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Soil carbon, nitrogen, and phosphorus stoichiometry and its influencing factors in Chinese fir plantations across subtropical China

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The crucial roles of soil carbon (C) and nutrients and their stoichiometric characteristics in indicating the soil interior nutrient cycling and plant nutrient supply of forest ecosystems have been widely verified, whereas it has been less explored when considering the influencing factors regionally, especially for the widely cultivated plantation tree species. In the current study, the patterns of soil organic C (SOC), total nitrogen (TN), and total phosphorus (TP) stoichiometry in Chinese fir [*Cunninghamia lanceolata* (Lamb.) Hook] plantations across subtropical China were analyzed, and their influencing factors were also investigated. The results showed that the range of SOC: TN (C:N), SOC: TP (C:P), and TN: TP (N:P) ratios were 7.32–18.27, 20.15–230.48, and 2.11–15.05 with a mean value of 13.22, 83.50, and 6.05, respectively. Well-constrained correlations were found in SOC and TN, as well as in TN and TP. Soil TN and TP contents increased with increasing altitude, whereas soil C:N, C:P, and N:P ratios decreased. Soil TP content decreased, and the C:P ratio increased with increasing mean annual temperature (MAT) and annual total solar radiation (ATSR). Soil C:N, C:P, and N:P ratios increased with increased mean annual precipitation (MAP) and mean annual evaporation (MAE). Overall, our findings suggested that the soil nutrient supply is relatively adequate in Chinese fir plantations across subtropical China. Meanwhile, soil C, N, and P stoichiometric characteristics were affected by geographical and climatic variables to different degrees.

KEYWORDS

Chinese fir, regional scale, soil carbon and nutrient, stoichiometry, climate change, geography

1. Introduction

Most recently, ecological stoichiometry has been widely applied to the research of nutrient cycling and limitation, and many studies examined the carbon (C), nitrogen (N), and phosphorus (P) interactions of plants, soil, or litter in terrestrial ecosystems (Sistla and Schimel, 2012; Cao et al., 2022; Rahman et al., 2022). Woodland soil is the largest source of nutrient supply in the forest ecosystem, providing the majority of essential elements for plant growth. Accordingly, the investigations for woodland soil stoichiometry are helpful in revealing the recycling utilization level of nutrients and the feedback mechanism as the external environment changes and further provide key theoretical supports for sustainable forest management (Fan et al., 2015; Zhao et al., 2015; Sanaei et al., 2022).

Soil C and nutrients and their stoichiometric characteristics are important indicators for the quality and quantity of soil organic matter, reflecting the relationships between nutrient mineralization and consolidation in the process of organic matter decomposition (Kirkby et al., 2013). Soil carbon: nitrogen (C:N) ratio can be used to predict the concentrations of dissolved organic C and the leaching degree of nitrate N and further indicate the stocks and temporal dynamics of C and N in forest ecosystems (Vesterdal et al., 2008; Gundersen et al., 2009; Hume et al., 2016). Moreover, soil nitrogen: phosphorus (N:P) and carbon: phosphorus (C:P) ratios play regulatory roles in the response of soil microbial community composition and enzyme activities to environmental changes (Delgado-Baquerizo et al., 2017; Shen et al., 2019). Therefore, soil stoichiometric patterns could be widely applied to describe the C turnover and nutrient dynamics in the ecological processes (Tipping et al., 2016; Hassan et al., 2021).

Soil C and N always originated from the litter inputs, which led to the highly well-constrained relations between them (Yang and Luo, 2011; Zhang et al., 2019). Meanwhile, the primary source of soil P was mainly bedrock minerals. Thus, a well-constrained relationship was usually observed between SOC and TN. However, it was not always found between SOC and TP as well as between TN and TP. Previous studies showed that well-constrained soil C, N, and P contents were observed within 0–100 cm across the desert ecosystem of Hexi Corridor, northwestern China, while it was not found across the entire soil depth (as deep as 250 cm for some soil profiles) in China (Tian et al., 2010; Zhang et al., 2019). In addition, the decoupling relationships between C and nutrients occurred during the forest restoration in subtropical forest soils (Xu et al., 2018). Furthermore, whether the variation in the vegetation types and soil parent material at the regional or larger scales would affect the coupling relationships between C and nutrients remains to be explored.

Geographical and climatic factors would affect soil C, N, and P stoichiometric characteristics directly or indirectly by regulating vegetation growth (Zhou et al., 2018; Zhang et al., 2019; Wang X. G. et al., 2020; Boudjabi and Chenchouni, 2022). On a global scale, the soil C:N ratio increased, while the C:P ratio decreased with latitude, indicating that temperature and precipitation might regulate the soil stoichiometric patterns (Xu et al., 2013). While on a national scale, soil N:P and C:P ratios in the subtropical and tropical regions showed higher levels than those in temperature desert regions, which were induced by the differences in vegetation productivity, temperature, and precipitation (Tian et al., 2010). Therefore, it would be helpful for evaluating the influences of geographical or climatic variables on soil stoichiometric patterns under the premise of consistent vegetation types.

Chinese fir [*Cunninghamia lanceolata* (Lamb.) Hook] is a widely cultivated plantation tree species in subtropical China; with the features of rapid growth, strong adaptability, and excellent materials, it plays a positive role in driving the national economy and enhancing ecological efficiency. Currently, stoichiometric patterns on plant leaves, litters, and roots have been widely explored, while the understanding of soil stoichiometry is relatively deficient. Cao et al. (2015) explored the effects of stand age on soil C, N, and P stoichiometry, suggesting that the regulation of organic C content was a critical target in the sustainable management of Chinese fir plantations. Moreover, several studies on soil stoichiometry for plantation species were conducted more at the local scales combined with stand age or specific environmental gradients but less at the regional or larger scales (Cao et al., 2015; Chen et al., 2018).

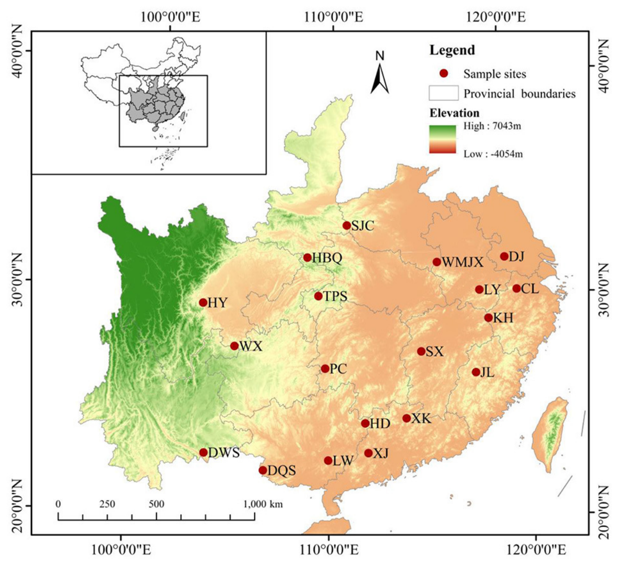

FIGURE 1
A map of the sample sites of Chinese fir plantations. More details can be found in Supplementary Table 1.

In this study, we examined the soil C, N, and P stoichiometric patterns in Chinese fir plantations across subtropical China. We also analyzed the impacts of geographical and climatic factors on soil stoichiometric patterns. Our objectives were to reveal (1) the stoichiometric patterns of soil C and nutrients; (2) the relations of SOC, TN, and TP contents; and (3) the relationships between soil C, N, and P stoichiometry and environmental factors.

2. Materials and methods

2.1. Study area

We obtained sample soil from 19 sites across 12 provinces from July to August 2018, and the sample sites covered the representative and traditional production area divided by the Cooperation Group of Chinese fir, including northern, middle, and southern cultivated regions. The zoning manner was widely accepted and used at present (Figure 1). The study area was geographically located 103.30° to 119.32°E and 22.25° to 33.55°N, and the altitude varied from 60 m to 1,150 m above the sea level. The climate in this region was dominated by a subtropical monsoon climate with a mean annual temperature (MAT) of 10.7 to 22.4°C and a mean annual precipitation (MAP) of 773–1,782 mm. The soils from the sampling sites could be grouped into ferralosols and luvisols according to the World Reference Base (WRB) for Soil Resources (Schad and Dondeyne, 2017). More details can be found in Supplementary Table 1.

2.2. Soil sample and analysis

The middle-aged plantations with similar site conditions were chosen, and finally, a total of 19 soil sampling sites were selected in the subtropical region of China. At each sampling site, three 20-m × 20-m sampling plots with the same slope were set as a repetition. The mean age at the time of the sampling was 16 years, with a range of 12–22 years. The stand density of the plantations was ∼1,600 trees/hm^2. All plantations belonged to the first rotation and were not fertilized with any fertilizer in the past 10 years. The undergrowth vegetation was relatively sparse, mainly including ferns, greenbriers, and miscanthus.

The 0–20-cm depth topsoil samples were collected using a five-point sampling method within each plot. The five separate samples were mixed to form a single sample after removing the plant roots, litters, and stones carefully, and the soil samples were transported to the lab immediately at a low temperature. In the lab, the point-centered quarter sample method was used to extract 500 g of soil, and the soil samples were smashed with a wooden hammer. After air-drying, the soil samples were sieved through a 2-mm sieve to determine the SOC and nutrient contents.

We recorded the latitude, longitude, and altitude of each site. For each site, we derived the MAT, MAP, annual total solar radiation (ATSR), and mean annual evaporation (AE) from the WorldClimate website (https://www.worldclim.org) with 1-km × 1-km resolution. We chose the climate indexes of MAT, MAP, ATSR, and MAE, which are regarded as the important drivers of the formation of soil properties (Gao et al., 2010; Quade et al., 2013). The correlations between geographical and climatic variables are shown in Supplementary Table 2.

Soil organic C content was determined based on oxidation with potassium dichromate in a heated oil bath. The TN content was measured according to the semi–micro-Kjeldahl method. The TP content was determined by inductively coupled plasma-optical spectrometry. The soil pH value was determined by the potentiometric method.

2.3. Statistical analysis

To fit assumptions about the uniformity of data, all data, including soil C and nutrient stoichiometric characteristics, and environmental variables (except pH), were log-transformed before analysis. Pearson's correlation analysis was used to analyze the correlations between the geographical and climatic variables and between soil C and nutrient stoichiometric characteristics. Reduced major axis (RMA) regression was used to determine the allometric growth relationship between SOC, TN, and TP. The hierarchical partitioning (HP) analysis was performed to determine the relative importance and independent contribution of each influencing factor to soil C and nutrients, and their stoichiometric characteristics. The earlier analysis was conducted using R 3.6.0 software (R Development Core Team). The redundancy analysis (RDA) was conducted to rank the environmental factors influencing soil stoichiometry in Canoco 5.0 (Micro-computer Power, Ithaca, NY, USA) (ter Braak and Šmilauer, 2012).

3. Results

3.1. Descriptive statistics of soil C, N, and P stoichiometry

Soil organic C, TN, and TP contents were 24.32 ± 1.36, 1.82 ± 0.09, and 0.35 ± 0.03 g/kg, and the CVs were 42.25, 37.07, and 60.78%, respectively. The C:N, C:P, and N:P ratios were 13.22 ± 0.33, 83.50 ± 6.00, and 6.05 ± 0.35, and the CVs were 18.69, 54.22, and 44.24%, respectively (Figure 2).

3.2. Relations of SOC, TN, and TP contents

Significant correlations were found between SOC and TN as well as between TN and TP but not between SOC and TP. The correlation coefficients between SOC and TN as well as between TN and TP were 0.90 and 0.49, respectively (Supplementary Table 3). As shown in Table 1, the RMA slopes for SOC and TN as well as TN and TP were 0.81 and 1.31, which were significantly different from 1 ($P < 0.05$).

3.3. Effects of environmental variables on soil C, N, and P stoichiometry

The results of the RDA showed that the eigenvalues of soil stoichiometry and environmental variables for the first, second, third, and fourth axes were 0.202, 0.077, 0.004, and 0.000, respectively. The first axis explained 20.2% of the variabilities of soil stoichiometry and 71.4% of the variabilities of soil stoichiometry and environmental variables relations, respectively (Table 2). TP was located on the right and the C:N, C:P, and N:P ratios were on the left of the first axis. According to the arrow length, for the eight environmental variables, the effects of MAP, altitude, AE, ATSR, MAT, pH, longitude, and latitude on soil stoichiometry weakened orderly. Among them, MAP, AE, MAT, ATSR, and longitude were located on the left of the first axis, indicating positive effects on the C:N, C:P, and N:P ratios and negative effects on P (Figure 3).

The HP analysis revealed that the SOC, C:N, C:P, and N:P ratios were impacted more by climatic variables, and TN and TP were impacted slightly more by geographical variables than climatic variables (Table 3). Among geographical variables, altitude contributed the largest explanation for the variation of soil stoichiometry. Among climatic variables, water indicators (MAP and MAE) contributed more explanation than temperature indicators (MAT and ATSR) for the variation of soil stoichiometry. In addition, the C:N and C:P ratios were negatively related to soil pH (Table 3).

4. Discussion

4.1. Patterns of soil stoichiometry of Chinese fir plantations across China

Soil C and nutrient contents play an important role in maintaining and supplying energy and nutrient in forests (Wang et al., 2021; Waring et al., 2021). In this study, the mean SOC and TN contents in the 0–20-cm soil layer were both close to these of China (Tian et al., 2010), while much higher these of vegetation areas in the loess hilly–gully region, Junggar desert in an arid and semi-arid region, *Phragmites australis* tidal flat of Jiaozhou Bay in the temperate region, and typical alpine meadow on Qinghai–Tibetan Plateau in the cold temperate region (Li et al., 2009; Zhu et al., 2013; Liu et al., 2014; Tao et al., 2016). Overall, SOC and TN contents of Chinese fir plantations were at a moderate level regionally. This result might be due to the high temperature and humidity that promoted the formation of high vegetation biomass and the decomposition of plant residues and litter, which were the main source of soil C and N.

The soil TP content was much lower than the mean level of the topsoil in China (0.78 g/kg) (Tian et al., 2010) and far less than that of petrosphere (2.8 g/kg) (Tao et al., 2016), while it was higher than

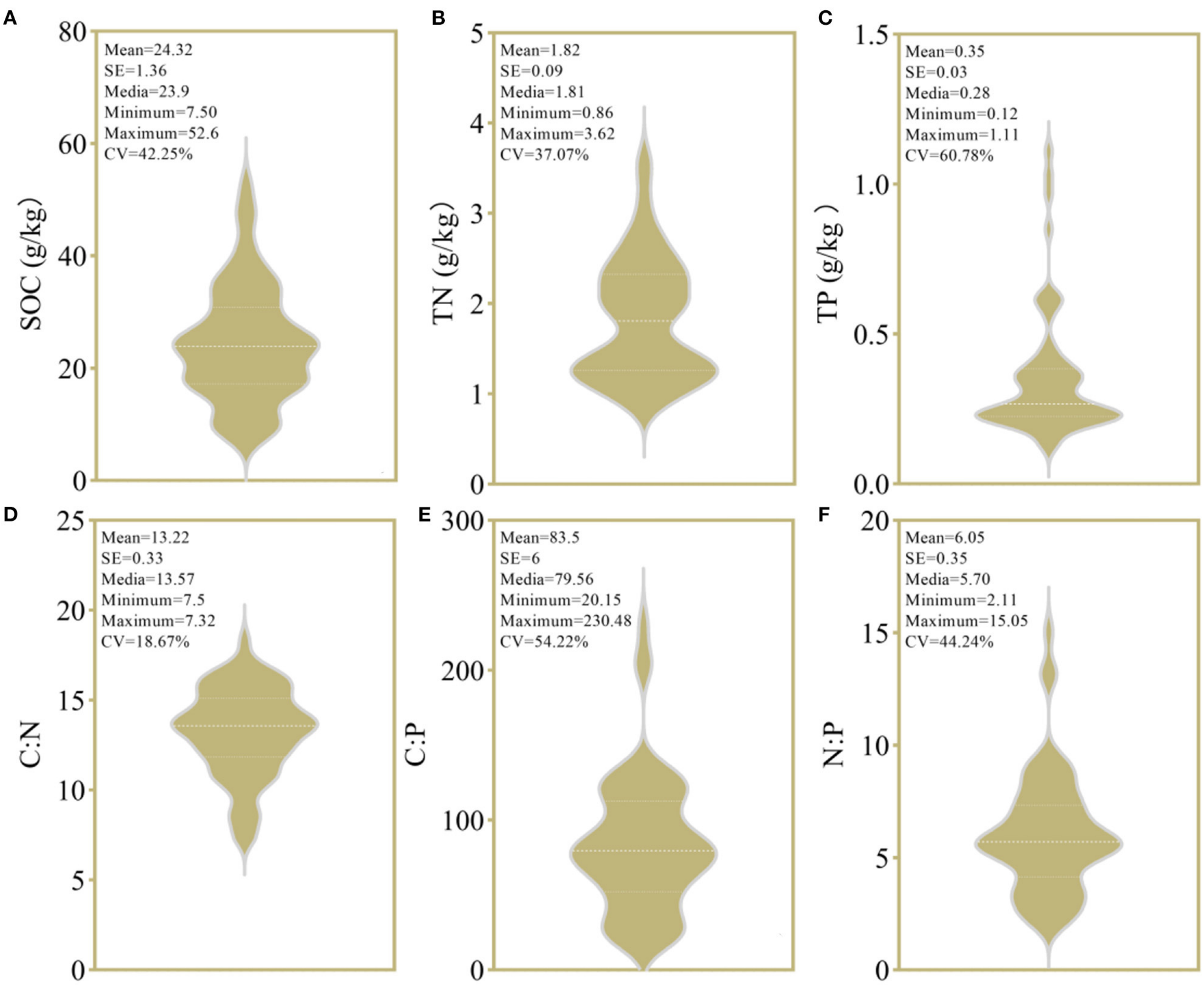

FIGURE 2
Statistics of the SOC, TN, and TP contents and stoichiometric ratios. SOC, soil organic carbon; TN, total nitrogen; TP, total phosphorus; C:N, the ratio of carbon to nitrogen; C:P, the ratio of carbon to phosphorus; N:P, the ratio of nitrogen to phosphorus; SE, standard error; CV, coefficient of variation.

TABLE 1 Summary of RMA regression results.

Variables	Number	Slope	95% CI	R^2	P (H_0: slope = 1)
SOC vs. TN	57	0.81	0.72–0.91	0.80	0.001
SOC vs. TP	57	–	–	–	–
TN vs. TP	57	1.31	1.03–1.66	0.24	0.023

TABLE 2 Eigenvalues and cumulative percentage variance of soil stoichiometry data for the four axes of RDA and their correlations with environmental variables.

Axes	RDA 1	RDA 2	RDA 3	RDA 4
Eigenvalues	0.202	0.077	0.004	0.000
Correlations between soil stoichiometry and environmental variables	0.539	0.549	0.435	0.608
Cumulative proportion of soil stoichiometry (%)	20.2	28.0	28.3	28.4
Cumulative proportion of soil and environmental variables (%)	71.4	98.5	99.8	100.0
Sum of all eigenvalues	1			
Sum of canonical eigenvalues	0.284			

that of forest topsoil in the karst areas in southwest China (0.28 g/kg) (Li et al., 2009). Moreover, the spatial variation of TP was high (CV = 60.78%). These findings were consistent with the fact that P was in shortage and uneven distribution in the soils of the subtropical region of China (Du et al., 2020).

The soil C:N ratio, a sensitive indicator of soil quality, could measure the nutritional balance of C and N and further affect their circulation in soils and even ecosystems (Zhu et al., 2013; Dai et al., 2019). In this study, the range of the soil C:N ratio was 7.32–18.27, with a mean of 13.22, which was slightly lower than that of topsoil in China (14.4) (Tian et al., 2010) but higher than that of the humid region in China (10–12) (Huang, 2000). A low soil C:N ratio indicated that it was in favor of the nutrient release in microorganisms during organic matter decomposition and further promoted the accumulation of available N in soils (Liu et al., 2014). In addition, the soil C:N ratio maintained relatively stable (CV = 18.69%), which was also observed at local and regional scales (Zhao et al., 2018; Wang Y. S. et al., 2020). Therefore, the stable soil C:N ratio conformed to the basic principles of ecological stoichiometry that C and N were the structural component of soil organic matter with a relatively stable ratio (Tian et al., 2010; Bui and Henderson, 2013).

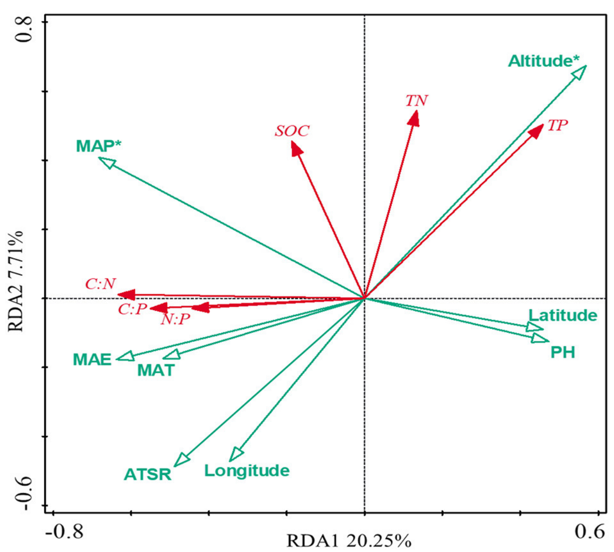

FIGURE 3
RDA biplot of environmental variables and soil stoichiometry. MAT, mean annual temperature; MAP, mean annual precipitation; MAE, mean annual evaporation; ATSR, annual total solar radiation. The asterisk (*) represents the significance.

The soil C:P ratio was used to measure the ability of P mineralization, playing crucial roles in regulating plant growth (Wang et al., 2014; Fu et al., 2015; Peng et al., 2022). The soil C:P ratio of <200 indicates that the organic matter would accumulate and further promote the net mineralization of microbial biomass P, increasing the soil P content (Paul, 2014). In this study, the range of the soil C:P ratio was 20.15–230.48, with a mean of 83.50, which was slightly higher than that of the soil in tropical and subtropical China (78) (Tian et al., 2010) but less than that of China (Tian et al., 2010). Meanwhile, it was also observed that the soil C:P ratio was more than 200 in the southern region, which might be due to high soil P leaching. In spite of this, we concluded that the soil P cycling was in relatively healthy status in Chinese fir plantations because of the fine ability of soil microbial biomass P mineralization, resulting in that durative P formation helped the plant's normal growth.

The soil N:P ratio could be used as the evaluating indicator of N saturation and even the plant nutrient status (Bui and Henderson, 2013; Zhao et al., 2015; Sheng et al., 2022). In this study, the range of the soil N:P ratio was 2.11–15.05, with a mean of 6.05, which was less than that in the topsoil of China (9.3) (Tian et al., 2010) but slightly higher than that of topsoil in the semi-arid steppe of Inner Mongolia (Yang et al., 2017). Moreover, a positive relationship was observed in the leaf and the soil N:P ratio in another study (Tong et al., 2020). Therefore, we assumed that the soil N:P ratio should reflect the nutrient limitation for plant growth, at least in Chinese fir plantations, although less accurate and direct than plant tissue, especially leaf N:P ratios (Gao, 2008).

4.2. Coupling relationships between SOC, N, and P contents across Chinese fir plantations

The coupling balance and circulation among soil C, N, and P would influence the healthy and sustainable development of woodland soils (Yang and Luo, 2011; Yu et al., 2018; Zhu et al., 2022). In this study, well-constrained relations were found in SOC and TN, as well as in TN and TP, which was in line with most previous studies focused on surface soil layers (Cleveland and Liptzin, 2007; Tian et al., 2010; Zhang et al., 2019). However, the relationship between SOC and TP was not well-constrained, which might be induced by their

TABLE 3 Percentage of the total variance in soil stoichiometry explained by environmental variables.

Variables	Full model (R^2)	Geographical variables (%)			Climatic variables (%)				Soil property (%)
		Latitude	Longitude	Altitude	MAT	MAP	MAE	ATSR	pH
SOC	0.25	6.30	6.04	11.38	10.96	51.39*	2.66	3.55	7.72
TN	0.33	4.65	18.79*	29.70**	6.76	23.78	4.24	11.31*	0.77
TP	0.47	5.21	14.56**	30.97**	8.44**	2.75	17.10**	13.83**	7.15
C:N	0.45	5.88	14.53*	10.31**	8.11	23.45**	16.19**	6.83*	14.72*
C:P	0.32	6.66	7.73	11.65*	7.17*	18.71**	21.16**	7.57*	19.34*
N:P	0.22	7.96	4.92	11.20*	8.10*	14.76*	23.08*	8.15	21.03

MAT, mean annual temperature; MAP, mean annual precipitation; MAE, mean annual evaporation; and ATSR, annual total solar radiation.
The asterisk (*) represents the significance.

different resources. Allocation growth rates among SOC, TN, and TP were further explored: TP > SOC > TN, which was consistent with the ranked results of their CVs. Moreover, the SOC regulated the variation in soil the C:N ratio and TP did the same in the soil C:P and N:P ratios. Overall, these findings suggested that elements with larger CVs might play a key role in regulating the related stoichiometric ratio at regional scales.

4.3. Factors related to soil C, N, and P stoichiometry across Chinese fir plantations

The driving factors for the variation of soil stoichiometric characteristics are relatively complex, mainly focusing on the biotic and abiotic factors (Zhou et al., 2018; Wang X. G. et al., 2020; Chen Y. et al., 2022). In this study, we evaluated the influences of abiotic factors on the variation of soil C and nutrient stoichiometric characteristics. It was observed that altitude was the critical geographical factor for soil stoichiometry. Specifically, the contents of TN and TP increased with the increasing altitude, and the opposite trend was found in the soil C:N, C:P, and N:P ratios, all showing a certain vertical distribution. This result was consistent with the finding from the previous study that soil TN and TP contents significantly increased with the increasing altitude in the evergreen broad-leaved forest of China (Lu et al., 2017). Yet, our result was contrary to the observations that the soil C:P and N:P ratios significantly increased with increasing altitude in the wetlands of China, which was mainly due to the differences in the ecosystem types (Zhang et al., 2016). Overall, altitude was assumed to be the decisive factor for the soil stoichiometry of Chinese fir plantations, regionally because of its extremely significant correlations with soil stoichiometry. Otherwise, it was unexpected that no significant correlations were found between soil stoichiometry and latitude, contrasting with most previous studies (Fang et al., 2019; Zhang et al., 2019).

Moreover, macro-climate variables such as MAT, MAP, MAE, and ATSR might better reflect the actual variations in soil stoichiometry (Li et al., 2020; Zhu et al., 2021). In this study, it was observed that MAT and ATSR had negative effects on the TP content and C:P ratio, which was mainly due to the fact that high air and soil temperature accelerated P leaching in the tropical and subtropical region, as reported in previous studies (Gardner, 1990). MAP and MAE, reflecting atmospheric precipitation and soil water content, respectively, both showed positive correlations with the soil C:N, C:P, and N:P ratios. This was in line with the study of Zhang et al. (2019) who reported that the soil C:N, C:P, and N:P ratios increased with increasing I_{DM} (de Martonne aridity index) across the desert ecosystem of the Hexi Corridor. These findings could be attributed to the enhancement of soil water availability, vegetation biomass, and biological weathering induced by low aridity degree. Overall, among climatic variables, the explanation of water indexes for the variation in soil stoichiometry was more than that of temperature indexed, which had also been confirmed in previous studies (Tian et al., 2018; Zhang et al., 2019).

pH was one of the basic soil properties, with an important influence on the turnover of soil organic matter (Voltr et al., 2021; Chen Y. C. et al., 2022). Our results showed that no correlation was found between SOC and pH, which was not consistent with the observations on the topsoil of zonal soils in China (Dai et al., 2009). However, we observed that soil C:N and C:P ratios significantly decreased with the increasing pH, which was consistent with the findings for a wetland in China (Zhang et al., 2016). These results suggested that the weakening soil acidity might promote the enhancement of soil microbial biomass mineralization capacity, providing a basic theory for the necessity of acid soil improvement of southern plantations.

5. Conclusion

To our knowledge, this is the first study to investigate the soil C, N, and P stoichiometric characteristics of Chinese fir plantations regionally. Our findings suggested that SOC and TN contents were at a moderate level, while the TP content was relatively low. Soil nutrient balance and circulation were in a relatively healthy state based on the soil C:N, C:P, and N:P ratios. Well-constrained relations were found in SOC and TN as well as in TN and TP. Soil TN and TP were regulated by the geographical and climatic variables, while the soil C:N, C:P, and N:P ratios were mainly regulated by climatic variables. Altitude and water indicators (MAP and MAE) were the major geographical and climatic variables influencing soil stoichiometry, respectively. Overall, our study evaluated the soil nutrient state and its correlations with external environmental variables, which would be helpful for the construction of reasonable and sustainable management measures for Chinese fir plantations.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

RT and BZ: conceptualization, data curation, and writing. TW and BJ: methodology and supervision. RT, ZW, and BX: software, formal analysis, writing—original draft preparation, and visualization. BZ: resources. TW: funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2022.1086328/full#supplementary-material

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