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Status and influential factors of soil nutrients and acidification in Chinese tea plantations

Dan Wang [1, 2, 3], Fei Li [1, 2, 3], Benjuan Liu [1, 2, 3], Zhihui Wang [1, 2, 3], Jianfeng Hou [1, 2, 3], Rui Cao [1, 2, 3], Yuqian Zheng [1, 2, 3], Wanqin Yang [1, 2, 3]

[1]Zhejiang Provincial Key Laboratory of Plant Evolutionary Ecology and Conservation, School of Life Sciences, Taizhou University, Taizhou, Zhejiang, 318000, PR China
[2]Linhai Station of Zhejiang Provincial Forest Ecological Research, Taizhou University, Taizhou, Zhejiang, 318000, PR China
[3]Taizhou Key Laboratory of Mountain Ecological Restoration and Special Industry Cultivation, Taizhou University, Taizhou, Zhejiang, 318000, PR China

Correspondence to: Wanqin Yang (scyangwq@163.com)

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 tea industry. However, a study addressing this topic at a national level is lack. Thereby, we assessed the status, spatial variations, and influential factors of soil nutrients and acidification in China's tea plantations based on 1,843 data pairs collected from 379 published articles. The results showed that only 40.90% of the observed tea plantations could meet the standards of high-quality tea plantations and most tea plantations were facing soil acidification, and nutrient deficiencies and imbalance. Furthermore, the status of soil nutrients and pH varied among cultivation zones due to the impacts of geolocations, 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 ($P<0.05$). The status of soil nutrients and pH was also significantly shaped by management practices (e.g., rotational life cycle and fertilization strategies). Applying organic fertilizer, extending rotational life cycle duration of cultivation, planting shading trees were recommended to improve the soil nutrient availability and balance and to 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 for tea (FAO, 2022). China is the largest tea grower and producer at globe (FAO and CAAS, 2021). Its cultivation area, including Taiwan (CAEY, 2023), grows fast, expanding from 1.11 million hectares in 2000 to 3.40 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) and phosphorus (P) are important indicators indicating the health and fertility level of soil to support plant growth (Zhu et al., 2021), and the stoichiometric ratios of carbon (C), N, P and K reflect the restriction, overload and/or imbalance of soil nutrients (Su et al., 2019), which determines nutrients availability for plants and soil microorganisms and further influencing 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 is another vital property for the fertility and chemistry of soils, which affects many soil physical, chemical and biological properties and processes that affect 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 attentions 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, analyzed its historical change trend and compared it to other ecosystems. Zhang et al. (2022) reported the soil pHs in China's tea-planting provinces and the variations on altitudes and tea varieties. However, few information about what and how influential factors affects 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 geolocation (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, geolocation 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 remain 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 thus 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 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 and resisting soil acidification (e.g., total C, N, P) (Shi et al., 2019), as well as reduce 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 plantation (Yan et al., 2020). The combined application of organic fertilizer and inorganic fertilizer was considered as the best way for improving 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 S1). 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).

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’ and ‘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, and in total, 1843 data pairs 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, soil 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). 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 the consistency among studies.

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 soil 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 were regarded 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 only reported part of the 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). In terms of 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 before analysis.

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 in 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, as well as 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. 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 1) 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 1. Soil nutrients 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 were summarized in Table 2. The frequency distributions of soil nutrients and pH in China and each cultivation zone were illustrated in Figure S2–S6. 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 plantation (Table 1–2). However, the concentrations of soil nutrients showed great variations, especially for available nutrients (AN, AP, and AK). The status of soil nutrients in 40.90% of the observed tea plantations could meet the standards of high-quality tea plantation, and more than 20% of tea plantations were classified as level Ⅲ tea plantations because of the deficiency of soil nutrients and unsuitable soil pHs. Importantly, 46.49% and 32.02% of observed tea plantations showed a deficiency in soil AK and TP and the pHs of 52.92% 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 2 and Figure S5–S6), indicating some of China's tea plantations was facing serious imbalance of soil nutrients. We also observed that the concentration of available N, P and K in some tea plantations were very high (Figure S3).

Table 2. Concentrations and stoichiometric ratios of soil nutrients in Chinese tea plantations.

Indicator	n	Range	Mean	Std. Error	Std. Deviation (%)	Distribution frequency (%)			
						High-quality tea plantation	Level I	Level II	Level III
pH	1610	2.97–8.38	4.74	0.018	0.74	47.08	-	-	-
AN (mg·kg^{-1})	1147	0.84–649.71	118.14	2.40	81.17	51.09	51.09	31.65	17.26
AP (mg·kg^{-1})	1561	0.13–713.60	40.51	1.95	77.16	40.29	59.25	17.30	23.45
AK (mg·kg^{-1})	1368	0.23–1011.79	105.03	2.43	89.86	39.98	29.90	23.61	46.49
TN (g·kg^{-1})	1167	0.01–20.50	1.51	0.04	1.29	35.48	68.04	11.91	20.05
TP (g·kg^{-1})	506	0.05–5.40	0.69	0.03	0.59	15.61	39.32	28.66	32.02
TK (g·kg^{-1})	427	0.10–79.35	14.11	0.56	11.49	60.89	60.89	19.20	19.91
SOM (g·kg^{-1})	1843	0.60–159.59	27.57	0.48	20.45	59.96	77.54	13.94	8.52
Average percentage	-	-	-	-	-	40.90	52.79	19.77	21.39
C:N	1165	0.08–1244.78	16.49	1.23	42.11	-	-	-	-
C:P	506	1.58–573.39	41.85	1.91	43.05	-	-	-	-
N:P	484	0.06–34.31	2.92	0.13	2.94	-	-	-	-
C:K	427	0.08–485.04	13.48	3.29	68.17	-	-	-	-
N:K	402	0.01–8.84	4.01	0.06	1.22	-	-	-	-
P:K	347	0.004–4.00	0.18	0.29	0.53	-	-	-	-

Note: n is the number of observations.

Besides, the ecological stoichiometry of soil nutrients and soil pH showed significant spatial variations among cultivation zones (Table 3 and Figure S2–S6). 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 plantation in north Yangtze zone were significantly higher than other zones ($P<0.05$) (Table 3). In terms of the percentage of high-quality tea plantations, the south Yangtze zone showed the highest percentage of high-quality tea plantations while the southern zone had the lowest percentage of high-quality tea plantations because of the low concentrations of AN, AK, TK and extremely low concentration of TP. Stoichiometric ratios, except for the ratios of C:N and C:P, of soil nutrients in the southern zone were significantly higher than other cultivation zones. Furthermore, 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 concentrations 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 concentrations 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 concentrations of TP and the stoichiometric ratios of soil nutrients ($P>0.05$). The concentrations 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 ($P>0.05$).

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Table 3. Concentrations and stoichiometric ratios of soil nutrients, and the percentage of high-quality tea plantations among tea cultivation zones.

Variable	Southern zone			Southwestern zone			North Yangtze zone			South Yangtze zone		
	n	Mean	HQP (%)	n	Mean	HQP (%)	n	Mean	HQP (%)	n	Mean	HQP (%)
pH	357	4.58±0.03^{b}	47.90	545	4.67±0.02^{b}	54.13	200	5.61±0.07^{a}	33.50	508	4.59±0.03^{b}	43.11
AN (mg·kg^{-1})	303	72.88±3.13^{c}	21.45	480	147.56±4.28^{a}	64.79	149	119.48±4.79^{b}	59.06	215	115.33±4.41^{b}	56.74
AP (mg·kg^{-1})	334	49.40±5.34^{a}	38.02	595	19.57±1.11^{b}	28.40	208	49.83±6.14^{a}	42.79	424	58.32±4.49^{a}	57.55
AK (mg·kg^{-1})	291	61.95±2.54^{c}	16.84	541	108.68±4.19^{b}	40.48	207	134.97±5.25^{a}	63.29	329	118.31±5.62^{ab}	44.98
TN (g·kg^{-1})	151	1.34±0.09^{ab}	27.81	506	1.55±0.05^{a}	40.51	124	1.23±0.05^{b}	28.23	386	1.60±0.08^{a}	34.46
TP (g·kg^{-1})	46	0.44±0.03^{b}	0	258	0.76±0.05^{a}	21.32	35	0.70±0.08^{ab}	14.29	167	0.63±0.03^{ab}	13.77
TK (g·kg^{-1})	62	6.97±1.04^{c}	30.65	244	12.02±0.51^{b}	54.92	34	21.24±1.68^{a}	88.24	87	22.27±1.70^{a}	89.66
SOM (g·kg^{-1})	382	23.91±1.36^{bc}	41.88	663	34.45±0.82^{a}	78.88	235	20.86±0.95^{c}	35.74	563	24.74±0.56^{b}	60.57
Average percentage of HQP	-	-	28.07	-	-	47.93	-	-	45.64	-	-	50.10
C:N	150	14.65±1.04^{ab}	-	506	21.94±2.78^{a}	-	124	10.92±0.40^{b}	-	385	11.85±0.46^{ab}	-
C:P	46	64.02±7.98^{a}	-	258	50.47±3.14^{a}	-	35	13.71±1.32^{b}	-	167	28.34±1.32^{b}	-
N:P	46	4.83±0.91^{a}	-	258	3.11±0.17^{b}	-	35	1.62±0.21^{c}	-	145	2.28±0.10^{bc}	-
C:K	62	75.29±21.05^{a}	-	244	3.53±0.47^{b}	-	34	0.76±0.23^{b}	-	87	2.33±1.29^{b}	-
N:K	62	1.55±0.36^{a}	-	234	0.23±0.02^{b}	-	34	0.10±0.04^{b}	-	72	0.12±0.02^{b}	-
P:K	38	0.79±0.21^{a}	-	197	0.12±0.02^{b}	-	34	0.06±0.01^{b}	-	78	0.07±0.01^{b}	-

Note: n is the number of observations; HQP represents high-quality tea plantation; letters on values indicate significant differences among cultivation zones at the 0.05 level.

Table 4. Peason correlation analysis showing the influences of geological and climatic factors and stand age of tea plantations on 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.

In addition, the status of soil nutrients and pH varied among soil classifications (Table 5). 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.

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Table 5. The variations of concentrations and stoichiometric ratios of soil nutrients among soil classifications.

Variable	Red earth	Brown earth	Latosol	Lateritic red earth	Paddy soil	Purplish soil	Yellow earth	Yellow-brown earth
pH	4.59±0.07^{c}	5.66±0.21^{a}	4.79±0.14^{bc}	4.40±0.09^{c}	4.78±0.11^{bc}	4.71±0.15^{c}	4.73±0.04^{c}	5.45±0.12^{ab}
AN (mg·kg^{-1})	142.31±12.01^{b}	123.92±14.37^{b}	263.11±48.19^{a}	108.45±36.04^{b}	136.56±13.18^{b}	107.51±14.98^{b}	157.20±6.55^{ab}	105.67±7.97^{b}
AP (mg·kg^{-1})	38.47±5.24^{b}	83.98±14.21^{a}	41.50±9.33^{b}	11.18±2.95^{b}	29.05±3.08^{b}	22.06±5.24^{b}	16.23±2.98^{b}	25.18±2.97^{b}
AK (mg·kg^{-1})	100.53±7.82^{abc}	192.36±40.26^{a}	103.29±13.55^{abc}	50.41±14.17^{c}	79.06±2.32^{bc}	60.50±8.92^{c}	123.11±8.24^{abc}	168.63±16.59^{ab}
TN (g·kg^{-1})	1.39±0.08^{ab}	1.01±0.13^{b}	1.18±0.14^{ab}	1.35±0.38^{ab}	1.66±0.34^{ab}	1.47±0.12^{ab}	1.35±0.08^{ab}	1.85±0.17^{a}
TP (g·kg^{-1})	0.65±0.09^{ab}	1.26±0.30^{a}	0.22±0.07^{b}	0.83±0.73^{ab}	0.71±0.06^{ab}	1.00±0.54^{ab}	0.62±0.07^{ab}	0.75±0.10^{ab}
TK (g·kg^{-1})*	12.77±1.50	18.28	6.62±0.76	6.37±0.17	17.21±3.59	12.54±2.66	14.80±0.86	6.78±2.88
SOM (g·kg^{-1})	33.83±2.28^{ab}	16.72±2.09^{c}	48.07±6.44^{a}	31.09±4.47^{bc}	23.44±4.44^{bc}	26.33±2.27^{bc}	30.01±1.19^{bc}	27.06±1.55^{bc}
C:N	13.03±1.11^{b}	11.21±2.12^{b}	9.90±1.09^{b}	12.39±1.99^{b}	11.17±1.70^{b}	11.27±0.94^{b}	37.21±10.89^{a}	10.14±0.46^{b}
C:P	34.99±3.62^{b}	13.64±7.76^{c}	104.11±36.07^{a}	40.30±22.34^{b}	31.54±5.45^{bc}	29.93±8.35^{c}	56.12 ±4.61^{b}	33.57±5.92^{bc}
N:P	4.30±0.82^{b}	0.89±0.40^{c}	9.26±2.90^{a}	3.55±2.45^{bc}	2.80±0.59^{bc}	2.79±0.90^{bc}	3.11±0.29^{bc}	3.64±0.62^{bc}
C:K*	5.22±2.91	0.37	2.03±0.49	2.64±1.63	1.78±0.69	1.84±0.60	1.97±0.58	3.52±0.78
N:K*	0.25±0.04	0.02	0.19±0.03	0.18±0.08	0.15±0.06	0.16±0.06	0.14±0.03	0.40±0.15
P:K*	0.11±0.03	0.10	0.03±0.01	0.13±0.11	0.05±0.01	0.08±0.03	0.09±0.02	0.16±0.06

Note: letters on values indicate significant differences among fertilizer modes 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 life cycle duration) had positive effects on the concentrations of AN and SOM, and the ratios of C:N and C:P, but negatively influences 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 6, 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.

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209 **Table 6. The influence of fertilization strategies on the status of soil nutrients.**

Variable	Chemical fertilizer	Compound fertilizer	Organic fertilizer	No fertilizer	Organic fertilizer + Chemical fertilizer	Organic fertilizer + Compound fertilizer	Chemical fertilizer + Compound fertilizer	Organic fertilizer + Chemical fertilizer + Compound fertilizer
pH	4.41±0.10^{bc}	4.94±0.21^{ab}	4.98±0.10^{a}	4.58±0.09^{abc}	4.26±0.12^{c}	4.21±0.04^{c}	4.38±0.08^{c}	4.11±0.07^{c}
AN (mg·kg^{-1})	122.43±10.43^{b}	75.73±15.81^{c}	159.15±14.29^{a}	142.10±11.31^{a}	173.48±54.44^{a}	81.95±26.11^{c}	116.29±24.79^{b}	109.18±25.17^{b}
AP (mg·kg^{-1})	81.82±25.76^{a}	67.55±30.20^{a}	22.20±6.06^{c}	65.37±19.56^{a}	42.66±20.47^{b}	20.12±10.99^{c}	25.10±8.87^{c}	29.33±4.78^{bc}
AK (mg·kg^{-1})	129.63±12.17^{ab}	116.30±19.41^{b}	142.34±16.00^{a}	122.44±8.25^{b}	85.50±41.93^{c}	87.31±20.38^{c}	128.28±23.89^{ab}	107.33±29.78^{bc}
TN (g·kg^{-1})	1.70±0.18^{ab}	1.07±0.13^{ab}	1.73±0.13^{a}	1.50±0.13^{ab}	1.11±0.17^{ab}	1.14±0.18^{ab}	1.21±0.14^{ab}	0.86±0.17^{b}
TP (g·kg^{-1})	0.48±0.06^{ab}	0.35±0.06^{b}	0.64±0.10^{a}	0.45±0.04^{ab}	0.41±0.06^{ab}	0.50±0.08^{ab}	0.54±0.05^{ab}	0.56±0.01^{ab}
TK (g·kg^{-1})*	16.55±1.42	11.98±2.74	17.22±1.97	9.97±1.70	22.52±1.78	4.37	7.46±3.18	15.44±0.3
SOM (g·kg^{-1})	27.54±2.68^{ab}	16.65±2.49^{b}	39.57±3.31^{a}	43.40±4.44^{a}	25.21±2.45^{ab}	31.94±4.03^{ab}	26.66±2.68^{ab}	31.41±2.33^{ab}
C:N	10.77±0.84^{b}	12.96±2.16^{b}	12.65±0.7^{b}	15.96±1.64^{b}	17.00±1.56^{ab}	13.37±0.99^{b}	10.86±1.17^{b}	26.49±4.73^{a}
C:P	28.64±3.03^{b}	45.65±9.66^{ab}	47.39±4.91^{ab}	74.57±12.09^{a}	31.40±2.56^{b}	33.05±11.77^{b}	26.87±6.58^{b}	27.61± 0.94^{b}
N:P	3.69±0.67^{a}	3.74±0.79^{a}	3.84±0.37^{a}	3.02±0.24^{ab}	2.17±0.42^{ab}	2.49±1.09^{ab}	2.05±0.34^{ab}	1.18±0.07^{b}
C:K*	0.82±0.15	1.55±0.43	1.27±0.16	10.26±5.3	0.62±0.27	4.22	5.50±1.99	0.92±0.08
N:K*	0.10±0.01	0.12±0.02	0.11±0.02	0.33±0.13	0.16	0.35	0.45±0.20	0.04±0.01
P:K*	0.03±0.01	0.04±0.01	0.04±0.01	0.11±0.04	0.02±0.01	0.06	0.18±0.08	0.03±0.01

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

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4 Discussions

4.1 Implications of soil ecological stoichiometry and pH

The results indicated that Chinese tea plantations were experiencing deficiencies in soil nutrients, especially deficiencies in soil TN, TP and AK according to the soil nutrients classification standards for tea plantations (Table 1–2). Strategies, such applying organic fertilizer and K fertilizer, should be made to improve the level of TN, TP and AK. 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 (21.12 g·kg^{-1}), forests (24.69 g·kg^{-1}) and croplands (19.23 g·kg^{-1}) (Pan et al., 2021), but lower than that in global terrestrial ecosystems (98.64 g·kg^{-1}) (Xu et al., 2013). This means that soils in tea plantations stock a certain quantity of organic carbon and can be work as a carbon pool showing great carbon sequestration potentiality.

The stoichiometric ratios of soil nutrients indicated that some tea plantations were facing imbalance of soil nutrients, which would influence the cycling of soil nutrients and further affect the growth of tea and the activities of soil microorganism, eventually the yield and quality of tea. It may also reduce the resilience of the tea plantation ecosystem to global change (Zheng et al., 2021). Soil C:N ratio (16.49) in tea plantations were higher than that in terrestrial ecosystems of China (10.69) (Pan et al., 2021) and globe (16.4) (Xu et al., 2013), but 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 (41.85) and N:P (2.92) in tea plantations were lower than that in global terrestrial ecosystems (286.5 and 17.5) (Xu et al., 2013), and that in China's terrestrial ecosystems (100.19 and 10.33), forests (92.54 and 13.83), grasslands (143.36 and 13.08) and croplands (113.85 and 8.89) (Pan et al., 2021). This would accelerate 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, and the deficiency and imbalance of K nutrients would restrict the growth tea plant and increase the risk of disease infestation (Amtmann et al., 2008), and thus the yield and quality of tea (Li, et al., 2017).

The possible reasons of soil nutrients deficiencies and imbalance might be that biomass harvest, mechanical disturbance of surface soil and improper fertilization accelerate soil nutrient loss and imbalance. At least 1.01 tons tea per hectare (on a dry basis) (NBS, 2022) were removed from tea plantations every year and the concentrations of C, N, P and K in tea without fertilization were around 450 g·kg^{-1} (Yin et al., 2021), 50 g·kg^{-1}, 10 g·kg^{-1}, and 15 g·kg^{-1}, respectively (Shu et al., 2023). This means that tea harvest would remove about 454.50 g·kg^{-1}, 50.05 kg·ha^{-1}, 10.01 kg·ha^{-1} and 15.15 kg·ha^{-1} of C, N, P and K from the nutrient cycle of the tea plantations every year, which might lead to deficiencies and/or imbalance at last if no extra fertilizer containing these nutrients were added. Mechanical disturbances such as tillage, together with rainfall and irrigation, may accelerate the decomposition of SOM (Fan and Han, 2020) and weathering of soil nutrients, and thus soil nutrient loss (de la Paix Mupenzi et al., 2011). Besides, the high concentrations of available nutrients and extreme stoichiometric ratios of soil nutrients in a certain part of tea plantations indicated that they might experience over fertilization, which could result in an imbalance of soil nutrients (Bhatt et al., 2019). Over-fertilization can also cause waste of resources, environmental pollution and eutrophication downstream of the catchment. This indicates that managers should adjust their fertilizer strategy, such as applying compound and/or organic fertilizers, to improve the balance of soil nutrients. Organic fertilizer can improve the soil nutrient balance and reduce environmental pollution by slowly releasing nutrients (Shaji et al., 2021).

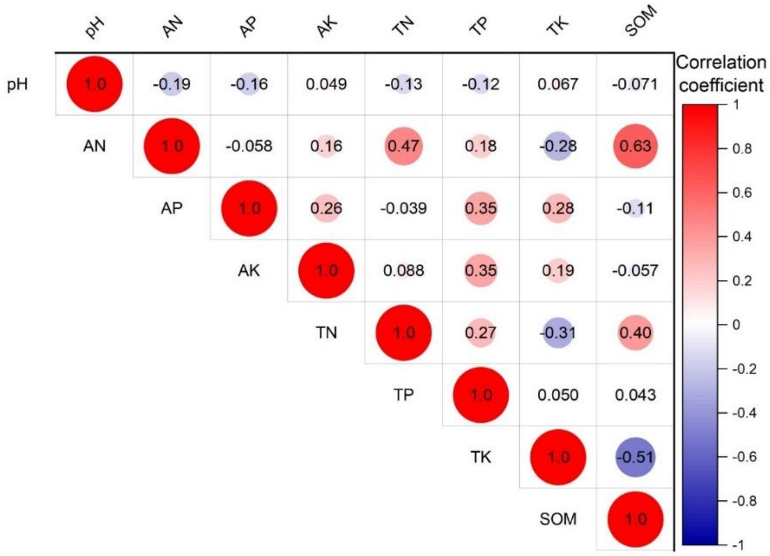
Chinese tea plantations were also experiencing soil acidification (Table 2 and Figure S2). The average soil pH of tea plantations for all of China was 4.74, which was a little higher than the 4.68 from Yan et al. (2020), possibly because some measurements, e.g. less chemical fertilization, had been applied to tackle soil acidification, more tea plantations encroached to other land uses which had higher base pH. Even though the soil pH still located in the lower band of the optimal soil pH for tea growth, and the soil pHs in many tea plantations were lower than 4.5, especially in southern and south Yangtze zones (Figure S2). What's more, only 47.08% of soil samples in the present study had pHs in the interval of 4.5–5.5, while the pHs of 40.80% and 10.14% 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 inhibits tea growth and decreases 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.

Interestingly, there were a few tea plantations, mostly in the north Yangtze zone, having soil pHs higher than 6.0. The possible reasons might be the expansion of tea cultivation invaded ecosystems where soil pHs were high because of different vegetation (Chen et al., 2018) and land uses (Zhu et al., 2017). This may be another reason why the average soil pH was higher than that of Yan et al. (2020). However, tea requires acidic soil for growth, high soil pH will influence the growth of tea (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.

4.2 Factors influencing ecological stoichiometry

The status of soil nutrients and pH in China's tea plantations was varied among cultivation zones (Table 3, Fig S2 – S6) and closely related to geographic and climatic factors (Table 4). At the national level, longitude, latitude and elevation were the key factors affecting soil nutrient status. 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) 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 concentration 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 1), thus stimulating soil C sequestration. Fertilizer application was another factor influencing the status of soil nutrients. The comparison among fertilizer strategies indicated that the application of organic fertilizer was beneficial for the improvements of soil nutrients and pH, especially for the improvements of AK and TK (Table 6). As Figure 1 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.



	pH	AN	AP	AK	TN	TP	TK	SOM
pH	1.0	-0.19	-0.16	0.049	-0.13	-0.12	0.067	-0.071
AN		1.0	-0.058	0.16	0.47	0.18	-0.28	0.63
AP			1.0	0.26	-0.039	0.35	0.28	-0.11
AK				1.0	0.088	0.35	0.19	-0.057
TN					1.0	0.27	-0.31	0.40
TP						1.0	0.050	0.043
TK							1.0	-0.51
SOM								1.0

Figure 1. 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 was 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 the soil problems of soil acidification, nutrient deficiencies and imbalance. Third, as Table 4 illustrated, high temperature harms the accumulation of soil nutrients and contributes to soil acidification. Cultivating shading trees in tea plantations, especially for the plantations in 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 and reduce the risk of environmental pollution. At last, extending the cultivation duration of tea plantations was also recommended for soil C sequestration in tea plantations 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 soil C sequestration in tea plantations. This should contribute to the achievement of carbon neutrality in the tea industry and mitigation of global warming.

5 Conclusions

In this study, we assessed the status and spatial variations of soil nutrients and pH in Chinese tea plantations, analyzed the relationships between the soil nutrients and pH and influential factors including soil classification, management practices, 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 plantation, 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, SOC sequestration ability, in Chinese tea plantations.

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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