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EDITED BY
Ling Zhang,
Jiangxi Agricultural University, China

REVIEWED BY
Xintong Xu,
Nanjing Agricultural University, China
Xiaojun Liu,
Ningxia University, China

*CORRESPONDENCE
Shaoming Ye
yshaoming@163.com

†These authors have contributed equally to this work and share first authorship

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Mixed planting improves soil aggregate stability and aggregate-associated C-N-P accumulation in subtropical China

Yaqin He[1†], Qianchun Zhang[1†], Chenyang Jiang[1], Yahui Lan[1], Han Zhang[1] and Shaoming Ye[1,2*]

[1]College of Forestry, Guangxi University, Nanning, China, [2]Guangxi Key Laboratory of Forest Ecology and Conservation, Nanning, China

Research on the variations in soil aggregate stability and ecological stoichiometry at aggregate scales by stand type is of great significance in investigating the distribution, limitation, balance, and cycling of organic carbon, nitrogen, and phosphorus (C-N-P). However, the effect of pure and mixed Chinese fir plantations on soil aggregate stability, organic carbon (OC), total nitrogen (TN), and total phosphorus (TP) stoichiometry characteristics at aggregate scales is still unclear. In this research, we explored the variations in soil aggregate mean weight diameter (MWD) and geometric mean diameter (GMD); soil OC, TN, and TP contents and stocks and the C:N:P ratios as affected by different stand types (mixed stands of Chinese fir and *Mytilaria laosensis*, mixed stands of Chinese fir and *Michelia macclurei*, and pure stand of Chinese fir); and aggregate size ($<$0.25, 0.25–1, 1–2, and $>$2 mm) at 0–20 and 20–40 cm depths in subtropical China. The soil OC and TN contents, as well as C:N:P ratios declined as aggregate size increased, whereas the C-N-P stocks showed the opposite tendencies, which were more distributed in $>$2 mm aggregates. Mixed stands of Chinese fir and *M. laosensis* with Chinese fir and *M. macclurei* displayed significantly higher soil aggregate stability, aggregate-associated TP content, OC and TN contents and stocks, and C:N and C:P ratios than did pure stands of Chinese fir. Soil aggregate stability was significantly positively correlated with the C-N-P contents and stocks as well as the C:N and C:P ratios, especially the C:N ratio and TN content. Overall, this work offers further information for scientific management and sustainable development of Chinese fir plantations, soil OC and nutrient cycling with ecological stoichiometry in the global terrestrial ecosystem.

KEYWORDS

Chinese fir plantations, stand type, soil aggregate, ecological stoichiometry, soil organic carbon and nutrient

1. Introduction

Plantations are considered one of the most widely distributed forest types worldwide, mitigating land degradation and facilitating material cycles and energy fluxes in ecosystems (Yang et al., 2021). China has the greatest plantation area (Zhou L. et al., 2020). Among different plantations, Chinese fir, also called *Cunninghamia lanceolata*, is a vital afforestation species in China, due to its rapid growth, superior material, and high economic value, with plantations comprising approximately 19% of the country's plantation area (Zhou L. et al., 2020; Tong et al., 2021). Guangxi has one of the most major Chinese fir plantations (CFPs) in widely cultivated provinces in China, and this is due to its unique climate and geographical location. However, the decreased productivity of CFPs has long been a major impediment in Guangxi. To pursue rapid tree growth and timber productivity, long-term succession cropping of CFPs has resulted in homogeneous stand structures and decreased soil fertility and productivity (Wang et al., 2020). Mixed forests of Chinese fir can also contribute to soil productivity, quality and health (Huang K. X. et al., 2020). Thus, the establishment of mixed forests is an effective approach for stabilizing soil structure and enhancing the soil nutrient status and sustainability of CFPs. This research has important theoretical guidance and practical significance for improving the quality and sustainable development of CFPs and the sustainable utilization of soil resources in CFPs.

Aggregates widely constitute the basic unit of soil structure, and they can affect soil structural stability and fertility maintenance (Six and Paustian, 2014). Soil aggregate stability is a vital index that is closely associated with soil organic carbon (OC) mitigation and nutrient restitution (Guo et al., 2020; Ma et al., 2022). It is generally evaluated by using the changes in the mean weight diameter (MWD, mm) and geometric mean diameter (GMD, mm) (Zhang Y. et al., 2021). Soil aggregate stability is impacted by soil physical-chemical properties, tree litter, root exudates, and surface runoff (Rivera and Bonilla, 2020; Feng et al., 2021). In addition, the stability of soil aggregates is strongly closely related to soil C and nitrogen (N) stability (Lu et al., 2019). Substantial studies have focused on exploring the relationship between soil aggregate stability and organic carbon (OC) content (Shen et al., 2021; Ma et al., 2022; Yao et al., 2022), indicating that OC content is a key factor affecting soil aggregate stability. During Chinese fir planting, soil OC and total nitrogen (TN) contents have a significant positive correlation with soil aggregate stability (Mao et al., 2021). Forest conversion can impact soil aggregate stability (Li et al., 2022). Additionally, introducing broadleaved tree species into CFPs can improve soil aggregate stability (Gao et al., 2022; Tang et al., 2023). However, most studies have not determined the key factors affecting variation in soil aggregate stability under different stand types of CFPs. Therefore, it is vital to reveal the soil aggregate stability of CFPs with different stand types to evaluate the soil structure and storage stability of soil nutrients.

Ecological chemometrics is an excellent way to determine covariation patterns and coupling relations of chemical elements (such as major elements: C, N, P), and this method has received more attention in exploring soil nutrient cycling and limiting effects (Zhang J. H. et al., 2021). Soil aggregates with different particle sizes have specific roles in nutrient supply, storage, and limiting elements. In addition, the composition of aggregates can significantly affect the distribution of C–N–P contents, and the changes in their content distribution significantly impact the regulation of soil aggregate stability (Xu et al., 2019). A common agreement among studies is that mixed stands of Chinese fir increase the contents of OC and TN within different sizes of aggregates (Wang et al., 2020; Xu et al., 2020). Moreover, compared to pure stands, mixed stands have shown a significant increase in soil C:N:P ratios (Xu et al., 2020). Soil C–N–P contents and stocks are significantly influenced by various sizes of aggregates, but these studies display different results (Six et al., 2004). According to certain research, soil C, N, and P contents decrease as aggregate size increases (Tang and Wang, 2022), although the soil C, N, and P stocks show the opposite trend (Wang et al., 2020). Thus, further studies should investigate the variations in aggregate-associated C–N–P stoichiometry in relation to multiple stand types of CFPs to provide a new strategy for evaluating the correlations between soil aggregate stability and soil nutrient stoichiometry in plantation ecosystems.

Our previous research showed that soil depth can affect aggregate-associated C-N-P stoichiometry in a chronosequence of CFPs (Tang and Wang, 2022). However, how soil aggregate size and stand type in CFPs affect soil aggregate stability and C, N, and P stoichiometric properties is still unknown. Therefore, this study aimed to comprehensively quantify the responses of soil aggregate stability, the C–N–P contents and stocks, and the ratio of C:N:P to aggregate sizes (>2, 1–2, 0.25–1, and <0.25 mm) and stand types (mixed Chinese fir with *Mytilaria laosensis* Lecomte plantations, mixed Chinese fir with *Michelia macclurei* Dandy plantations, and pure CFPs) at 0–20 and 20–40 cm. This research assumed that (i) soil C–N–P stocks are more distributed in >2 mm aggregates; (ii) mixed CFPs have higher soil aggregate stability, aggregate-related C–N–P contents and stocks than pure CFPs; and (iii) soil TN content is the key parameter related to the changes in soil aggregate stability.

2. Materials and methods

2.1. Experimental site

We conducted this study in November 2020 at the Qingshan Experimental Field, which is in Longzhou County, Chongzuo city, Guangxi Zhuang Autonomous Region, China (22°08′–22°44′ N, 106°33′–107°12′ E) (**Figure 1**). The Qingshan Experimental Field has a subtropical monsoon environment and is in the concentrated production region of Chinese fir in Guangxi. The annual mean temperature and precipitation are 21°C and 1400 mm, respectively. The primary types of terrains include low mountains and hills. The native rock is dominated by limestone. The soil type is mainly latosol (pH 4.8–5.5), and the soil depth is over 80 cm. Due to long-term and intense human disturbance, the native vegetation in the region has been almost completely destroyed, and large-scale CFPs have rapidly expanded. Experimental and demonstration forests of valuable and high-quality Chinese fir mixed with broad-leaved tree species are mainly plantations of mixed Chinese fir and *M. laosensis* as well as mixed Chinese fir and *M. macclurei* in this study region. Meanwhile, *Maesa japonica*, *Brassaia actinophylla*, *Rubus alceaefolius*, *Litsea variabilis*, *Blechnum orientale*, *Mussaenda pubescens*, *Pteris semipinnata*, and *Evodia lepta* comprise most of the understory vegetation.

2.2. Experimental design

In this research, we collected soil samples from three stand types of CFPs, which were established in 1992 (**Table 1**). To reduce soil spatial variations, the three stand types were placed in similar geomorphologic units with similar altitude, slope gradient and aspect, soil parent material, and fertilization practices. The spacing between the three stand types was 2 m × 3 m. Mixed stands had a 3:1 mixed proportion. For each stand type, we performed a complete random design and duplicated in quintuplicate to produce in fifteen CFPs (3 stand types × 5 replicates) (**Figure 1**). Every two CFPs were separated by more than 800 m to avoid pseudo-replication and reduce spatial self-correlation. A plot (20 m × 20 m) was randomly selected at more than 50 m across the plantation edge for each CFP.

2.3. Litter and soil sampling

The mixed litterfall samples were acquired from the soil surface by five randomized 1 m × 1 m subplots. The 15 mixed litterfall samples (3 stand types × 5 replicates) were then desiccated in an oven at 80°C until they reached a constant weight (**Table 1**). In addition, soil specimens in the research were acquired from places similar to the litterfall samples and were collected through spades from 0 to 20 and 20 to 40 cm, separately. Afterward, 5 soil samples were combined. Then, 30 mixed soil specimens (3 stand types × 5 replicates × 2 soil depths) were separated into natural aggregates, and macrofauna, coarse roots, and stones were removed. To measure the bulk density (BD), total porosity (Pt), pH, OC, TN, and TP contents in bulk soil, cutting rings were used to randomly collect from every soil layer for the other 5 soil samples for each plot (**Table 2**).

2.4. Soil aggregate separation

Different sized sieves (continuous diameters: 2, 1, 0.25 mm) were used for soil aggregate isolation by a dry-sieving approach (Six and Paustian, 2014). Eventually, the aggregate sizes were categorized as >2, 1–2, 0.25–1, and <0.25 mm.

2.5. Soil property analyses

Before examining the physical-chemical characteristics of the soil, air drying at room temperature was applied to soil samples, including aggregates and bulk soil. Soil BD and Pt were detected using a cutting ring (Lu, 1999). A glass electrode was used to measure soil pH (Lu, 1999). The micro-Kjeldahl approach was performed to measure soil TN (Bremner, 1996), while the Olsen approach was used to detect soil TP (Bray and Kurtz, 1945). The acid dichromate wet oxidation approach by Nelson and Sommers (1996) was used to detect soil OC.

2.6. Data statistics

Soil MWD and GMD are the key indicators used to evaluate the stability of soil aggregates (Kong et al., 2022). Larger values of MWD and GMD indicate stronger soil aggregate stability (Zhou L. et al., 2020). The formula calculations for MWD and GMD are as follows (Zhang Y. et al., 2021):

$$\mathrm{MWD} = \sum_{i=1}^{4} (\mathrm{X}_i \times \mathrm{W}_i) \quad (1)$$

$$\mathrm{GMD} = \exp\left[\sum_{i=1}^{4} (\mathrm{W}_i \times \ln(\mathrm{X}_i)) / \sum_{i=1}^{4} (\mathrm{W}_i)\right] \quad (2)$$

where X_i (mm) is the mean diameter of the *i*th-sized aggregates, and W_i (% in weight) is the proportion of the *i*th-sized aggregates in bulk soil.

The formula used to calculate soil OC stocks (OCS, g m^{-2}) is as follows (Eynard et al., 2005):

$$\mathrm{OCS} = \sum_{i=1}^{4} (\mathrm{X}_i \times \mathrm{W}_i) \times \mathrm{B} \times \mathrm{H} \times 10 \quad (3)$$

where B (g cm^{-3}), H (cm), and X_i (g kg^{-1}) denote the bulk density, soil depth, and OC content within *i*th size aggregates, respectively. The number 10 is the unit conversion factor. Similarly, soil TN and TP stocks (TNS and TPS, g m^{-2}) were also calculated.

Since stand type and aggregate size were the two main factors, statistical analyses were performed according to soil depth. SPSS 26.0 was used to conduct statistical analysis (**Table 3**). All datasets were tested for homogeneity of variances and the normal distribution of residuals prior to performing analysis of variance (ANOVA) to ensure that the assumptions of statistical analysis were met. We performed one-way and two-way ANOVAs to explore the effects of stand type on litter and bulk soil properties and the influences of aggregate size and stand type on soil aggregate properties, respectively. Then, to compare various stand types and aggregate sizes, the post-hoc Tukey HSD test was used, with $P < 0.05$ denoting statistical significance. The effect of different soil depths on aggregates in the same stand type was evaluated using a two-tailed independent sample *t* test, with $P < 0.05$ considered statistically significant. Furthermore, a generalized linear model was utilized to analyze the correlation between aggregate-related OC and nutrients in different stand types. Redundancy analysis (RDA) was utilized by CANOCO 5.0 to determine the influences of environmental parameters on soil aggregate stability. The association of soil aggregate stability with ecological stoichiometric characteristics in bulk soil was analyzed by Pearson's correlation analysis.

3. Results

3.1. Bulk soil properties under different stand types

The soil Pt, OC, TN, TP, OCS, TNS, TPS, C/N, and C/P in mixed stands had significantly higher levels than those in pure

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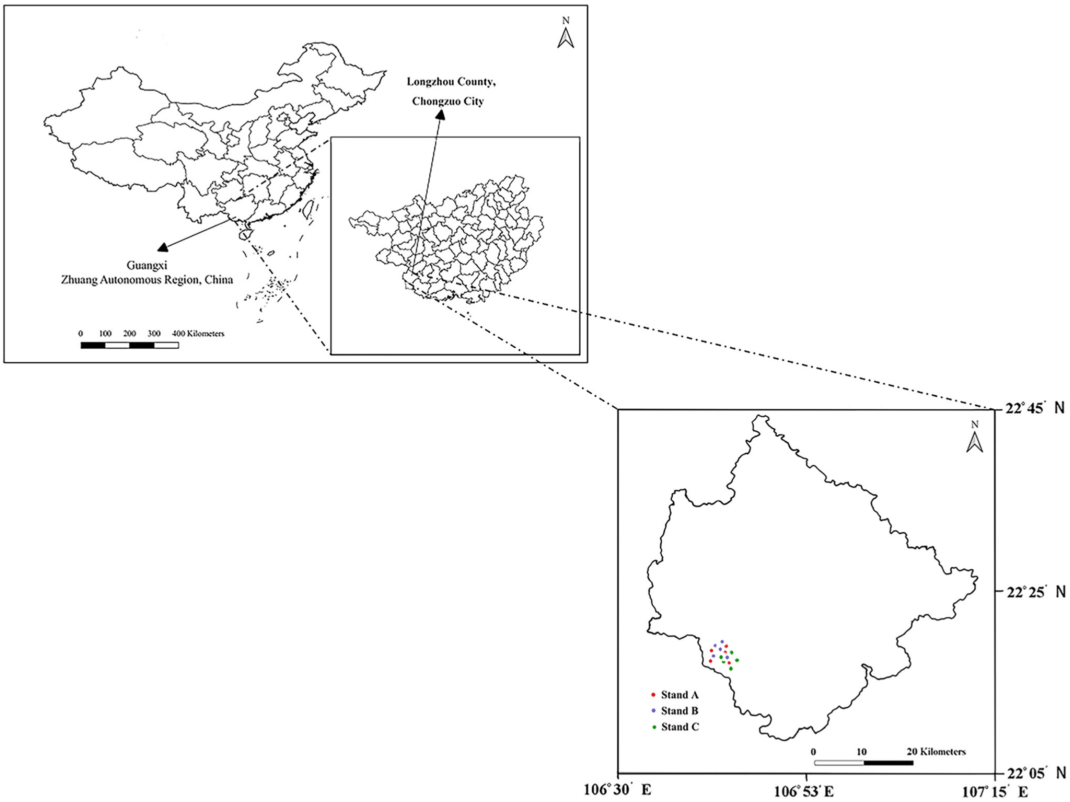

FIGURE 1
Study site. Stand A indicates a mixed plantation of Chinese fir and *Mytilaria laosensis*. Stand B indicates a mixed plantation of Chinese fir and *Michelia macclurei*. Stand C indicates a pure plantation of Chinese fir.

TABLE 1 Basic information of sample plots in Chinese fir plantations with different stand types.

Stand type	Altitude (m)	Slope (°)	Aspect (°)	Mean height (m)	Mean diameter (cm)	Crown density	Litterfall amount (gm^{-2})
Stand A	730	27	185	16.29 ± 0.21 a	21.03 ± 0.63 a	0.85 ± 0.01 a	455 ± 23 b
Stand B	725	25	178	16.47 ± 0.33 a	21.30 ± 0.49 a	0.85 ± 0.01 a	504 ± 27 a
Stand C	728	30	183	13.64 ± 0.12 b	16.92 ± 0.37 b	0.85 ± 0.01 a	324 ± 12 c

Data indicate the average of five replicates ± standard deviations. Stand A indicates a mixed plantation of Chinese fir and *Mytilaria laosensis*. Stand B indicates a mixed plantation of Chinese fir and *Michelia macclurei*. Stand C indicates pure plantation of Chinese fir. Various lowercase letters indicate significant differences among the different stand types at $P < 0.05$.

stands among both layers (0–40 cm), whereas the soil BD and pH showed opposite trends (Table 2). In the three stands, soil OC and nutrients significantly decreased with increasing, whereas soil BD presented the opposite trend.

3.2. Aggregate distribution and stability among diverse stand types and aggregate sizes

Most fractions, regardless of the stand type, were composed of >2 mm aggregates, with average proportions of 43.33% (0–20 cm) and 39.26% (20–40 cm) (Figure 2). Mixed stands had considerably greater distributions of >2 mm and <0.25 mm aggregates at both depths compared to pure stands, but this tendency was reversed for the 1–2 mm and 0.25–1 mm aggregates. Additionally, for every soil profile, mixed stands had much higher MWD (Figure 3A) and GMD (Figure 3B) values than did pure stands. The MWD and GMD values increased significantly among the three stands as the soil depth decreased.

3.3. Aggregate-associated OC, TN, and TP contents and stoichiometric characteristics

The soil OC and TN contents among the three stands displayed significant increases with decreasing aggregate size at both depths, but the TP content showed no significant variations in aggregates (Table 4). Moreover, the OC, TN, and TP contents in aggregates among mixed stands were higher than those among pure stands at both depths, especially in mixed stand B. Besides, soil aggregate-associated OC, TN, and TP contents

TABLE 2 Bulk soil properties in Chinese fir plantations with different stand types.

Variable	0–20 cm soil depth			20–40 cm soil depth		
	Stand A	Stand B	Stand C	Stand A	Stand B	Stand C
BD (g cm^{-3})	1.26 ± 0.01 b*	1.24 ± 0.01 b*	1.31 ± 0.02 a**	1.27 ± 0.01 b*	1.26 ± 0.01 b*	1.33 ± 0.01 a**
Pt (%)	52.38 ± 0.38 a**	53.13 ± 0.22 a**	50.42 ± 0.28 b**	52.92 ± 0.19 a**	52.60 ± 0.19 a**	49.96 ± 0.83 b**
pH	4.33 ± 0.01 b**	4.31 ± 0.01 c**	4.37 ± 0.00 a**	4.30 ± 0.01 b**	4.27 ± 0.01 b**	4.41 ± 0.02 a**
OC (g kg^{-1})	24.80 ± 0.84 b**	33.34 ± 1.16 a**	20.96 ± 0.42 c**	10.17 ± 0.73 b**	17.16 ± 0.82 a**	7.25 ± 0.47 c**
TN (g kg^{-1})	1.25 ± 0.03 b**	1.46 ± 0.01 a**	1.26 ± 0.01 b**	0.75 ± 0.01 b**	1.21 ± 0.03 a**	0.68 ± 0.02 c**
TP (g kg^{-1})	0.27 ± 0.00 a**	0.28 ± 0.00 a*	0.24 ± 0.01 b**	0.25 ± 0.00 a**	0.25 ± 0.01 a*	0.20 ± 0.01 b**
C/N	19.92 ± 0.53 b**	22.9 ± 0.88 a**	16.67 ± 0.33 c**	13.38 ± 0.86 a**	14.14 ± 0.61 a**	10.67 ± 0.40 b**
C/P	95.75 ± 4.61 b**	124.52 ± 5.71 a**	90.15 ± 2.70 b**	42.43 ± 3.46 b**	71.14 ± 5.40 a**	37.56 ± 2.02 b**
N/P	4.82 ± 0.13 b**	5.43 ± 0.07 a**	5.38 ± 0.19 a**	3.13 ± 0.07 b**	4.95 ± 0.30 a**	3.52 ± 0.17 b**
OCS (g m^{-2})	624.93 ± 47.31 b**	826.83 ± 64.48 a**	549.05 ± 24.62 c**	258.42 ± 41.48 b**	426.1 ± 44.88 a**	192.81 ± 27.87 c**
TNS (g m^{-2})	31.39 ± 1.52 b**	36.24 ± 0.51 a**	32.96 ± 0.39 b**	19.17 ± 0.43 b**	30.45 ± 1.61 a**	18.01 ± 1.26 b**
TPS (g m^{-2})	6.72 ± 0.26 a**	6.83 ± 0.2 a^{ns}	6.32 ± 0.38 b**	6.23 ± 0.21b**	6.33 ± 0.51 a^{ns}	5.23 ± 0.55 c**

Pt stands for total porosity. BD stands for bulk density. OC, TN and TP represent the organic carbon, total nitrogen and total phosphorus contents in bulk soil, respectively. C/N, C/P and N/P represent the organic carbon, total nitrogen and total phosphorus ratios in bulk soil, respectively. OCS, TNS and TPS represent the stocks of organic carbon, total nitrogen, and total phosphorus in bulk soil, respectively. Various lowercase letters indicate significant differences among the different stand types at $P < 0.05$. ** and * stand for significant differences among the different soil depths at $P < 0.01$ and $P < 0.05$, respectively. ^{ns}Stands for no significant differences among the different soil depths.

TABLE 3 Litterfall and soil properties as influenced by aggregate size and stand type in Chinese fir plantations.

Variable	Litterfall	0–20 cm soil depth			20–40 cm soil depth		
	S	S	A	S x A	S	A	S x A
Litterfall amount (g m^{-2})	**						
BD (g cm^{-3})		**			**		
Pt (%)		**			**		
Soil pH		**			**		
Soil aggregate proportion		Ns	**	**	Ns	**	**
MWD		**	**	**	**	**	**
GMD		**	**	**	**	**	**
OC (g kg^{-1})		**	**	Ns	**	**	**
TN (g kg^{-1})		**	**	**	**	**	Ns
TP (g kg^{-1})		**	Ns	**	**	Ns	Ns
C/N ratio		**	**	Ns	**	**	*
C/P ratio		**	**	**	**	**	**
N/P ratio		Ns	**	**	**	**	Ns
OCS (g m^{-2})		**	**	**	**	**	**
TNS (g m^{-2})		**	**	**	**	**	**
TPS (g m^{-2})		Ns	**	**	**	**	**
Percentage contribution of OCS (%)		Ns	**	**	Ns	**	**
Percentage contribution of TNS (%)		Ns	**	**	Ns	**	**
Percentage contribution of TPS (%)		Ns	**	**	Ns	**	**

S stands for stand type. A stands for aggregate size. Ns stands for no significant differences. MWD and GMD stand for mean weight diameter and geometric mean diameter, respectively. OC, TN and TP stand for organic carbon, total nitrogen and total phosphorus contents, respectively. OCS, TNS with TPS stand for the stock of organic carbon, total nitrogen, and total phosphorus, respectively. C/N, C/P and N/P stand for organic carbon, total nitrogen and total phosphorus ratios, respectively.
*$P < 0.05$; **$P < 0.01$.

among the three stands increased as the soil depth decreased. There was a significant positive correlation ($P < 0.05$) between the OC, TN and TP contents for different soil aggregate sizes in the three stand types (Figure 4). The linear relationship between the OC and TN contents is shown in Figure 4A ($R^2 = 0.86$, $P < 0.01$). However, the linear fits between OC and TP contents (Figure 4B) as well as the TN and TP contents (Figure 4C) were low. In addition, the change in TP

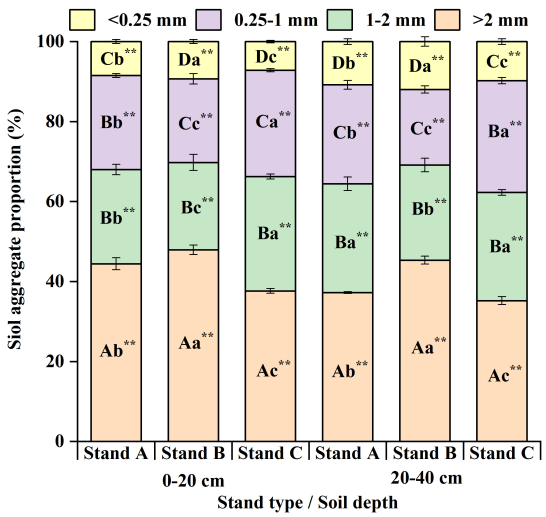

FIGURE 2
Soil aggregate distribution in Chinese fir plantations with different stand types. Data indicate the average of 5 replicates ± standard deviations. Various capital letters stand for significant differences among the different aggregate sizes at $P < 0.05$. Various lowercase letters stand for significant differences among the different stand types at $P < 0.05$. ** and * stand for significant differences among the different soil depths at $P < 0.01$ and $P < 0.05$, respectively. ^{ns}Stands for no significant differences among the different soil depths.

content lagged behind TN and OC contents based on the slope (Figures 4B, C).

Irrespective of the stand type, the C:N:P ratio (Table 4) significantly increased as aggregate size decreased at both depths. In the 0–40 cm layer, the mixed stands aggregate-associated C/N (12.02–23.66) and C/P ratios (36.19–136.3) were greater than those in pure stands (C/N: 10.39–19.46; C/P: 31.79–116.57). Additionally, the aggregate-associated N/P ratio in stand B was notably higher than that of stands A and C at the 20–40 cm depth.

3.4. Aggregate-associated OCS, TNS, and TPS under different stand types

Regardless of the stand type, OCS (Figure 5A), TNS (Figure 5B), and TPS (Figure 5C) and their contribution percentages had a dominant distribution in >2 mm aggregates at both depths. For example, among the three stands, the OCS associated with the >2 mm aggregates was 196.92–381.01 g m^{-2} (0–20 cm) and 60.36–164.93 g m^{-2} (20–40 cm), accounting for 35.59–45.75% (0–20 cm) and 31.40–38.02% (20–40 cm) of the OCS in bulk soil (Supplementary Figure 1A), respectively, but the OCS associated with the <0.25 mm aggregates was only 46.12–66.54 g m^{-2} (0–20 cm) and 22.69–68.86 g m^{-2} (20–40 cm) (Figure 5A), contributing to 8.34–10.74% (0–20 cm) and 11.81–15.84% (20–40 cm) of the OCS in bulk soil (Supplementary Figure 1A), respectively. The TNS (Figure 5B) and TPS (Figure 5C) associated with soil aggregates showed similar trends. Regardless of the soil depth, the aggregate-associated OCS, TNS, and TPS showed the higher levels in mixed stand than those in pure stand. Notably, mixed stands had greater percentage contributions of OCS, TNS, and TPS within the >2 and <0.25 mm aggregates than did pure stands, while other aggregates showed the opposite pattern.

3.5. Soil aggregate stability as influenced by soil ecological stoichiometric characteristics

The influences of soil ecological stoichiometric characteristics (such as OC, TN, TP, C/N, C/P, N/P, OCS, TNS, and TPS) on soil aggregate stability (such as MWD and GMD) across the three stands of Chinese fir were determined by RDA. The influence order was C/N > TP > TPS > N/P > C/P > OCS > OC > TN > TNS at the 0–20 cm depth (Figure 6A). Specifically, the C/N and TP represented the key factors that explained 77.4 and 11.3% of

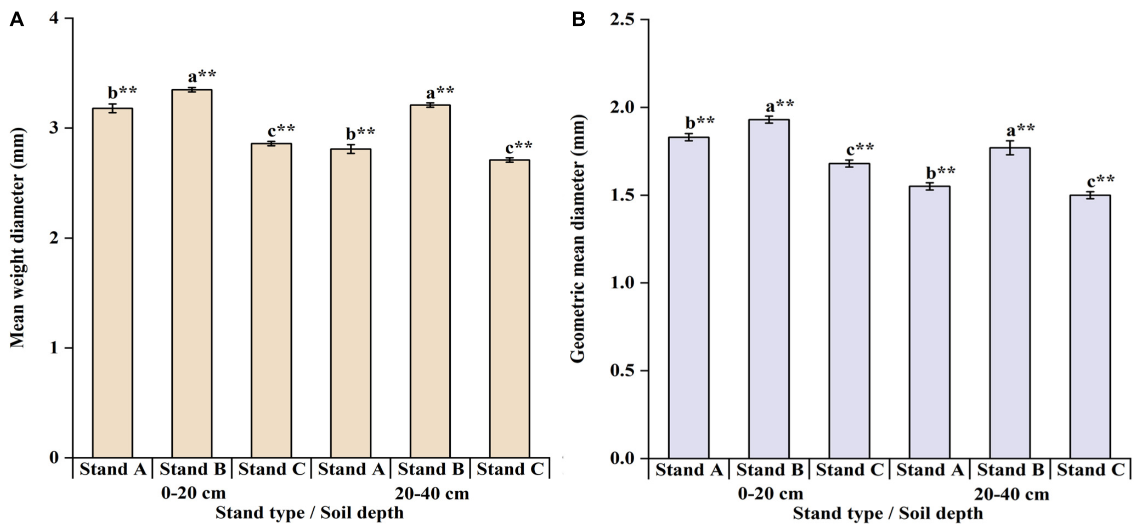

FIGURE 3
Distribution of mean weight diameter **(A)** and geometric mean diameter **(B)** in Chinese fir plantations with different stand types.

TABLE 4 Aggregate-associated OC, TN and TP contents and stoichiometric characteristics.

Variable	Soil depth (cm)	Stand type	Aggregate size (mm)			
			>2	1–2	0.25–1	<0.25
OC (g kg^{-1})	0–20	Stand A	21.42 ± 2.13 Bb**	24.77 ± 2.76 Bb**	29.02 ± 3.7 Ab**	30.88 ± 2.81 Ab**
		Stand B	31.82 ± 3.14 Ba**	32.85 ± 3.73 Ba**	35.07 ± 2.45 ABa**	38.37 ± 2.3 Aa**
		Stand C	19.81 ± 0.86 Bb**	20.11 ± 1.63 Bc**	22.58 ± 1.89 Ac**	24.33 ± 2.16 Ac**
	20–40	Stand A	8.57 ± 1.87 Bb**	9.22 ± 1.76 Bb**	12.28 ± 1.54 Ab**	13.25 ± 2.2 Ab**
		Stand B	14.38 ± 2.9 Ba**	15.49 ± 2.49 Ba**	22.41 ± 3.29 Aa**	22.75 ± 3.02 Aa**
		Stand C	6.46 ± 0.55 Bb**	7.25 ± 1.69 ABb**	7.71 ± 1.53 ABc**	8.76 ± 1.05 Ac**
TN (g kg^{-1})	0–20	Stand A	1.1 ± 0.12 Cc**	1.33 ± 0.03 Bb**	1.34 ± 0.11 Bb**	1.5 ± 0.03 Ab**
		Stand B	1.36 ± 0.06 Da**	1.57 ± 0.04 Ba**	1.48 ± 0.04 Ca*	1.68 ± 0.05 Aa**
		Stand C	1.25 ± 0.04 Ab**	1.27 ± 0.06 Ab**	1.26 ± 0.02 Ac**	1.25 ± 0.06 Ac**
	20–40	Stand A	0.68 ± 0.04 Bb**	0.72 ± 0.04 Bb**	0.85 ± 0.02 Ab**	0.88 ± 0.07 Ab**
		Stand B	1.19 ± 0.04 Aa**	1.17 ± 0.09 Aa**	1.26 ± 0.14 Aa*	1.26 ± 0.09 Aa**
		Stand C	0.63 ± 0.08 Bb**	0.68 ± 0.08 ABb**	0.71 ± 0.05 ABc**	0.76 ± 0.03 Ac**
TP (g kg^{-1})	0–20	Stand A	0.29 ± 0.02 Aa^{ns}	0.21 ± 0.04 Bb^{ns}	0.27 ± 0.01 Aa^{ns}	0.27 ± 0.03 Aa^{ns}
		Stand B	0.23 ± 0.01 Bc*	0.33 ± 0.02 Aa**	0.32 ± 0.04 Aa**	0.25 ± 0.03 Ba**
		Stand C	0.26 ± 0.02 Ab**	0.24 ± 0.05 Ab^{ns}	0.22 ± 0.05 Ab^{ns}	0.21 ± 0.01 Ab^{ns}
	20–40	Stand A	0.25 ± 0.04 Aab^{ns}	0.24 ± 0.03 Aa^{ns}	0.25 ± 0.04 Aa^{ns}	0.23 ± 0.01 Aab^{ns}
		Stand B	0.27 ± 0.03 Aa*	0.24 ± 0.03 ABa**	0.22 ± 0.05 Bab**	0.25 ± 0.01ABa**
		Stand C	0.21 ± 0.02 Ab**	0.19 ± 0.03 Ab^{ns}	0.18 ± 0.03 Ab^{ns}	0.21 ± 0.04 Ab^{ns}
C/N	0–20	Stand A	19.60 ± 1.28 Ab**	18.63 ± 0.95 Aa**	21.60 ± 0.64 Aa**	20.60 ± 0.74 Ab**
		Stand B	23.49 ± 1.33 Aa**	20.87 ± 0.99 Aa**	23.66 ± 0.92 Aa**	22.90 ± 0.49 Aa**
		Stand C	15.88 ± 0.36 Bc**	15.80 ± 0.55 Bb**	17.96 ± 0.73 Ab**	19.46 ± 0.74 Ab**
	20–40	Stand A	12.52 ± 1.05 Aa**	12.89 ± 1.04 Aa**	14.47 ± 0.96 Ab**	15.02 ± 0.90 Ab**
		Stand B	12.02 ± 0.98 Ba**	13.32 ± 0.90 Ba**	17.82 ± 1.26 Aa**	17.96 ± 0.70 Aa**
		Stand C	10.39 ± 0.46 Aa**	10.55 ± 0.79 Aa**	10.80 ± 0.71 Ac**	11.60 ± 0.52 Ac**
C/P	0–20	Stand A	73.58 ± 3.77 Bb**	119.05 ± 11.89 Aa**	107.54 ± 5.78 Aa**	114.96 ± 6.85 Ab**
		Stand B	136.3 ± 8.35 Aa**	99.63 ± 6.49 Bab**	111.36 ± 8.25 Ba**	151.59 ± 5.94 Aa**
		Stand C	76.27 ± 3.75 Cb**	84.93 ± 7.04 BCb**	108.24 ± 12.31 ABa**	116.57 ± 7.91 Ab**
	20–40	Stand A	36.19 ± 5.17 Bb**	38.81 ± 4.65 Bb**	49.19 ± 3.85 ABb**	57.48 ± 5.46 Ab**
		Stand B	53.20 ± 5.20 Ba**	65.62 ± 5.67 Ba**	108.43 ± 13.68 Aa**	90.98 ± 4.13 Aa**
		Stand C	31.79 ± 2.13 Ab**	38.50 ± 4.62 Ab**	42.38 ± 3.80 Ab**	41.89 ± 1.71 Ac**
N/P	0–20	Stand A	3.78 ± 0.15 Cc*	6.38 ± 0.48 Aa**	4.97 ± 0.16 Bab**	5.59 ± 0.30 ABb**
		Stand B	5.81 ± 0.16 Ba**	4.77 ± 0.14 Cb^{ns}	4.71 ± 0.30 Cb^{ns}	6.62 ± 0.25 Aa**
		Stand C	4.80 ± 0.16 Ab**	5.43 ± 0.59 Aab*	5.98 ± 0.51 Aa**	5.97 ± 0.24 Aab**
	20–40	Stand A	2.85 ± 0.27 Bb*	2.99 ± 0.18 Bb**	3.41 ± 0.19 ABb**	3.82 ± 0.21 Ab**
		Stand B	4.43 ± 0.25 Ba**	4.97 ± 0.40 ABa^{ns}	6.13 ± 0.77 Aa^{ns}	5.06 ± 0.05 ABa**
		Stand C	3.07 ± 0.18 Ab**	3.65 ± 0.39 Ab*	3.93 ± 0.25 Ab**	3.65 ± 0.23 Ab**

Various capital letters stand for significant differences among the different aggregate sizes at $P < 0.05$. Various lowercase letters stand for significant differences among the different stand types at $P < 0.05$. ** and * stand for significant differences among the different soil depths at $P < 0.01$ and $P < 0.05$, respectively. ^{ns}Stands for no significant differences among the different soil depths.

the stand type variations in soil aggregate stability, respectively. However, it is worth noting that the influence order was TN > TPS > N/P > TNS > TP > C/P > OC > C/N > OCS at the 20–40 cm depth (**Figure 6B**). Specifically, TN and TPS explained 96.4 and 1.1% of the stand type variations in soil aggregate stability, respectively. In addition, there was consensus between the Pearson's correlation analysis results (**Supplementary Figure 2**) and the RDA results. We also found that MWD and GMD had significant and positive correlations with C/N, C/P, OC, TN, TP, OCS, TNS, and TPS.

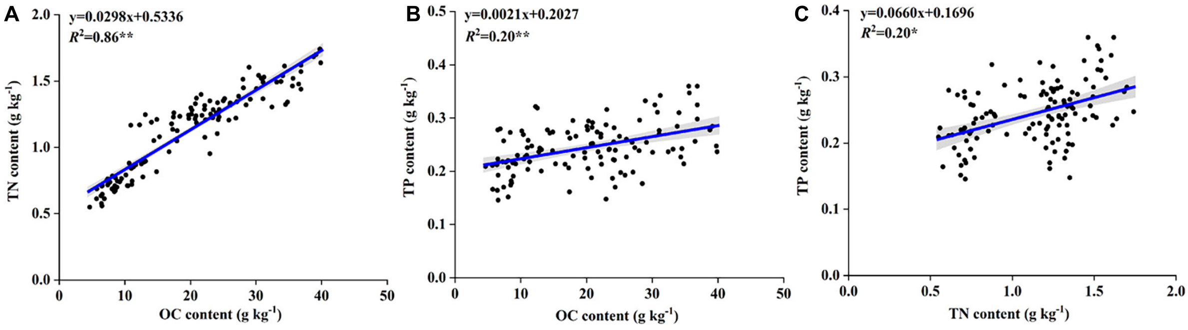

FIGURE 4
Relationships of aggregate-associated OC **(A)**, TN **(B)**, and TP **(C)** contents in Chinese fir plantations with different stand types. OC, TN, and TP stand for the contents of organic carbon, total nitrogen and total phosphorus in different aggregate sizes, respectively. ** and * stand for significant correlations at $P < 0.01$ and $P < 0.05$, respectively.

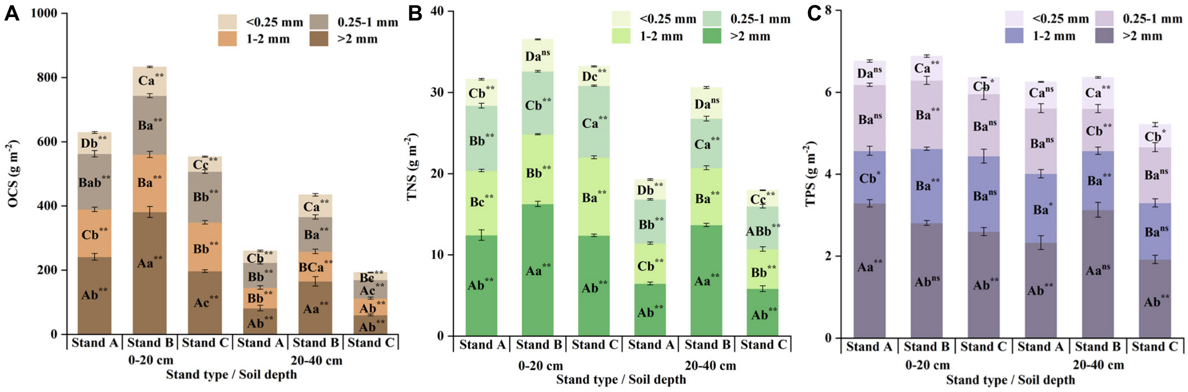

FIGURE 5
Aggregate-associated OCS **(A)**, TNS **(B)**, and TPS **(C)** in Chinese fir plantations with different stand types. OCS, TNS and TPS stand for the stocks of organic carbon, total nitrogen, and total phosphorus in different aggregate sizes, respectively. ** and * stand for significant differences among the different soil depths at $P < 0.01$ and $P < 0.05$, respectively. ^{ns}Stands for no significant differences among the different soil depths.

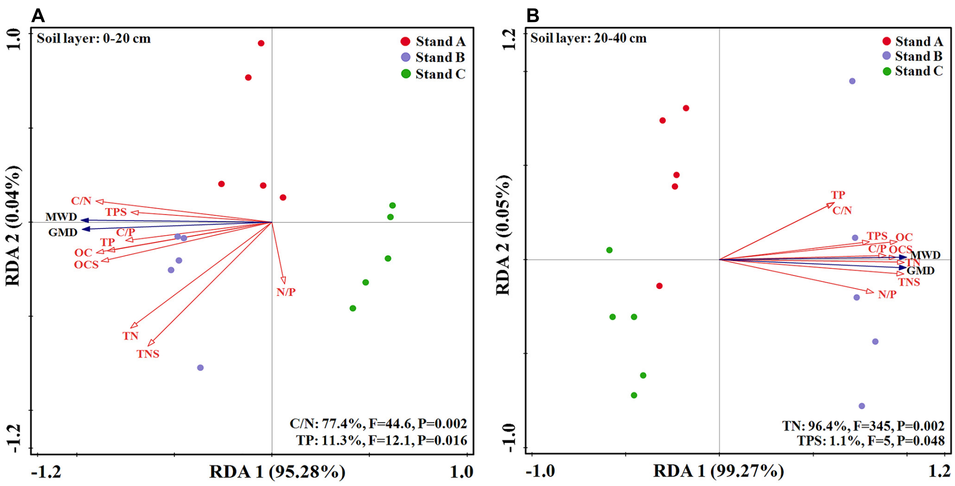

FIGURE 6
Redundancy analysis of soil aggregate stability and soil ecological stoichiometric characteristics across the three stand types at 0–20 cm **(A)** and 20–40 cm **(B)**. MWD and GMD stand for mean weight diameter and geometric mean diameter, respectively. OC, TN, and TP stand for the contents of organic carbon, total nitrogen and total phosphorus in bulk soil, respectively. OCS, TNS, and TPS stand for the stocks of organic carbon, total nitrogen, and total phosphorus in bulk soil, respectively. C/N, C/P, and N/P stand for the ratios of organic carbon, total nitrogen and total phosphorus in bulk soil, respectively. The red and blue arrows stand for explanatory variable and response variable, respectively.

4. Discussion

4.1. Aggregate distribution and stability

Variation in the proportion of soil aggregates confirms the distribution of soil porosity and its morphological characteristics (Six et al., 2004). Moreover, soil aggregate stability can represent the ability of soil to supply and store soil nutrients (Gelaw et al., 2015). Therefore, exploring soil aggregate distribution and stability is vital for evaluating soil structure. In this study, mixed stands favored the formation of >2 mm aggregates, confirming earlier studies that aggregate distribution is significantly affected by stand type (Wang S. Q. et al., 2021). According to the hierarchical concept of soil aggregates, plant litterfall quality can be used to identify soil aggregate distribution, thereby influencing the composition of soil aggregates (Six and Paustian, 2014; Tang and Wang, 2022). In this study, the litter amount (**Table 1**) in the mixed stands was significantly higher than that in the pure stands. Likewise, the increased amount of plant litterfall and coverage area in the mixed stands decreased rainfall leaching, thus resulting in the protection of >2 mm aggregates from dispersion with water. To encourage the creation of cementing agents and the development of >2 mm aggregates, mixed forests have a better capacity to contain a significant amount of organic matter derived from plant residue inputs (Picariello et al., 2021; Zhao et al., 2021). Moreover, organic matter can stimulate the formation of soil aggregates and regulate soil aggregation (Feng et al., 2020).

The conversion of forest can significantly impact soil aggregate stability (Meng et al., 2022). Forest conversion affects the decomposition of litter to change organic colloids, thereby modifying soil aggregation and stability (Kerdraon et al., 2020; Li et al., 2022). Likewise, based on **Table 3**, the MWD and GMD were influenced by stand type. Due to the greater stability index (MWD, GMD) values (**Figure 3**) in mixed stands, the mixed stands in this study had had stronger soil aggregate stability than pure stands, which is consistent with the findings from Tang et al. (2023). This result might be due to the greater litterfall residue (**Table 1**) and the proportion of >2 mm aggregates proportions (**Figure 2**) in the mixed stands. The >2 mm aggregates can provide a physical protection for organic matter, resulting in a significant increase in soil aggregate stability (Xie et al., 2018). In addition, a highly significant correlation between soil aggregate stability and organic matter has been reported (Li et al., 2022). Soil aggregate stability has a negative relationship with BD and a positive relationship with Pt (Liu et al., 2021). In contrast to pure stands, where the soil BD was much higher, mixed stands had significantly lower soil BD (**Table 3**), while soil Pt showed the reverse pattern, which suggested the mixed stands had higher soil aggregate stability. The reduced soil organic matter may be driven by increased soil densification, causing lower soil aggregate stability in pure stands (Faustino et al., 2020). Notably, this study discovered that there were more >2 mm aggregates in the 0–20 cm layer than in the 20–40 cm layer (**Figure 2**). Similarly, a large amount of organic matter from litter is mostly distributed in the soil surface (You et al., 2020). Organic matter is one of the most important persistent binding agents for facilitating soil aggregate formation (Smith et al., 2014). Organic matter is beneficial for the soil aggregation process because it binds different chemical bonds in the form of micelles (Sarker et al., 2018). Moreover, some studies have demonstrated that the interaction between organic matter and metal oxides is a key factor promoting soil aggregate formation and affecting aggregate stability (Li et al., 2023). These factors might explain the higher stability of soil aggregates in the 0–20 cm layer.

4.2. Aggregate-associated OC, TN, and TP contents under different stand types

In this research, OC and TN (**Table 4**) contents were mainly distributed in <0.25 mm aggregates. Because <0.25 mm aggregates have larger specific surface areas than other aggregates, they have a higher adsorption capacity for nutrients derived from litter residues and root exudates (Egan et al., 2018). Therefore, OC and TN contents showed significant decreases as aggregate size increased. However, Xu et al. (2020) reported the opposite result, probably because plantation management measures and site conditions can influence the OC and TN contents in the various-sized aggregates. Similarly, in the present study, there was a covariation pattern between the contents of OC and TN within different-sized aggregates. Since C and N act on the structural elements of organic matter, the aggregate-associated OC and TN contents within aggregates can affect variations in the content of soil organic matter (Cooper et al., 2020). However, TP has different responses to aggregate size. Some studies have demonstrated that aggregate size has no significant effects on TP, which showed a random distribution in different-sized aggregates (Huang K. X. et al., 2020; Wang S. Q. et al., 2021). Notably, consistent with other studies, the soil TP contents of the three stands were spread uniformly throughout the aggregates (Zhang et al., 2022). P is a sedimentary mineral that readily mixes in soil with iron (Fe) and aluminum (Al) but is not utilized by plants (Dong et al., 2020). In this study, the change in soil TP content lagged behind the soil OC and TN contents at aggregate scale, indicating that soil TP content is a limiting nutrient. In addition, the soil TP content was relatively low (**Table 2**) due to the relatively fixed P sources, which is a common phenomenon in subtropical China (Tong et al., 2021). Meanwhile, the soil in southern China is typically acidic, and the utilization of soil TP for plant growth is commonly low in these subtropical regions (Hou et al., 2020; Zhang et al., 2022).

Stand conversion could affect soil physicochemical properties and soil nutrient inputs due to variations in forest structure and tree species composition by changing litterfall quality and tree root exudates (Koutika et al., 2020). Our findings demonstrated that mixed stands, particularly mixed Chinese fir with *M. macclurei* plantations, significantly enhanced the accumulation of aggregate-related OC and nutrients compared to pure stands. The promotion of mixed stands was mainly driven by the higher soil aggregate stability and increased litter volumes, which are key factors for improving soil structure and organic matter content accumulation by regulating microbial communities, thereby increasing the soil OC and TN contents in aggregates (Huang K. X. et al., 2020; Gao et al., 2022). Moreover, the litter quality and root distribution of *M. macclurei* were better than those of *M. laosensis* and Chinese fir; therefore, *M. macclurei* has a stronger capacity for nutrient return and availability to plant residue decomposition and stimulates organic matter production for soil aggregation (Xu et al., 2020; Wang S. Q. et al., 2021).

4.3. Aggregate-associated stoichiometric ratios under different stand types

Generally, stoichiometric ratios, as key parameters of soil fertility and quality, are important for determining the cycling and limitation of chemical elements (Wang et al., 2022). The C/N rate impacts organic matter degradation according to the study by Six and Paustian (2014). In this current research, C/N was higher in <0.25 mm aggregates across various stands, suggesting that the organic matter in the <0.25 mm aggregates was more stable and older than that in other sized aggregates, confirming the results of the study from Six et al. (2004). Our research found that the contents of OC and TN were also higher in the aggregate of <0.25 mm across various stand types, but the TP content was even in diverse-sized aggregates. This result is because P has selective adsorption properties on aggregates of different particle sizes (Huang Y. Z. et al., 2020). A coordinated trend was visible in the OC and TN components that were related to aggregates (**Figure 4A**). Thus, the present study indicated that the responses of C/P and N/P to different aggregate sizes mainly determined the responses of OC and TN to the different-sized aggregates. Despite the results being consistent with those of the studies from Cui et al. (2021), previous studies have reported that the aggregate distribution can influence the key biogeochemical cycling of N and P. The high ratio of C/N improves OC as well as nutrient retention in the short term (Six and Paustian, 2014). Moreover, C/P and N/P can be widely used to represent the vegetation constraints by nutrient demand and soil nutrient supply. The aggregate-related C/N and C/P were considerably higher in the mixed stands than in the pure stand at both depths, favoring OC and nutrient accumulation. Our most recent findings relate to the mechanisms described in the paragraphs below. This result may have occurred as a result of the higher soil aggregate stability in mixed stands, which offered physical protection for soil organic matter and nutrients (Six et al., 2004). More importantly, our study suggested that the contents of OC, TN, and TP in mixed stands had significantly greater distributions than those in pure stands, increasing the inputs of organic matter in the mixed stands (Wang Z. C. et al., 2021). The introduction of broadleaf trees into monoculture coniferous stands (Chinese fir) can improve plant species composition and diversity to increase quantity and quality of litterfall and soil nutrient return (Tan et al., 2022). Additionally, *M. laosensis* and *M. macclurei* produce litterfall residues of greater quality than Chinese fir, promoting the growth and reproduction of soil microorganisms or increasing enzyme activity (Wang S. Q. et al., 2021). Previous studies confirmed that the C:N:P ratio in the >2 mm aggregates among mixed stands notably increased (Xu et al., 2020), resulting in a lower consumption of soil OC and nutrients and a greater nutrient availability in mixed stands.

Among the three CFPs, the mean ratio of the soil C/N ratio (16.28) was higher than the mean soil in China (14.3) and the mean soil globally (11.9), while the mean ratios of C/P (76.93) and N/P (4.54) were lower than the average soil in China (136.93 and 186.13, respectively) and the average soil globally (Tian et al., 2010; Tang and Wang, 2022). This result indicated that the organic matter decomposition rates were relatively low and that soil specimens in the study site were possibly limited by the OC or TN contents. This result may be due to the fast growth of Chinese fir, and many soil nutrients are supplied, generally leading to soil nutrient limitations. Moreover, these results were mainly related to the low levels of OC and nutrients. The average soil OC, TN, and TP contents across all stand types in this study were 18.95, 1.10, and 0.25 g kg^{-1}, respectively. These values were lower than the average soil OC, TN, and TP contents in China, which were 30.40, 2.21, and 0.20–1.10 g kg^{-1}, respectively (Tian et al., 2010). Early studies have indicated that N is regarded as a common nutrient limitation in the CFPs of Guangxi (Tong et al., 2020; Tang and Wang, 2022), while China has one of the highest N levels reported worldwide, especially in subtropical forests (Wang et al., 2018). This study site with long-term high temperatures and heavy rainfall has experienced surface weathering and erosion, which accelerated significant losses in the contents of OC and TN, thus resulting in lower C/P and N/P with the limitations of OC and TN.

4.4. Aggregate-associated OCS, TNS, and TPS under different stand types

In this study, the OCS, TNS, and TPS in the >2 mm aggregates were the highest, indicating that the >2 mm aggregates mainly carried soil OC and nutrients. Thus, this finding supports our first hypothesis. Generally, the OCS, TNS, and TPS distributions were closely related to their contents with aggregate size (Egan et al., 2018). The >2 mm aggregates had the lowest contents of C–N–P (**Figure 5**) but made the largest contributions to the OCS, TNS, and TPS (**Supplementary Figure 1**). The turnover time of the OC content in the >2 mm aggregates was shorter than that in the <0.25 mm aggregates, thus promoting the higher OCS in >2 mm aggregates (Lu et al., 2019; Wang et al., 2023). In addition, it is considered that the litter residues are easily combined with >2 mm aggregates (Six et al., 2004). According to this research, aggregate-associated OCS, TNS, and TPS would be influenced by aggregate size, not the aggregate-associated OC, TN, and TP contents. Thus, >2 mm aggregates were the greatest contributors to the OCS, TNS, and TPS, as evidenced by the highest composition of >2 mm aggregates compared with the other fractions (**Figure 2**). Our result was confirmed in previous study findings (Wu et al., 2022).

In comparison to pure stands, mixed stands showed greater levels of OCS (**Figure 5A**), TNS (**Figure 5B**), and TPS (**Figure 5C**) among the different-sized aggregates, suggesting that mixed stands were better able to store OC and nutrients. Due to the stability of the soil aggregates, mixed stands in this study had much higher tree height and diameter with litter quantities than did pure stands, which increased the ability of the plantations to intercept rainwater and lessened the effects of leaching. Moreover, stable soil aggregates can store more organic matter and nutrients, thereby achieving soil fertilizer retention (Gelaw et al., 2015). The successive cropping of CFPs resulted in excessive accumulation of alleles and relatively low accumulation rates of soil organic matter, which caused the occurrence of self-toxicity, influenced soil enzyme activity and decreased soil fertility (Huang et al., 2000), thus returning fewer nutrients to the soil. Overall, the above explanation of the mechanism supports our second hypothesis. Notably, OCS, TNS and TPS within 0.25–1 mm and 1–2 mm aggregates in mixed stands were greater than those in pure stand (**Figure 5**), but the percentage contribution of OCS, TNS and TPS in 0.25–1 mm and 1–2 mm aggregates to bulk soil in pure stand were greater than that in mixed stands (**Supplementary Figure 1**). This may be owing to the significant higher proportion of 0.25–1 mm and 1-2 mm aggregates in pure stand. Consequently, based on our results, the effect of stand type on the OCS, TNS and TPS within soil aggregates seem to be mostly depended on the composition of different soil sized aggregates.

4.5. Soil aggregate stability as influenced by soil ecological stoichiometric characteristics

In this study, the stability of soil aggregates in mixed stands was dramatically greater than that in pure stands, which positively affected OC and nutrient accumulation. Thus, the stability of aggregates may be influenced by forest management, mixed plantation structure and tree species. This is likely because mixed stands have improved stand structural heterogeneity, species richness and litter amount. Moreover, mixed stands improve soil structure to reduce nutrient loss from the soil. Similarly, our results were confirmed by RDA (**Figure 6**) and Pearson's correlation analysis (**Supplementary Figure 2**). Likewise, there is a notably positive correlation between soil aggregate stability and the contents of TN with TP, TPS, in addition to the C/N ratio. The results of this study differed from those of Mao et al. (2021), who found that the contents of OC and TN can have a significant impact on soil aggregate stability across different stand ages of CFPs. Rather, this study found that the C/N ratio and TN content in 0-20 cm (**Figure 6A**) and 20-40 cm (**Figure 6B**), respectively, were the main key factors of variation in soil aggregate stability across various stands. The soil C/N ratio is considered the best predictor of soil aggregate stability, and the impacts of the soil C/N ratio on soil aggregate stability have been reported (Liu et al., 2020). The higher soil C/N ratio could reduce the degree of humification to increase the retention of organic matter. Similarly, higher contents of OC and nutrients were found in mixed stands, while this result can be explained by the greater organic matter input in mixed stands. Generally, soil aggregate stability is strongly associated with organic matter. Organic matter plays a critical role in the cementing agents of soil aggregation, and it has an impact on soil aggregation stabilization. Moreover, C and N are structural elements of organic matter, which can provide material for soil aggregation (Cooper et al., 2020). Our results showed that the accumulation and decomposition of the OC and TN in soil were relatively consistent and probably limiting elements of plant growth, especially TN. In addition, soil TN has a significant positive correlation with soil aggregate stability (Zhu et al., 2021). In particular, the study site has been affected by strong weathering due to extreme heat and rainfall, resulting in the P limitation of the regional soils, which affects plant growth and causes a decrease in organic matter inputs; thus, soil aggregate stability declines (Wu et al., 2018; Zhang et al., 2022). As a result, the four parameters, including the C/N ratio, the TN and TP concentrations, and the TPS, had a substantial impact on soil aggregate stability with stand type in CFPs. Specifically, the TN content and C/N ratio were key contributors affecting soil aggregate stability in the three stands, which supports our third hypothesis.

5. Conclusion

Irrespective of the diverse stand types of CFPs, the soil OC and TN contents together with the C/N, C/P, and N/P ratios significantly increased as the aggregate size decreased in all soil profiles, but the OCS, TNS, and TPS showed clearly opposite trends. At the aggregate scale, mixed CFPs with *M. laosensis* and mixed CFPs with *M. macclurei* had better soil aggregate stability and nutrient conditions than did pure CFPs at both soil depths. The soil C/N ratio in this research region was higher than that in other CFP planted regions in China and around the world, while the C/P and N/P ratios were much lower, indicating lower OC and TN contents, especially TN content. In addition, soil aggregate stability was dominantly influenced by the C/N ratio, TN, TP, and TPS. Therefore, the present research is conducive to providing supplementary information for our understanding of promoting degraded soil restoration and sustainable forest management in global forest ecosystems.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

YH: investigation, data curation, experimental results analysis, and writing—original draft. QZ: conceptualization, investigation, methodology, and experimental results analysis. CJ: investigation, methodology, data processing, and visualization. YL: conceptualization, data curation, and writing—reviewing and editing. HZ: investigation, validation, and writing—reviewing and editing. SY: conceptualization, supervision, and writing—reviewing and editing. All authors contributed to the article and approved the submitted version.

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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.2023.1141953/full#supplementary-material

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