Effects of Stand Age and Density on Leaf Litter Nutrient Dynamics in Pinus massoniana Plantations (Postprint)

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Abstract

To investigate the effects of different stand ages and densities on the nutrient structure and return dynamics of litterfall in Pinus massoniana plantations, eight forest stands were selected for study at Zhenlong Forest Farm in Heng County, Nanning City, Guangxi, including four age classes (young, middle-aged, mature, and over-mature forests) and four density levels (low, low-medium, medium-high, and high density) of Pinus massoniana forests. The C, N, and P contents and their ecological stoichiometric characteristics were analyzed for both intact and fragmented litter at two different decomposition stages. The results showed that: (1) Among different stand ages, the initial C content of litterfall was higher in over-mature and mature forests, N content was higher in over-mature and middle-aged forests, while P content showed no significant changes. This resulted in the highest C:N and C:P ratios of litterfall in mature forests, whereas the N:P ratio showed no significant differences among stand ages, indicating that young and middle-aged Pinus massoniana forests in rapid growth phases may have greater demands for N and P nutrients. (2) Among different density stands, with increasing stand density, the initial C content of litterfall gradually increased, N content showed no significant changes, while P content decreased. High-density stands exhibited higher initial C:P and N:P ratios in litterfall, suggesting that Pinus massoniana under high planting density may have greater demands for N and P nutrients and stronger P reabsorption. (3) The C content, C:N ratio, C:P ratio, and N:P ratio of fragmented litterfall in Pinus massoniana forests of different ages and densities were lower than those of intact litterfall, while N and P contents were higher, indicating an enrichment phenomenon of N and P nutrients during litter decomposition. (4) The difference in C content between fragmented and intact litterfall was greatest in middle-aged and higher-density Pinus massoniana forests, while the C:N and C:P ratios were also lower, suggesting that the litter C decomposition rate may be higher in these two stand types. These results indicate that middle-aged and medium-high to high-density Pinus massoniana forests may have greater demands for N and P nutrients, higher reabsorption efficiency, and higher potential decomposition rates of litter C, which may facilitate faster incorporation of organic carbon into the soil.

Full Text

Preamble

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Title: Effects of Stand Age and Density on Litter Nutrient Dynamics in Planted *Pinus massoniana* Forests

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Abstract

To understand how stand age and density influence litter nutrient composition and return patterns in *Pinus massoniana* plantations, we selected eight stand types in Zhenlong Forest Farm, Hengxian County, Nanning, Guangxi, including four age classes (young, half-mature, mature, and over-mature stands) and four density levels (low, medium-low, medium-high, and high density). We analyzed carbon (C), nitrogen (N), and phosphorus (P) contents and their stoichiometric ratios in both intact (early decomposition stage) and fragmented (late decomposition stage) litter. The results showed: (1) Among different stand ages, initial litter C content was higher in over-mature and mature stands, N content was higher in over-mature and half-mature stands, while P content showed no significant variation. This resulted in the highest C:N and C:P ratios in mature stands, though N:P ratios did not differ significantly among ages, suggesting that young and half-mature stands in rapid growth phases may have greater N and P demands. (2) Across density levels, initial litter C content increased with stand density, N content remained stable, and P content decreased. High-density stands exhibited higher initial C:P and N:P ratios, indicating greater N and P demand and stronger P resorption under high planting density. (3) Fragmented litter had lower C content, C:N, C:P, and N:P ratios but higher N and P contents compared to intact litter, demonstrating N and P enrichment during decomposition. (4) Half-mature and high-density stands showed the greatest difference in C content between fragmented and intact litter, along with lower C:N and C:P ratios, suggesting potentially higher C decomposition rates in these stands. These findings indicate that half-mature and medium-to-high density *P. massoniana* stands have greater N and P requirements, higher nutrient resorption efficiency, and potentially faster litter C decomposition, which may facilitate rapid organic carbon input to soils.

Keywords: *Pinus massoniana*, stand age, density, litter, ecological stoichiometry, nutrients

Introduction

During China’ s 13th Five-Year Plan period, commercial logging quotas for natural forests were completely eliminated nationwide, making planted forests a critical resource for meeting the country’s timber demands. Southern China represents the primary region for planted forest establishment, with well-developed forestry industries. Statistics show that Guangxi Zhuang Autonomous Region maintains over 240 million mu of forest land, with 96 million mu of planted forests accounting for approximately one-tenth of the national total—the largest in China. In 2018, timber production reached 31 million m³, representing 46% of national output, while the forestry industry’s total output value grew to 562.8 billion RMB in 2018, following an average annual growth rate of 24.1% during the previous five years (Zhang and Wu, 2018). Over recent decades, timber forests have comprised 52.76% of Guangxi’ s species composition, with Chinese fir accounting for 17.66%, pines for 11.50%, and eucalypts for 11.86% (Qin and Nong, 2018). Thus, pine plantations constitute one of Guangxi’ s three major timber forest types.

Pinus massoniana is the dominant pine plantation species, valued for its drought tolerance, poor-soil adaptability, and strong resilience (Wang et al., 2015). Its extensive planting area and high yield meet national timber demands. However, long-term pure-stand management has led to poor nutrient balance, slow nutrient cycling (Hao et al., 2018), reduced productivity, soil erosion, and diminished ecosystem service values (He et al., 2013; Wu et al., 2019). With China's ecological civilization development, these management issues have garnered widespread attention, prompting a shift from timber-focused single-objective management toward multi-purpose management that enhances both ecosystem services and economic benefits (Liu et al., 2018). Consequently, near-natural transformation strategies for *P. massoniana* pure stands have been proposed and preliminarily implemented (Ming et al., 2017), with studies showing increased soil organic carbon after transformation (Lai et al., 2013). However, improving ecosystem functions requires not only enhanced soil organic matter but also increased nutrients in other components.

Carbon, nitrogen, and phosphorus are essential for plant growth and ecosystem function maintenance: C constitutes the primary element of plant dry matter, while N and P form proteins and genetic material, with deficiencies limiting plant growth (Yang and Wang, 2011). Recent studies indicate that soil N and P contents are generally low in Guangxi' s *P. massoniana* plantations (Qin et al., 2017), making these nutrients critical management considerations. To develop scientifically sound management strategies, a deeper understanding of nutrient cycling in *P. massoniana* plantation ecosystems is needed.

Ecological stoichiometry examines energy and multi-element balance (primarily C, N, and P) in organisms and ecosystems (Elser et al., 1996), serving as an important theoretical tool for analyzing nutrient cycling processes and states (Pant et al., 2015; Zhang et al., 2015; Huang et al., 2018). Litter represents a crucial nutrient pool in forest ecosystems: (1) Initial litter nutrient content correlates closely with soil nutrients, plant nutrient content, and resorption efficiency (Pan et al., 2011). When soil nutrient availability is low, plants exhibit reduced nutrient content and enhanced resorption to meet growth demands, resulting in lower litter nutrient content. (2) Initial litter nutrient status influences return quality and rate (Li et al., 2008). High N:P ratios, often indicating low P or high N and lignin content, correspond to slower decomposition (Gallardo et al., 1999). Additionally, litter C:N:P ratios significantly affect soil nutrient accumulation, microbial growth, and extracellular enzyme activity, altering above- and below-ground nutrient cycling rates (Pan et al., 2018). Therefore, studying litter C, N, and P dynamics and stoichiometric ratios reveals nutrient variation patterns under different conditions and informs plantation management.

Previous research has shown that plant respiration rates and soil carbon flux vary among *P. massoniana* stands of different ages (Wu et al., 2014), while appropriate stand density can enhance understory diversity and soil nutrient content (Sun et al., 2018). Thus, both stand age and density affect ecosystem nutrient cycling. Based on long-term monitoring plots, this study selected eight stands representing four ages and four densities, collecting intact (early decomposition) and fragmented (late decomposition) litter samples along with surface soil samples to analyze C, N, and P contents and ratios. Our objectives were:

(1) to characterize litter C, N, and P contents and ratios across different stand ages and densities, and (2) to analyze differences between decomposition stages and explore nutrient dynamics during litter decomposition. These findings will provide a scientific basis for managing *P. massoniana* pure stands.

1.1 Study Area Description

The study was conducted at Zhenlong Forest Farm in northern Hengxian County, Nanning, Guangxi (109°08 -109°19 E, 23°02 -23°08 N). The region features low hills at 400–700 m elevation, with acidic to slightly acidic lateritic red soils (pH 3.72–4.14; Table 1). The forest farm covers 6,069.9 ha, primarily planted with *Eucalyptus grandis*, *Pinus massoniana*, and *Cunninghamia lanceolata*. The climate is south subtropical monsoonal, with mean annual precipitation of 1,477.8 mm, mean annual temperature of 21.5 °C, and annual sunshine duration of 1,758.9 h (Fan and Yang, 2012).

1.2.1 Plot Establishment

In 2018, we selected eight stand types representing four age classes [6-year-old young stand (AF1), 17-year-old half-mature stand (AF2), 32-year-old mature stand (AF3), and 58-year-old over-mature stand (AF4)] and four density levels [2,500 stems · ha^{1} (2 m × 2 m spacing, DF1, low density), 3,300 stems · ha^{1} (1.5 m × 2 m spacing, DF2, medium-low density), 4,500 stems · ha^{1} (1.5 m × 1.5 m spacing, DF3, medium-high density), and 6,000 stems · ha^{1} (1 m × 1.67 m spacing, DF4, high density)] (Table 1). For each stand type, three 20 m × 20 m standard plots were established in areas with consistent site conditions, soil depth, texture, and tree growth (plot spacing >50 m). These plots were part of long-term monitoring sites established by the Guangxi Forestry Research Institute (Fan and Yang, 2012), totaling 24 plots for this study.

1.2.2 Sample Collection

In July 2018 (growing season), each plot was divided into four 10 m × 10 m subplots. At the plot center and each subplot center, 0.5 m × 0.5 m sampling areas were established for collecting litter at two decomposition stages: (1) Intact litter, representing freshly fallen or recently deposited material from the upper litter layer, was used to characterize initial litter quality; (2) Fragmented litter, representing long-decomposed material in contact with soil from the lower litter layer. Litter samples from the five sampling points were thoroughly mixed to create a composite plot sample, yielding 48 litter samples (24 intact and 24 fragmented). Approximately 100 g of each composite sample was oven-dried at 65 °C to constant weight, then ground and sieved through a 0.15 mm mesh (100 目) for analysis.

Concurrently, surface soil samples (0–20 cm) were collected beneath each litter sampling point and mixed into composite plot samples. Soil samples were stored in plastic bags in ice boxes for immediate laboratory processing. Fine roots and debris were removed, and soils were sieved through a 2 mm mesh (10 目), then divided into two portions: one stored at -20 °C for other analyses, and one air-dried, ground, and sieved through 0.85 mm (20 目) and 0.15 mm meshes for nutrient determination.

1.2.3 Litter and Soil Sample Analysis

For litter analysis, 0.015 g of sample (precision 0.0001 g) was used to determine total carbon content via K Cr O -H SO oxidation. For total nitrogen and phosphorus, 0.4 g of sample (precision 0.0001 g) was digested using H SO -H O oxidation, with N measured by FIA flow injection analysis and P determined by molybdenum-antimony colorimetric spectrophotometry.

Soil organic carbon (SOC) was measured using K Cr O + H SO oxidation. Total nitrogen (TN) was determined by Kjeldahl digestion followed by flow injection analysis (FIAstar 5000, FOSS, Hillerød, Denmark). Ammonium and nitrate were extracted with 2 M KCl and measured by flow injection. Total phosphorus (TP) was digested with NaOH in a muffle furnace, then measured spectrophotometrically after H SO + HCl washing and molybdenum blue color development. Available phosphorus (AP) was extracted with NaHCO solution and measured spectrophotometrically after molybdenum blue color development (Pan et al., 2015).

1.2.4 Statistical Analysis

Data were processed using Excel and analyzed with SPSS 11.5. Descriptive statistics, one-way ANOVA, and LSD multiple comparisons were used to examine differences in soil and litter nutrient contents and ratios among stand ages and densities. Pearson correlation analysis was performed to assess relationships between litter and soil nutrient parameters.

2.1 Soil Nutrient Status Across Stand Ages and Densities

Soil total nitrogen, total phosphorus, ammonium nitrogen, and nitrate nitrogen differed significantly among stand ages, while available phosphorus showed no significant variation (Table 2). Half-mature stands (AF2) had the highest total N, total P, and ammonium N contents. Young stands (AF1) had the lowest total P, while mature stands (AF3) had the lowest total N and ammonium N. Mature stands exhibited the highest nitrate N, whereas over-mature stands (AF4) had the lowest.

Across density levels, total N, total P, ammonium N, and total P showed no significant differences. Nitrate N was lowest in DF1 (low density) but did not differ among the other three densities (Table 2).

Table 2 Soil carbon, nitrogen, and phosphorus contents in the eight stand types of planted *Pinus massoniana* forests (mean ± SE)

Stand Type	Total Nitrogen (g · kg ^{1})	Total Phosphorus (g · kg ^{1})	Ammonium N (mg · kg ^{1})	Nitrate N (mg · kg ^{1})	Available P (mg · kg ^{1})
AF1 (Young)	1.79 ± 0.11 ab	0.22 ± 0.02 a	10.68 ± 1.62 ab	4.37 ± 0.53 ab	3.67 ± 0.51 a
AF2 (Half-mature)	2.14 ± 0.09 b	0.48 ± 0.01 b	15.23 ± 0.80 b	4.71 ± 0.64 ab	3.22 ± 0.18 a
AF3 (Mature)	1.45 ± 0.07 a	0.32 ± 0.02 ab	8.48 ± 1.48 a	6.35 ± 0.96 b	3.32 ± 0.12 a
AF4 (Over-mature)	1.77 ± 0.31 ab	0.48 ± 0.13 b	14.29 ± 0.97 ab	3.62 ± 0.28 a	3.05 ± 0.25 a
DF1 (Low density)	1.40 ± 0.08 a	0.38 ± 0.04 a	7.78 ± 0.29 a	5.13 ± 0.19 a	1.59 ± 0.11 a
DF2 (Medium-low)	1.51 ± 0.15 a	0.39 ± 0.05 a	6.43 ± 0.17 a	7.02 ± 0.40 b	0.50 ± 0.12 a
DF3 (Medium-high)	1.64 ± 0.16 a	0.45 ± 0.01 a	8.02 ± 0.69 a	4.97 ± 0.38 a	1.64 ± 0.16 a
DF4 (High density)	1.59 ± 0.11 a	0.50 ± 0.12 a	6.89 ± 0.81 a	6.94 ± 0.61 b	0.45 ± 0.01 a

Note: Different lowercase letters within the same row indicate significant differences among stand ages or densities at P < 0.05.

2.2 Litter C, N, P Contents and C:N:P Ratios Across Stand Ages

Litter C, N, and P contents did not increase progressively with stand age (Table 3). Intact litter C content ranged from 451.24–470.12 g · kg ^{1}, showing the pattern: half-mature < young mature < over-mature. Intact litter N content ranged from 9.30–10.43 g · kg ^{1} (mature < young < half-mature over-mature), while intact litter P content ranged from 0.59-0.71 g · kg ^{1} with no significant differences among ages. Fragmented litter C content ranged from 321.08–390.29 g · kg ^{1} (half-mature < young mature over-mature). Fragmented litter N content ranged from 10.87-13.08 g · kg ^{1} (over-mature < half-mature young < mature), and fragmented litter P content ranged from 0.88–1.18 g · kg ^{1} (over-mature < mature < half-mature young). Intact litter C content was significantly higher than fragmented litter across all ages, while N and P contents showed the opposite pattern.

Litter C:N:P ratios also did not increase progressively with stand age (Table 3). Intact litter C:N ratios ranged from 44.09–49.85 (half-mature over-mature young < mature). Intact litter C:P ratios ranged from 675.51–788.10 (young half-mature over-mature < mature), while N:P ratios showed no significant differences (14.57–15.90). Fragmented litter C:N ratios ranged from 26.78–36.10 (half-mature young mature < over-mature). Fragmented litter C:P ratios ranged from 276.27–464.66 (half-mature < young < mature < over-mature), and N:P ratios ranged from 10.30–12.74 with no significant differences. All C:N, C:P, and N:P ratios were significantly higher in intact versus fragmented litter.

Table 3 Litter carbon, nitrogen, and phosphorus contents and C:N:P mass ratios between two decomposition periods in different stand ages of planted *Pinus massoniana* forests (mean ± SE)

Stand Age	Litter Type	C (g · kg ^{1})	N (g · kg ^{1})	P (g · kg ^{1})	C:N Ratio	C:P Ratio	N:P Ratio
Young (AF1)	Intact	460.09 ± 8.30 AB	9.85 ± 0.16 AB	0.68 ± 0.05 A	46.75 ± 1.56 A	677.57 ± 41.68 A	14.57 ± 1.33 A
	Fragmented	378.33 ± 57.28 b	12.53 ± 1.05 ab	1.18 ± 0.06 b	29.83 ± 2.30 a	326.64 ± 63.09 a	10.75 ± 1.37 a
Half-mature (AF2)	Intact	451.24 ± 4.68 A	10.24 ± 0.19 B	0.66 ± 0.00 A	44.09 ± 1.24 A	675.50 ± 7.34 A	15.34 ± 0.34 A
	Fragmented	321.08 ± 15.12 a	11.98 ± 0.41 ab	1.17 ± 0.08 b	26.78 ± 0.49 a	276.27 ± 20.85 a	10.30 ± 0.60 a
Mature (AF3)	Intact	462.78 ± 5.20 AB	9.30 ± 0.23 A	0.59 ± 0.03 A	49.85 ± 1.82 B	788.09 ± 32.03 B	15.89 ± 1.18 A
	Fragmented	381.33 ± 22.59 b	13.08 ± 0.65 b	1.04 ± 0.08 ab	29.17 ± 1.03 a	368.24 ± 25.21 ab	12.70 ± 1.23 a

Stand Age	Litter Type	C (g · kg ^{1})	N (g · kg ^{1})	P (g · kg ^{1})	C:N Ratio	C:P Ratio	N:P Ratio
Over-mature (AF4)	Intact	470.12 ± 1.24 B	10.43 ± 0.18 B	0.71 ± 0.07 A	45.11 ± 0.67 A	678.44 ± 73.84 A	15.00 ± 1.43 A
	Fragmented	390.29 ± 4.10 b	10.87 ± 0.52 a	0.88 ± 0.12 a	36.10 ± 1.89 b	464.66 ± 76.04 b	12.74 ± 1.41 a
Average	Intact	461.06 ± 3.09	9.96 ± 0.15	0.66 ± 0.03	46.45 ± 0.89	704.90 ± 24.20	15.20 ± 0.51
	Fragmented	367.76 ± 15.85	12.12 ± 0.39	1.07 ± 0.05	30.47 ± 1.24	358.95 ± 30.45	11.62 ± 0.61

Note: Different capital letters indicate significant differences among intact litter across stand ages; different lowercase letters indicate significant differences among fragmented litter across stand ages (P < 0.05). Bold values are higher than non-bold values. N = intact litter; B = fragmented litter.

2.3 Litter C, N, P Contents and C:N:P Ratios Across Stand Densities

Litter C, N, and P contents did not increase progressively with stand density (Table 4). Intact litter C content ranged from 466.36–484.27 g · kg ^{1} (DF1 < DF2 < DF3 < DF4). Intact litter N content ranged from 11.79–12.97 g · kg ^{1} with no significant differences among densities. Intact litter P content ranged from 0.64–0.90 g · kg ^{1} (DF2 < DF4 < DF3 < DF1). Fragmented litter C content ranged from 252.97–344.07 g · kg ^{1} (DF4 < DF3 < DF1 < DF2). Fragmented litter N content ranged from 11.06–13.48 g · kg ^{1} (DF4 < DF3 < DF1 < DF2), and fragmented litter P content ranged from 0.95–1.19 g · kg ^{1} (DF2 < DF3 < DF1 < DF4). Intact litter C content was significantly higher than fragmented litter across all densities, while P content showed the opposite trend.

Litter C:N:P ratios also did not increase progressively with density (Table 4). Intact litter C:N ratios ranged from 35.95–40.33 (DF1 < DF3 DF4 < DF2). Intact litter C:P ratios ranged from 521.63–740.93 (DF1 < DF3 < DF4 < DF2), and N:P ratios ranged from 14.51–18.79 (DF1 < DF3 < DF2 DF4). Fragmented litter C:N ratios ranged from 22.96–25.82 with no significant differences among densities. Fragmented litter C:P ratios ranged from 211.68–368.65 (DF4

< DF1 < DF3 < DF2), and N:P ratios ranged from 9.23–14.35 (DF4 < DF1 DF3 < DF2).

Table 4 Litter carbon, nitrogen, and phosphorus contents and C:N:P mass ratios between two decomposition periods in different stand densities of planted *Pinus massoniana* forests (mean ± SE)

Stand Density	Litter Type	C (g · kg ^{1})	N (g · kg ^{1})	P (g · kg ^{1})	C:N Ratio	C:P Ratio	N:P Ratio
DF1 (Low)	Intact	466.36 ± 7.33 A	12.97 ± 0.17 A	0.90 ± 0.06 B	35.95 ± 0.24 A	521.63 ± 31.74 A	14.51 ± 0.88 A
	Fragmented	309.21 ± 39.43 ab	12.42 ± 0.79 ab	1.11 ± 0.05 a	24.72 ± 2.00 a	278.13 ± 33.84 ab	11.22 ± 0.87 ab
DF2 (Medium-low)	Intact	474.71 ± 3.61 AB	11.79 ± 0.34 A	0.64 ± 0.02 A	40.33 ± 1.36 B	740.93 ± 19.84 B	18.42 ± 0.94 B
	Fragmented	344.07 ± 24.94 b	13.48 ± 0.70 b	0.95 ± 0.09 a	25.82 ± 3.03 a	368.65 ± 45.18 b	14.35 ± 1.20 b
DF3 (Medium-high)	Intact	480.46 ± 3.29 AB	12.48 ± 0.83 A	0.72 ± 0.01 A	38.82 ± 2.49 AB	670.81 ± 17.25 B	17.42 ± 1.23 AB
	Fragmented	306.10 ± 21.59 ab	12.20 ± 0.23 ab	0.97 ± 0.14 a	25.05 ± 1.27 a	336.77 ± 80.15 ab	13.20 ± 2.42 ab
DF4 (High)	Intact	484.27 ± 1.95 B	12.59 ± 0.37 A	0.68 ± 0.04 A	38.54 ± 1.15 AB	722.48 ± 38.85 B	18.79 ± 1.28 B
	Fragmented	252.97 ± 22.48 a	11.06 ± 1.06 a	1.19 ± 0.05 a	22.96 ± 0.96 a	211.68 ± 11.76 a	9.23 ± 0.49 a
Average	Intact	476.45 ± 2.80	12.46 ± 0.25	0.73 ± 0.03	38.41 ± 0.81	663.96 ± 28.63	17.29 ± 0.69

Stand Density	Litter Type	C (g · kg ^{1})	N (g · kg ^{1})	P (g · kg ^{1})	C:N Ratio	C:P Ratio	N:P Ratio
	Fragmented	303.09 ± 15.47	12.29 ± 0.41	1.06 ± 0.05	24.64 ± 0.90	298.81 ± 27.73	12.00 ± 0.85

Note: Different capital letters indicate significant differences among intact litter across densities; different lowercase letters indicate significant differences among fragmented litter across densities ($P < 0.05$). Bold values are higher than non-bold values. N = intact litter; B = fragmented litter.

2.4 Relationships Between Litter Nutrients and Soil Nutrients

In stands of different ages, litter C content was not significantly correlated with soil organic carbon, total N, or total P. Litter N content was positively correlated with soil organic carbon but not with total N or total P. Litter P content was positively correlated with soil organic carbon and total N but not with total P. Soil C:N ratio was negatively correlated with soil organic carbon but not with total N or total P. Soil C:P ratio was negatively correlated with soil organic carbon and total N but not with total P. Soil N:P ratio showed no significant correlations with soil nutrients (Table 5).

Across density levels, litter C content, N content, and C:N ratio were not significantly correlated with soil organic carbon, total N, or total P. Litter P content was negatively correlated with soil organic carbon but not with total N or total P. Soil C:P and N:P ratios were positively correlated with soil organic carbon but not with total N or total P (Table 5).

Table 5 Correlation of corresponding elements between litter and soil in planted *Pinus massoniana* forests

Stand Type	Litter Parameter	Soil Organic Carbon	Soil Total Nitrogen	Soil Total Phosphorus
Forest Age	Litter C content	0.757**	-0.061	-0.325
	Litter N content	0.607*	0.686*	-0.687*
	Litter P content	-0.358	-0.475	-0.302
	Litter C:N ratio	-0.586*	-0.600*	-0.468

Stand Type	Litter Parameter	Soil Organic Carbon	Soil Total Nitrogen	Soil Total Phosphorus
	Litter C:P ratio	-0.387	-0.770**	-0.529
	Litter N:P ratio	-0.125	0.706*	0.630*
Forest Density	Litter C content	-0.149	-0.234	-0.369
	Litter N content	-0.121	-0.358	-0.475
	Litter P content	-0.358	-0.475	-0.302
	Litter C:N ratio	-0.586*	-0.600*	-0.468
	Litter C:P ratio	-0.387	-0.770**	-0.529
	Litter N:P ratio	-0.125	0.706*	0.630*

*Note: ** indicates significance at $P < 0.01$, * indicates significance at $P < 0.05$ (2-tailed).*

3.1 Effects of Stand Age and Density on Litter C, N, P Contents and Ratios

Soil nutrient status and plant physiology are key factors influencing litter C, N, P contents and ratios (Cui et al., 2014). Initial litter nutrient composition relates closely to both soil nutrients and plant nutrient resorption for two primary reasons: (1) Plant nutrient content strongly couples with soil nutrients (Reich et al., 2004; Batterman et al., 2013). When soil N and P availability is low, plant nutrient content decreases, triggering enhanced resorption to conserve nutrients and accelerate internal cycling, thereby reducing litter N and P contents (Aerts et al., 2000). Nutrient resorption is often as important as soil uptake, being more direct and energy-efficient (Franklin et al., 2002). Our results show positive correlations between litter N and P contents and soil organic matter, total N, and total P (Table 5), indicating that higher soil nutrients correspond to higher litter nutrients. Accordingly, soil total N, total P, and ammonium N were higher in over-mature and half-mature stands but lower in young and mature stands (Table 2), while initial litter N and P contents were highest in over-mature stands (AF4), followed by half-mature (AF2), young (AF1), and lowest in mature stands (AF3) (Table 3).

(2) Different growth stages have varying nutrient demands, affecting organ and litter nutrient composition. During rapid growth, higher P content supports increased rRNA synthesis for cell proliferation, resulting in lower C:P and N:P ratios (Elser et al., 2000). We observed increasing litter C content with stand age (Table 3), indicating synchronized C accumulation and growth. Furthermore, C:P and N:P ratios increased from young to mature stands, suggesting that young and half-mature stands in high-growth phases have greater N and P demands and higher resorption efficiency. However, from mature to over-mature stands, C:P and N:P ratios decreased, possibly because: (i) over-mature stands have high C content but slower growth rates and reduced resorption, lowering these ratios; and (ii) absence of management and fertilization requires coordinated above- and below-ground cycling, where lower N:P ratios facilitate rapid decomposition and nutrient return.

Stand density also significantly affects litter nutrient dynamics (Kang et al., 2009). Litter C content increased with density while N content remained stable and P content decreased (Table 4). Soil N and P contents and availability did not differ significantly among densities (Table 2), suggesting minimal soil nutrient influence and pointing to density-driven physiological changes as the primary cause. The combined trends in C, N, and P contents resulted in lower C:N, C:P, and N:P ratios in DF1 (low density, 2 m × 2 m) compared to other densities (Table 4). Low-density stands showed less pronounced P limitation, weaker P resorption, and consequently higher litter P content. As density increased in DF2 (medium-low, 1.5 m × 2 m), DF3 (medium-high, 1.5 m × 1.5 m), and DF4 (high, 1 m × 1.67 m), C:P and N:P ratios increased markedly (Table 4), indicating greater P demand, stronger P resorption, and lower litter P content.

Mean initial litter C, N, and P contents across ages were 461.06, 9.96, and 0.66 g · kg ^{1}, respectively, with C:N, C:P, and N:P ratios of 46.45, 704.91, and 15.20 (Table 3). Across densities, mean values were 476.45, 12.46, and 0.73 g · kg ^{1}, with ratios of 38.41, 663.96, and 17.29 (Table 4). These values are similar to those reported by Ge et al. (2012). Soil total N and total P ranged from 1.40–2.14 g · kg ^{1} and 0.22–0.50 g · kg ^{1}, respectively (Table 2), indicating nutrient-poor conditions. Thus, litter C, N, P dynamics and stoichiometric ratios in *P. massoniana* plantations are influenced by stand age, density, and inherently low soil fertility.

3.2 Litter Nutrient Dynamics

Litter represents a primary soil nutrient source, with decomposition controlling nutrient return rates, which are influenced by initial litter quality and environmental factors. Studies indicate that high C:N and C:P ratios promote decomposition, while high N:P ratios slow it, with C:N and C:P decreasing and N:P increasing during decomposition (Li et al., 2008). High N:P ratios may reflect low P or high N and lignin content (Gallardo et al., 1999). However, in our study, litter stoichiometric ratios were poor indicators of decomposition rate across ages for two reasons: (1) Initial N:P ratios did not differ significantly among ages. Although mature stands had high C:N and C:P due to low initial N and P, all stands showed decreasing C:N, C:P, and N:P during decomposition (Table 4). (2) Litter exhibited N and P enrichment during decomposition (Table 4), consistent with other studies (Wang et al., 2013; Li et al., 2017; Lu et al., 2017). However, decreasing C content from intact to fragmented litter indicates substantial C input to soil, providing both organic matter and microbial energy. These combined factors create uncertainty in decomposition rates. Based on C loss magnitude, half-mature stands showed the greatest difference between intact and fragmented litter C content, along with lower C:N and C:P ratios, suggesting potentially higher C decomposition rates, though further research is needed.

Density effects on litter nutrient dynamics mirrored age effects: fragmented litter had lower C but enriched N and P compared to intact litter (Table 4). As density increased, intact litter C content rose while N and P patterns were complex, resulting in lowest C:N, C:P, and N:P ratios in DF1 (low density) and highest in DF2 (medium-low density), with DF3 and DF4 intermediate. Fragmented litter C:N ratios did not differ among densities, while C:P and N:P ratios were lowest in DF4 and highest in DF2. These patterns suggest that medium-high and high-density stands have higher decomposition rates, facilitating substantial C input and soil organic matter enhancement. This may relate to microenvironmental conditions, as higher densities create favorable moisture and temperature regimes that enhance microbial activity and enzyme function. However, the effect of high planting density on decomposition rates requires further investigation.

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4 Conclusions

1. **Stand Age Effects:** Over-mature and half-mature stands had higher soil and litter nutrient contents than young and mature stands, indicating positive correlations between soil and litter nutrients. Increasing C:P and N:P ratios from young to mature stands suggest greater N and P demand and higher resorption efficiency in young and half-mature stands.
2. **Stand Density Effects:** Despite no significant differences in soil N and P availability, increasing stand density elevated litter C content, maintained stable N content, and reduced P content, resulting in higher initial C:P and N:P ratios in medium-high and high-density stands, indicating stronger P resorption.
3. **Decomposition Dynamics:** Fragmented litter had lower C content and C:N, C:P, and N:P ratios but higher N and P contents than intact litter, demonstrating nutrient enrichment. Half-mature and high-density stands

showed the greatest C loss and lower C:N and C:P ratios, suggesting potentially higher litter C decomposition rates.

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