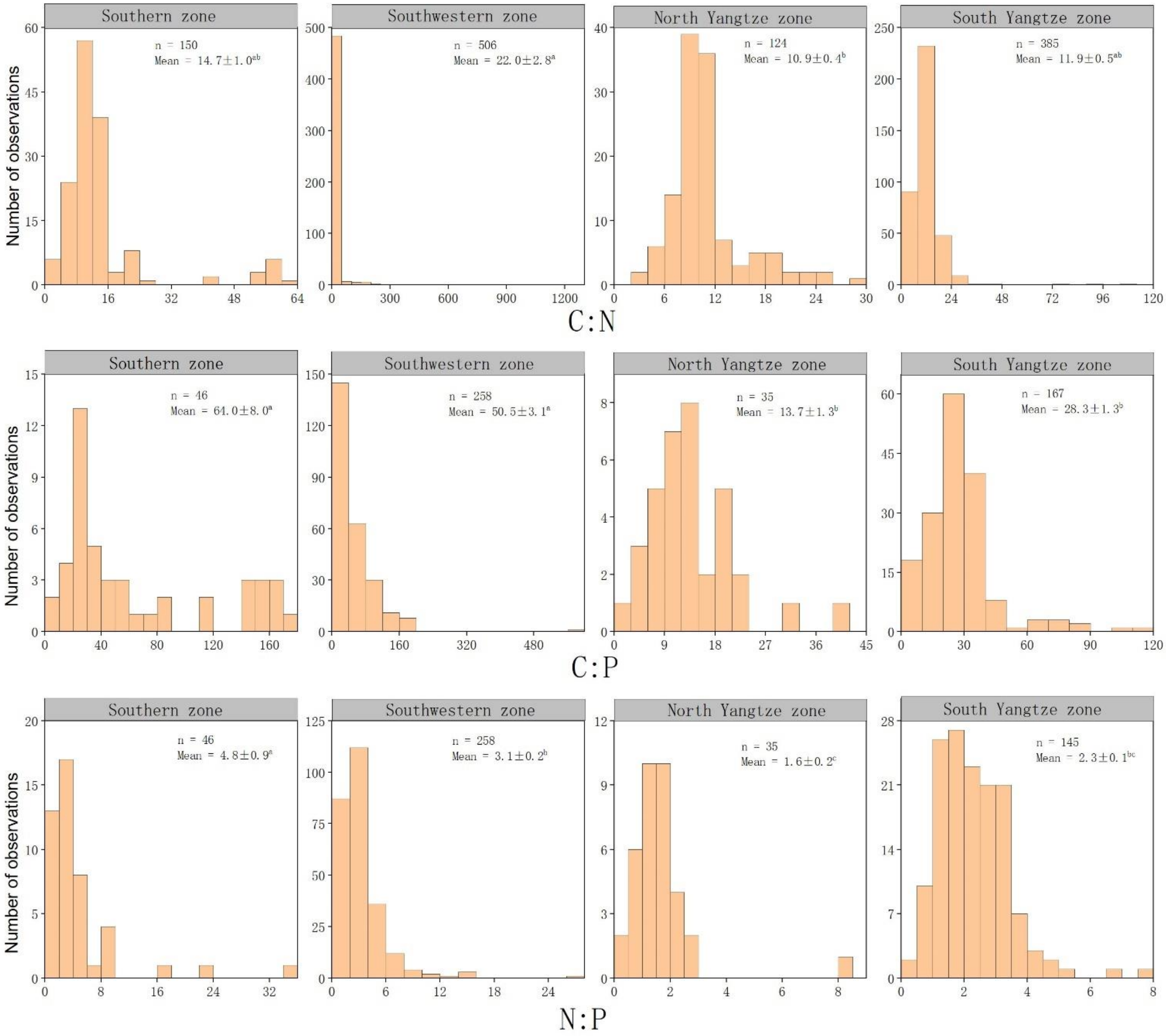

Figure 5. Frequency distribution of stoichiometric ratios of C:N, C:P and N:P in tea plantations in each cultivation zone. n is the number of observations; letters on values indicate significant differences among cultivation zones at the 0.05 level.

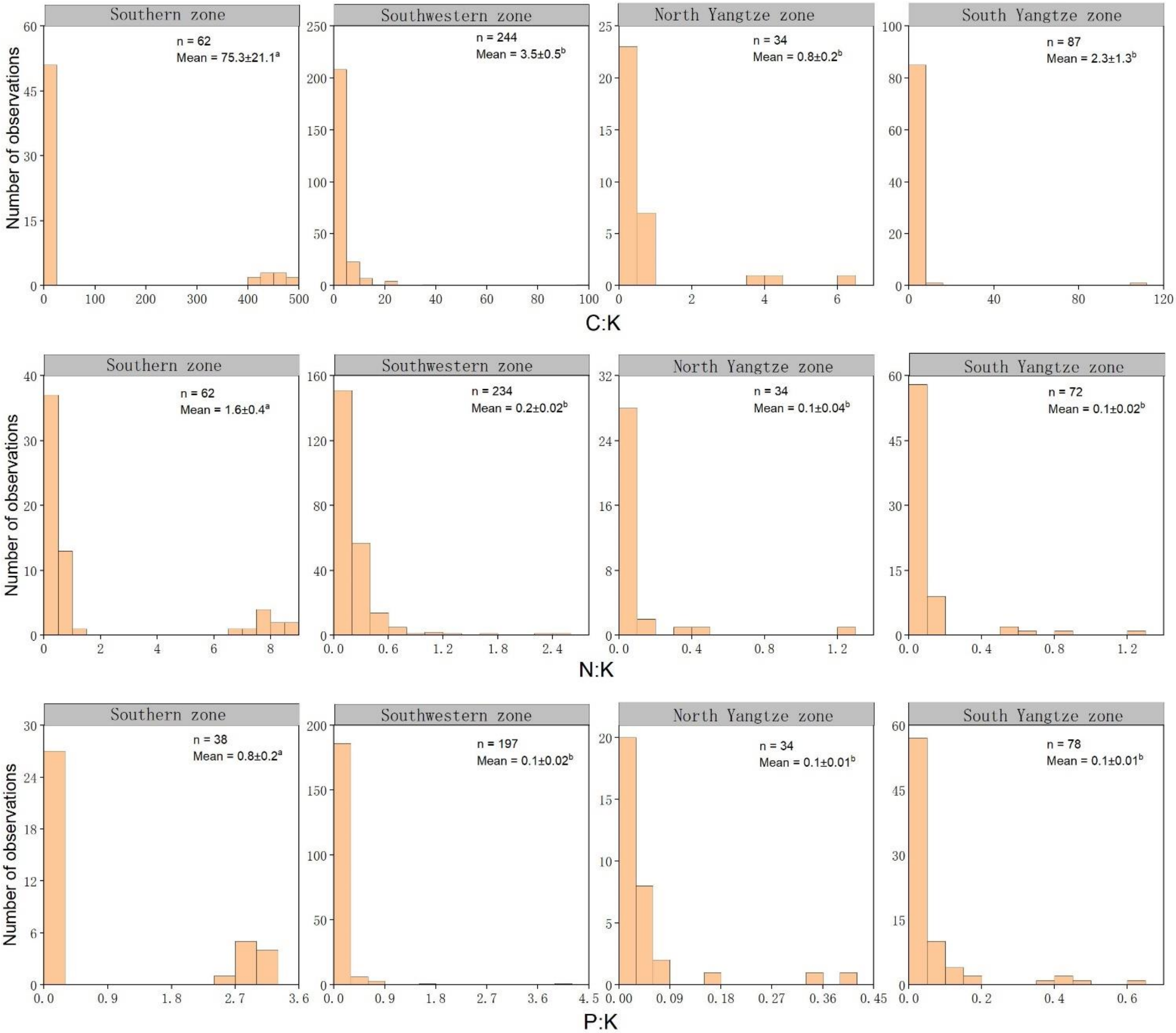

Figure 6. Frequency distribution of stoichiometric ratios of C:K, N:K and P:K in tea plantations in each cultivation zone. n is the number of observations; letters on values indicate significant differences among cultivation zones at the 0.05 level.

Besides, the ecological stoichiometry of soil nutrients and soil pH showed significant spatial variations among cultivation zones (Figure 2–6). Specifically, tea plantations in the southwestern zone had the highest concentrations of soil AN and SOM but varying with wide ranges, while tea plantations in the southern zone showed the lowest concentrations of soil AN, AK and TK ($P<0.05$). Soil pH of tea plantations in the north Yangtze zone was significantly higher than 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%) because of the low concentrations of AN, AK, TK and the extremely low concentration of TP (Figure 3–4). Less than half of tea plantations in southwestern (47.9%) and north Yangtze (45.6%) zones could meet the standards of high-quality tea plantations. Stoichiometric ratios, except for C:N and C:P, of soil nutrients in the southern zone were significantly higher than in other cultivation zones. Furthermore, the soil of tea plantations in the southwestern zone showed wide ranges of SOM, TP, TK, AN and AK, as well as the resulting ecological stoichiometric ratios of C:N, C:P, N:P and P:K, and tea plantations in the south Yangtze zone showed wide range of the soil nutrients in AN, AP, AK, TN and TK, while tea plantations in southern zone showed wide range of the soil nutrients in SOM and AP, as well as the resulting ecological stoichiometric ratios of N:P, C:K, N:K and P:K.

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 stoichiometric ratios of C:N and C:P decreased significantly from west to east ($P<0.05$), but the concentration of AP, and the stoichiometric ratios of C:K, N:K and P:K increased significantly from west to east ($P<0.05$), while N:P had no obvious variation at longitude gradient ($P>0.05$). Latitude had positive influences on the concentrations of AN, AP, AK, TP, TK and pH, but negatively affected the concentration of SOM and the stoichiometric ratios of C:N, C:P and N:P ($P<0.05$). There was no significant difference in the stoichiometric ratios of C:K, N:K and P:K from south to north ($P>0.05$). The concentrations of AN, AK, TN, SOM, pH, and the stoichiometric ratios of C:P, N:P, C:K, and N:K increased with elevation ($P<0.05$), but the concentrations of AP and TK showed decreasing trend with elevation ($P<0.05$). Elevation did not significantly affect the concentration of TP, and the stoichiometric ratios of C:N and P:K ($P>0.05$). The concentrations of AN, AK, TK and pH decreased significantly ($P<0.05$) with increasing MAP and MAT. The change of MAP had an insignificant influence on the concentration of TP and the stoichiometric ratios of soil nutrients ($P>0.05$). The concentration of AP and the stoichiometric ratios of C:K, N:K and P:K were positively correlated with MAT ($P<0.05$), while there was no significant correlation between MAT and TP, the stoichiometric ratios of C:N, C:P and N:P ($P>0.05$).

In addition, the status of soil nutrients and pH varied among soil classifications (Table 5–6). Compared with other soil classifications, brown earth had significantly higher pH, and concentrations of AP, AK and TP ($P<0.05$). The concentrations of AN and SOM, and the stoichiometric ratios of C:P and N:P of Latosol were significantly higher than that of other soil classifications ($P<0.05$). The concentrations of TN of yellow-brown earth and C:N of yellow earth were significantly higher than those of other soil classifications.

Table 4. Pearson correlation analysis showing the influences of geological and climatic factors and the stand age of tea plantations on the pH and the concentrations and stoichiometric ratios of soil nutrients.

Variable	Longitude	Latitude	Elevation	MAP	MAT	Stand 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: -, negative correlation; +, positive correlation; *, correlation is significant at the 0.05 level (2-tailed); **, correlation is significant at the 0.01 level (2-tailed); ***, correlation is significant at the 0.001 level (2-tailed); ns, correlation is not statistically significant.

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}
Latosol	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 has fewer than two cases.

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
Latosol	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}	37.2±10.9^{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 has fewer than two cases.

3.3 Influences of management on ecological stoichiometry

Management practices had significant influences on the status of soil nutrients in tea plantations. Specifically, the stand age of tea plantations (or rotational cycle duration) had positive effects on 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). In terms of the influence of fertilization strategies on the status of soil in tea plantations, as illustrated in Table 7–8, the concentrations of AN, AK, TN, TP, SOM, pH and N:P were relatively higher under the mode of applying organic fertilizer than that in other fertilization modes. Applying either chemical or compound fertilizer alone was beneficial for improving the concentration of soil AP but the combined application of chemical and compound fertilizer could reduce soil pH. Besides, a combination of organic fertilizer with chemical and/or compound fertilizer could also reduce soil pH and the concentrations of some nutrients, such as AK and TN.

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 has 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 has fewer than two cases.

4 Discussions

4.1 Implications of soil ecological stoichiometry and pH

The results indicated that Chinese tea plantations were experiencing soil nutrient deficiencies and imbalances, especially the deficiencies of TN, TP and AK. Soil C:N ratio (16.5) in tea plantations was lower than the appropriate C:N ratios (25) for soil microbial decomposition of organic matter (Zhang et al., 2019). The ratios of soil C:P (41.9) and N:P (2.9) in tea plantations were lower than those in global terrestrial ecosystems (110.9 and 7.9) (Xu et al., 2013). This would 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 that in previous research (Wang et al., 2024). This meant 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 the activities of soil microorganisms (Amtmann et al., 2008), finally 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 might be biomass harvest, mechanical disturbance of surface soil and improper fertilization. Besides, the high concentrations of available nutrients and extreme stoichiometric ratios of soil nutrients in certain parts of tea plantations indicated that they might experience over-fertilization, which can also cause waste of resources, environmental pollution and eutrophication downstream of the catchment. Strategies, such as applying organic fertilizer and K fertilizer, should be made to improve the level of TN, TP and AK and nutrient balance. Organic fertilizer can improve the soil nutrient balance and reduce environmental pollution by slowly releasing nutrients (Shaji et al., 2021). However, most tea plantations had a high level of SOM, even higher than those (in 0–20 cm soil layer) in China's terrestrial ecosystems (21.1 $g\cdot kg^{-1}$), forests (24.7 $g\cdot kg^{-1}$) and croplands (19.2 $g\cdot kg^{-1}$) (Pan et al., 2021), but lower than that in global terrestrial ecosystems (98.6 $g\cdot kg^{-1}$) (Xu et al., 2013). This means that soils in tea plantations stock a certain quantity of organic carbon and can work as a carbon pool.

Chinese tea plantations were also experiencing soil acidification. The average soil pH of tea plantations for all of 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 from Yan et al. (2020), possibly because some measurements had been applied to tackle soil acidification, more tea plantations encroached to other land uses which had higher base pH (Chen et al., 2018; Zhu et al., 2017), or the spatial distribution of soil parent materials. 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). We also noticed that there were a few tea plantations, mostly in the north Yangtze zone, having soil pH higher than 6.0. However, tea requires acidic soil for growth and high soil pH will influence tea growth (Yan et al., 2018). To ensure tea productivity, the soil should be pretreated with special materials, such as aluminum sulfate (Fung et al., 2008). This should increase the investment in tea cultivation and might harm the local ecosystems or increase the risk of environmental contamination, and eventually bring burdens on the sustainable development of the tea industry. Even though the soil pH was still located in the lower band of the optimal soil pH for tea growth, the soil pH in many tea plantations was lower than 4.5, especially in the southern and south Yangtze zones (Figure 2). Furthermore, only 47.1% of soil samples in the present study had pH in the interval of 4.5–5.5, while the pH of 40.8% and 10.1% of the soil samples were lower than 4.5 and 4.0. The 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 decreasing the yield and the quality of tea and increases greenhouse gas emissions (Fung et al., 2008), which would restrict 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 was varied among cultivation zones (Figure 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. The reason might be that geological positions influence climate gradient and parent material, which determine the development of soil (Tsozué et al., 2019), and eventually influence the concentrations and stoichiometric ratios of soil nutrients (Li et al., 2023). The significant correlations between the concentration of soil nutrients and MAP and MAT, as well as the significantly varied soil nutrient concentrations among soil classifications (Table 5–6) also confirmed this.

Soil management strategies also influence the status of soil nutrients and pH. The stand age of tea plantations significantly influenced soil pH, the concentrations of AN and SOM, and the stoichiometric ratios of C:N and C:P. Tea is an aluminum (Al)-accumulating plant and the increased Al-accumulation (Wang et al., 2010) with plantation years, associated with the application of N fertilizer, might be the main reason for the decrease in soil pH. In return, increased soil N and reduced pH could increase SOM (Figure 7), thus stimulating SOC sequestration. Fertilizer application was another factor 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 of AK and TK (Table 7–8). As Figure 7 illustrates, increased soil AN and TN can stimulate the accumulation of SOM and TP, but reduce the concentration of TK. Therefore, the application of N fertilizer might be good for the soil organic carbon sequestration but produce a negative effect on the nutrient balance of N-K.

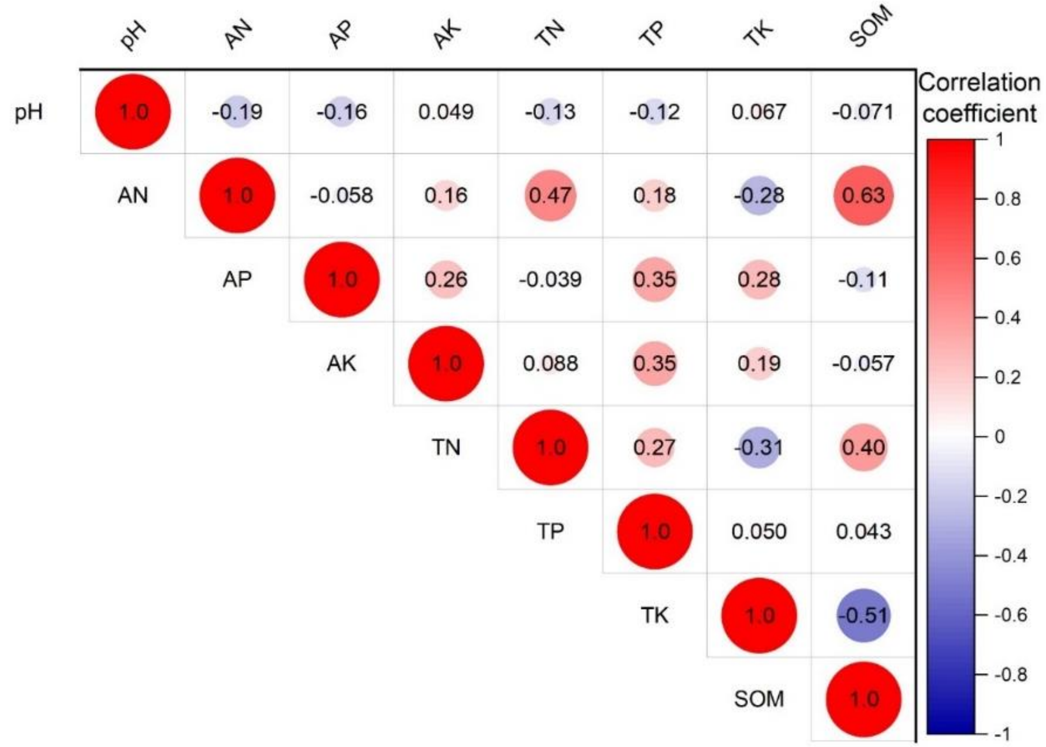

Figure 7. Correlations (Pearson's r) between pH, SOM and soil nutrients in Chinese tea plantations.

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, the concentrations of soil K were low in tea plantations and showed a decreasing trend from west to east and from north to south which was similar to that of Geng et al. (2020), and negatively affected by elevation. The application of K fertilizer was recommended for tea plantations, especially in southern regions and high altitudes. Besides, fertilization strategies should be based on the local geological and climatic conditions since they are influential factors in the concentrations and stoichiometric ratios of soil nutrients. Second, adjusting fertilizer strategies, such as using less chemical fertilizer or replacing it with organic fertilizer, was recommended to tackle soil acidification, nutrient deficiencies and imbalance. Third, as Table 4 illustrates, high temperature harms the accumulation of soil nutrients and contributes to soil acidification. Cultivating shading trees in tea plantations, especially for the plantations in the southern zone and low elevations, is recommended to alleviate the damage from heat (Wu et al., 2015) and improve the activities, number and richness of soil microorganisms (Wang et al., 2019) and thus benefit the soil nutrient balance and mitigation of soil acidification. Fourth, assessing the status of soil nutrients and pH should be made before converting other land uses to tea plantations to ensure the suitability of tea cultivation and proper plan-making on soil management, so as to reduce the risk of environmental pollution. At last, extending the cultivation duration of tea plantations was also recommended for SOC sequestration since Wang et al. (2010) indicated that soil acidification rate reduced with tea cultivation time and Wang et al. (2023) indicated the great potential of SOC sequestration in tea plantations. This should contribute to the achievement of carbon neutrality in the tea industry and the mitigation of 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 several soil types and fertilizer strategies were compared because of data deficiency, and the study period extended over ten years. However, the amount and method of fertilizer application also influence soil physiochemical and biological characteristics (Xie et al., 2019; Liu et al., 2024). In addition, more ecological management practices, such as intercropping, poultry raising, and applying biochar or microbial fertilizers, were also introduced to tea plantation management (Duan et al., 2024; Liang et al., 2023). The comparison among limited soil types and management strategies would restrict the application of the findings in this study. In this case, more efforts would be made to explore the effect of varied and combined management strategies on the soil physiochemical properties either via experiments or meta-analysis, to support the sustainable development of the tea industry. Besides, the extended study period may exacerbate the unavoidable uncertainties brought by the differences and variations in climate, soil texture, nutritional condition, and management practice among regions and provinces during this period. This will lead to uncertainties caused by legacy effects.

Data sources and the way of data collection, as well as the uneven amount of data for each soil nutrient and cultivation zone, in this study, will also introduce some uncertainties. As stated in Section 2.2, soil data were collected from published literature. Varied research methods among studies may lead to uncertainties. Besides, the imprecision longitude and latitude of the study sites extracted based on the name of the study area from the Baidu Map should cause uncertainty for sure. In addition, MAT and MAP were adopted as climatic factors influencing soil nutrients and pH. However, the annual averages of MAT and MAP cannot reflect soil temperature and moisture, and the distribution of temperature and precipitation in the whole 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. Therefore, the influence of climate factors on soil nutrients and pH requires further investigation. As illustrated in Table 3 and Figure 1–6. The numbers of observations for soil nutrients and cultivation zones were uneven, with more attention focused on available nutrients and pH, and concentrated in the southwestern zone. Less attention has been paid to nutrient balance and other cultivation zones. This may influence 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 heath growth of tea plants and thus the productivity and quality of tea (Han et al., 2011). Future research should pay more attention to other medium and micronutrients in tea plantation soils. Besides, A more accurate assessment of tea plantation soil nutrients should involve an in-depth investigation of the mechanisms of and interactions between influential factors to guide the potential 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, were often recommended as an effective way to improve soil fertility and buffer soil acidification (Xie et al., 2021), as well as increase profits. However, organic management strategies were not always environmentally and economically sustainable. For example, Mohamad et al. (2014) pointed out that applying manure in olive plantations resulted in higher costs and environmental impacts from a life cycle approach, which might be because of the higher energy or labour consumption for transport and application (Rahmah et al., 2022). De Keyser et al. (2024) also pointed out that mineral fertilizer had 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 the soil nutrients and pH 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 of high-quality tea plantations, and more than 20% of tea plantations were facing soil nutrient deficiency, especially the deficiency of TN, TP and AK. A certain part of tea plantations was also facing soil acidification. Besides, the status of soil nutrients and pH varied among cultivation zones because of the influence of geographic and climatic factors. In addition, management practices including the stand age of tea plantations and fertilization strategies have significant influences on the status of soil nutrients and pH. Based on the results, recommendations including 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 made to mitigate soil acidification and to improve the concentrations and balance of soil nutrients and SOC sequestration ability in Chinese tea plantations. In addition, more endeavours should be made to cover more soil nutrients and cultivation areas in the assessment and to explore the mechanism of 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.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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