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Variation Patterns of Fine Root Biomass, Production, and Turnover Rates in Four Subtropical Forests of China

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Abstract: Fine roots (diameter $\leq$ 2 mm) play a critical role in regulating soil organic carbon storage and nutrient cycling in forest ecosystems. However, the variability in fine root biomass, production, and turnover rates across different forest types remains poorly understood. This study investigates fine root dynamics, including biomass, distribution, and turnover, across four major monoculture plantation forests in subtropical China: Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook), Masson pine (*Pinus massoniana* Lamb.), Chinese sweet gum (*Liquidambar formosana* Hance), and camphor tree (*Cinnamomum camphora* (L.) J. Presl). Using a sequential coring method, soil samples were collected monthly to monitor live and dead fine root biomass across different soil depths (0–15 cm, 15–30 cm, 30–45 cm, and 45–60 cm). Fine root production and turnover rates were estimated using three methods: Max–Min, Integral and Decision Matrix. The results showed that fine root biomass was highest in the camphor tree forest (1.96 t ha^{-1}), followed by Masson pine (1.12 t ha^{-1}), Chinese fir (0.89 t ha^{-1}), and Chinese sweet gum (0.83 t ha^{-1}). Approximately 90% of the total fine root biomass was composed of live roots across all forest types, highlighting their significant role in nutrient uptake. Both live and dead fine roots were predominantly concentrated in the upper 0–30 cm soil layer, with a notable decline in biomass in deeper layers. Fine root biomass production was highest in the camphor tree forest (2.66–2.90 t ha^{-1} a^{-1}), followed by Masson pine (1.16–1.83 t ha^{-1} a^{-1}), Chinese fir (0.87–0.97 t ha^{-1} a^{-1}), and Chinese sweet gum (0.87–0.93 t ha^{-1} a^{-1}). Turnover rates were highest in the camphor tree forest (1.25–1.36 a^{-1}), followed by Masson pine (0.96–1.51 a^{-1}), and both Chinese fir and Chinese sweet gum (0.94–1.05 a^{-1} and 0.97–1.04 a^{-1}, respectively). This study identifies significant differences in fine root dynamics among subtropical forest types, providing baseline data critical for optimizing forest management, particularly in urban and peri-urban areas. These insights can enhance reforestation efforts, ecosystem resilience, and sustainable forest productivity.

Keywords: fine root biomass; fine root production; turnover; distribution; dynamics; subtropical forest

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1. Introduction

Forests are one of the most important components of the Earth's ecosystem and provide valuable ecological services, including supporting food and water, sequestering carbon storage, maintaining habitats and diversity, and preventing soil erosion [1–3]. Compared to the relatively straightforward observation of forest services in the aboveground portion, assessing the ecosystem functioning of the belowground part is more challenging [4]. For example, estimating soil carbon pools and fluxes remains uncertain due to the limited understanding of belowground carbon dynamics [5]. Therefore, a deeper understanding of belowground carbon dynamics is essential to accurately assess ecosystem functioning and improve our ability to estimate soil carbon pools and fluxes [6].

Forest roots are an important component of forest ecosystems, providing anchorage for the aboveground parts of trees, absorbing water and nutrients to support tree growth, returning carbon and nutrients to the soil to maintain fertility, and releasing chemical substances that influence microbial communities and contribute to the formation of rhizobium associations [7]. The root structure and function of forests play a key role in their growth, nutrient absorption, and adaptation to the environment. Fine roots, typically defined as less than 2 mm in diameter, are significant contributors to forest productivity and ecosystem function, playing essential roles in nutrient and water absorption, carbon sequestration, and soil structure formation [8,9]. Fine root turnover (FBT) is a key process in belowground carbon cycling, contributing significantly to soil carbon pools and influencing global nutrient dynamics [10]. Although fine roots account for less than 2% of the total forest biomass, they contribute up to 33% to the global terrestrial net primary productivity [9,11]. The quantity, biomass and structure of fine roots vary significantly among different forests at a regional scale.

Fine roots are integral to forest ecosystems, playing a pivotal role in nutrient uptake, carbon cycling, and overall forest productivity [12,13]. They are particularly sensitive to environmental changes, making them valuable indicators for assessing ecosystem health and responses to climate change [14]. Fine root biomass, production, and turnover rates vary significantly across forest types, driven by stand characteristics, soil properties, and species composition [15]. In evergreen broad-leaved tropical and subtropical forests, fine roots can constitute over 50% of the total root biomass, supporting dense canopies and year-round nutrient absorption [12]. In subtropical evergreen broadleaf forests, this proportion can reach up to 60%. Conversely, coniferous forests exhibit fewer but longer-lived fine roots, constituting about 30%–40% of total root biomass, a strategy that aids resilience in harsh conditions [15]. Deciduous broadleaf forests demonstrate dynamic fine root systems, comprising 40%–50% of root biomass, with rapid turnover during growth seasons to meet resource demands [13]. Fine root turnover (FBT) plays a crucial role in the carbon cycling and nutrient dynamics of forest ecosystems. This process, which involves the growth, death, and decomposition of fine roots, significantly contributes to soil carbon pools and soil fertility. Fine root turnover (FBT) rates vary across forest types, influenced by factors such as stand characteristics, soil properties, and climate conditions [2,3]. Cai et al. [12] emphasized that FBT is a key driver of belowground carbon cycling, impacting soil carbon storage and ecosystem function in both plantations and natural forests. Furthermore, fine root decomposition, a critical component of turnover, is essential for nutrient cycling and carbon sequestration. It contributes to the formation of soil organic matter, thereby enhancing soil fertility and supporting forest productivity [3]. Fine root turnover (FBT) rates are highly responsive to environmental changes, with variations influencing carbon fluxes and overall ecosystem health [14,16]. In subtropical forests, FBT is also influenced by root density and species-specific traits, which highlights the complex interactions between root dynamics and forest productivity [15].

Recent research has underscored the ecological significance of fine root turnover, particularly in forests experiencing seasonal droughts or nitrogen deposition [17]. However, variability in methodologies for studying fine root production, mortality, and decomposition calls for standardized approaches to improve comparability across studies [18]. Fine root decomposition has also been identified as a crucial link between soil organic matter dynamics and forest management practices, such as thinning intensity and recovery age. Despite these advancements, there remain significant knowledge gaps regarding fine root dynamics in subtropical forests. While temperate and boreal forests have been extensively studied, subtropical systems are comparatively understudied [19,20]. These forests are characterized by diverse plant functional groups and unique soil-plant interactions that significantly influence fine root dynamics, yet limited data exist on fine root biomass, production, and turnover rates across different subtropical forest types, particularly concerning their variation with environmental conditions and forest structure [12,13].

This study aims to address the knowledge gap regarding the variability in fine root dynamics across four plantation forests in subtropical China. Specifically, it examines fine root biomass, production, the live fine roots/dead fine roots ratio, and turnover rate dynamics to better understand their role in forest ecosystem functioning. The objectives of this research were: (1) to quantify fine root biomass and its distribution across the four forest types, (2) to examine seasonal variations in fine root biomass, and (3) to investigate the relationships between fine root dynamics and environmental factors, such as soil properties and climatic variables. By providing new insights into the variability and drivers of fine root processes, this study advances our understanding of their ecological significance and contributes valuable data to the growing body of literature on belowground forest ecology. It is hypothesized that (1) fine root biomass and production will vary significantly among the forest types due to differences in species composition and management practices, and (2) seasonal variations in fine root biomass will be driven by environmental factors, such as soil moisture and temperature, which influence root growth and turnover.

2. Materials and Methods

2.1. Study Site

The study was conducted in Hunan Botanical Garden (known as Tianjiling National Forest Park), situated in Changsha City, Hunan Province, China (113°01′–113°02′ E, 28°06′–28°07′ N). Covering approximately 4356 hectares, the park features elevations ranging from 46 to 114 m above sea level and slopes varying between 5° and 25°. The climate of the study area is characterized as a typical subtropical humid monsoon climate. Annual precipitation averages 1422 mm, with an average annual temperature of 17.2 °C. Monthly temperatures range from 4.7 °C in January to 29.4 °C in July. The frost-free period spans from 270 to 300 days annually, with an average sunshine duration of 1677.1 h. The predominant soil type is typical red soil derived mainly from Quaternary Pleistocene alluvial reticulated laterite and gravel, equivalenting to Alliti-Udic Ferrosols according to Chinese Soil Taxonomic Classification and Acrisols in the World Reference Base for Soil Resources (CRG-CST 2001). The vegetation primarily comprises evergreen broad-leaved forests, with main dominant tree species such as *Schima superba* Gardn et Champ., *Castanopsis sclerophylla, Cinnamomum camphora* (L.) Presl., *Liquidambar formosana* Hance., *Quercus fabrei* Hance., *Symplocos caudate* Wall., and *Cyclobalanopsis glauca* (Thunberg) Oersted. Herbaceous plants in the area include *Nephrolepis auriculata* (L.) Trimen, *Lophatherum gracile*, *Phytolacca acinosa* Roxb., *Miscanthus floridulus* Warb., and *Oxalis corniculata* L.

2.2. Experimental Design

The experiment was conducted using a split-plot design, where the main factor was forest type, and the sub-factor was soil depth. In this study, four main monoculture plantation forests were selected from the Garden: Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.) forests (CFF), Masson pine (*Pinus massoniana* Lamb.) forests (MPF), Chinese sweet gum (*Liquidambar formosana* Hance) forests (CGF), and camphor tree (*Cinnamomum camphora* (L.) J. Presl) forests (CTF). These species were chosen because of their distinct ecological and economic roles in subtropical forest ecosystems, as well as their varying growth rates, ecological functions, and adaptability to the local environmental conditions. Chinese fir and Masson pine are coniferous species commonly used in timber production, while Chinese sweet gum is a deciduous species, and the camphor tree is an evergreen species, valued for its aromatic wood and medicinal properties. These species are prevalent in subtropical plantation forests in China and were selected to provide a comprehensive view of fine root dynamics across different tree types. All measurements were completed from January to December 2020. The characteristics of the four selected forests at the study site are detailed in Table 1. A total of 16 plots (4 types of plantation forest × 4 replications) were established in the study area, each consisting of a 30 m × 30 m area, with a minimum distance of 100 m between plots to minimize spatial autocorrelation.

Table 1. Characteristics of the four plantation forests at the study site.

Plantation Forest	Age (year)	Stand Density (tree ha^{-1})	DBH (cm)	Tree Height (m)	High of Branch (m)	Crown Density (%)
C. lanceolata	18	1102	16.26	12.5	5.3	80
L. formosana	21	1146	12.46	12.8	5.3	90
P. massoniana	33	690	18.65	13.6	7.8	70
C. camphora	35	775	17.47	12.6	4.0	70

Within each plot, measurements were conducted for each tree, including diameter at breast height (DBH), tree height, and height under branches. Soil samples were collected from each plot to analyze physicochemical properties such as pH, organic matter content, and nitrogen levels. Additionally, fine roots were assessed monthly using eight soil cores per plot, each with a diameter of 12 cm, to measure fine root biomass and turnover rates. Detailed soil physicochemical properties and litter production data for the selected forest types at the study site are summarized in Table 2 and Figure 1.

Table 2. Soil physicochemical properties and litter production in the four plantation forests at the study site.

Plantation Forest	Total C (mg $C \cdot g^{-1}$)	Total N (mg $N \cdot g^{-1}$)	Soil C:N Ratio	pH Value	Soil Bulk Density ($g \cdot cm^{-3}$)	Litter ($g \cdot m^{-2}a^{-1}$)	Litter C:N Ratio
C. lanceolata	7.81 (0.24)	0.89 (0.5)	11.83	3.55 (0.15)	1.52 (0.02)	610.8 (66.8)	54.73
L. formosana	13.02 (2.15)	1.14 (0.31)	12.82	3.67 (0.09)	1.59 (0.8)	1023.9 (114.3)	51.93
P. massoniana	8.38 (0. 32)	0.67 (0.06)	12.76	3.7 (0.15)	1.57 (0.33)	1231.8 (171.3)	61.85
C. camphora	9.45 (1.01)	0.81 (0.18)	12.57	3.85 (0.18)	1.5 0(0.11)	1281.3 (131.1)	67.44

The values in the brackets are standard error.

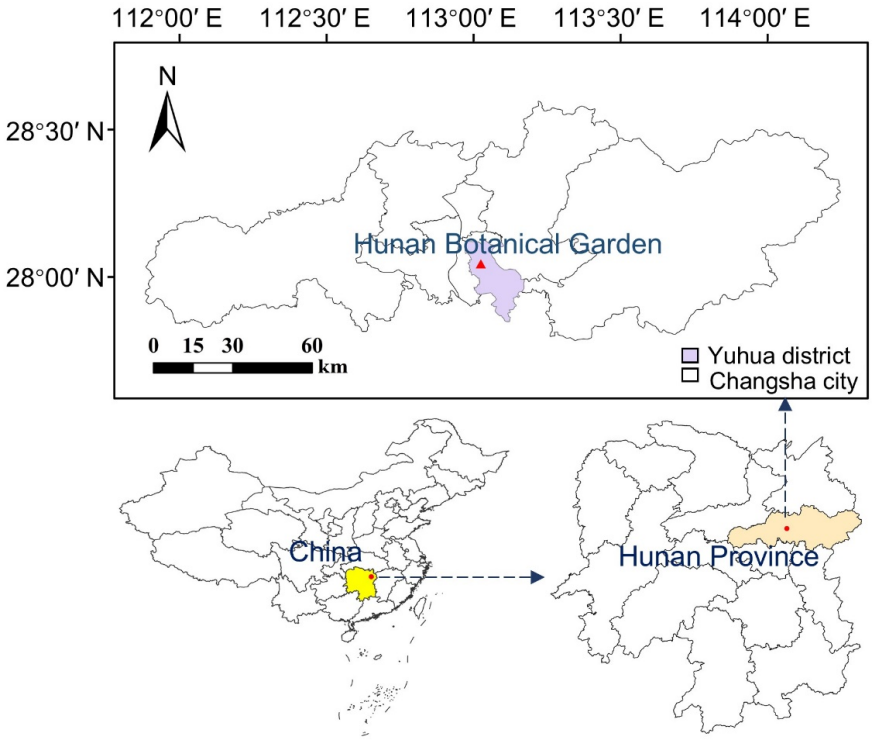


Figure 1. Location of the study site in the Hunan Botanical Garden in Changsha City, Hunan Province, China. The red triangle is the place of Hunan Botanical Garden.

2.3. Soil Sampling and Fine Root Measurements

Soil samples were collected using a soil auger with a diameter of 12 cm. Eight soil samples were taken in an S-shaped pattern within each plot and then pooled into three samples for each soil depth. Soil cores were extracted from four soil layers (0–15 cm, 15–30 cm, 30–45 cm, and 45–60 cm) at each sampling point. In total, 192 soil samples (4 forest types × 4 replications × 3 sampling points × 4 soil depths) were obtained for the entire experiment. The soil samples were placed in plastic bags, labeled and transported to the Central South University of Forestry and Technology Lab for further analysis. Soil samples were taken once monthly around the end of each month from January to December 2020. In the lab, soil samples were soaked in water to soften them and then rinsed through a 40-mesh (0.42 mm) sieve under running water. Roots were carefully selected and separated into tree roots and understory vegetation roots. Tree roots were further categorized into dead and live roots based on their appearance, color, and the ease of separating the elastic root bark from the central column of the root system. Live roots are typically elastic, firm, and brightly colored, whereas dead roots are darker and more brittle, making them easier to break. Fine roots (diameter $\leq$ 2 mm) were collected, weighed, and dried in an 80 °C oven until a constant weight was achieved.

2.4. Soil Physicochemical Property Measurements

Soil samples were passed through a 2-mm sieve to remove roots and stones before being air-dried. The soil pH value was measured using a pH meter (Lemag PHS-3C, Shanghai INESA Scientific Instrument Co., Ltd., Shanghai, China) at a water-to-soil ratio of 1:2.5 (w/v). Soil organic carbon (SOC) content was determined using the potassium dichromate external heating method for sulfuric acid oxidation. Total nitrogen (TN) content was assessed using the semi-micro Kjeldahl method. Additionally, soil bulk density was estimated using the cutting ring method.

2.5. Calculation of Fine Root Biomass Production and Fine Root Turnover Rate

In this study, fine root biomass production (FBP) was calculated using three methods. The first method employed is the Max–Min approach, defined as follows:

(1) The Max–Min method

$$FNPP = FB_{max} - FB_{min} \quad (1)$$

where, FB_{max} is the maximum monthly fine root biomass observed during the study period, and FB_{min} is the minimum monthly fine root biomass recorded. This method captures the difference between the peak and lowest fine root biomass, providing an estimate of the production associated with fine roots over the specified timeframe.

The second approach employed is the Integral method, defined as follows:

(2) The Integral method

$$FBP = \sum \Delta FBi \quad (2)$$

where, and ΔFBi denotes the increment value of fine root biomass measured at time i during the study period, with i = 1, 2, . . ., n. This method involves summing the incremental changes in fine root biomass over the specified timeframe, providing a comprehensive estimate of fine root production by accounting for all fluctuations in biomass throughout the study period.

The third approach employed is the Decision Matrix method, defined as follows:

(3) The Decision Matrix method

The Decision Matrix method evaluates fine net primary productivity by assessing the contribution of fine root biomass across different sampling periods and environmental conditions. FBP is calculated using the following equation (Table 3):

$$FBP = \sum Wi \sum (FBi \times Wi) \quad (3)$$

Table 3. Decision Matrix method for estimating fine root biomass production (FBP).

Change in Dead Root Biomass	Increase	Decrease
Increase in Live Root Biomass	FBP = ΔFBlive + ΔFBdead	FBP = ΔFBlive + ΔFBdead
	FBP = 0	FBP = 0
Decrease in Live Root Biomass	FBP = ΔFBlive	FBP = 0

ΔFBlive: change in live fine root biomass; ΔFBdead: change in dead fine root biomass.

(4) Estimation of fine root biomass turnover (FBT) rate (a^{-1})

The FBT rate is calculated to assess the dynamics of fine root biomass over time. It reflects the rate at which fine roots are produced and decompose within the ecosystem. The FBT can be estimated using the following formula:

$$FBT\ (a^{-1}) = FBP\ (kg\ hm^{-2}a^{-1}) / FB_{mean}\ (kg/hm^2) \quad (4)$$

where, FB_{mean} (kg/hm^2) represents the annual average fine root biomass observed during the year.

2.6. Data Analysis

Statistical analysis was performed using SPSS (version 13.0) software. To meet the assumption of normality, the original data was log-transformed. A three-way analysis of

variance (ANOVA) and the least significant difference (LSD) method were employed to test the differences in fine root biomass among the four types of forests, four soil layers, and four months, as well as their interactions ($p < 0.05$). Paired *t*-tests were conducted to assess differences between different stands ($p < 0.05$). Graphs were created using SigmaPlot 9.0 software.

3. Results

There were significant differences in the biomass of seasonal live and dead fine roots among CFF, MPF, CGF, and CTF (Figure 2). The peak value (1.31 t/hm^2) for CFF occurred in September, with the lowest value (0.56 t/hm^2) observed in January. Although MPF displayed three peaks, the first two were less pronounced, with the largest peak (1.89 t/hm^2) in October and the lowest value (0.70 t/hm^2) in January. A peak value (1.30 t/hm^2) in October and a lowest value (0.61 t/hm^2) in March occurred in CGF. In CTF, the peak value (3.69 t/hm^2) was observed in October, while the lowest value (1.16 t/hm^2) occurred in January (Figure 2a, $p < 0.05$). Overall, the live fine root biomass in the four forest types exhibited a fluctuating upward trend from January to May, a significant increase from May to October, and a subsequent decrease from October to December.

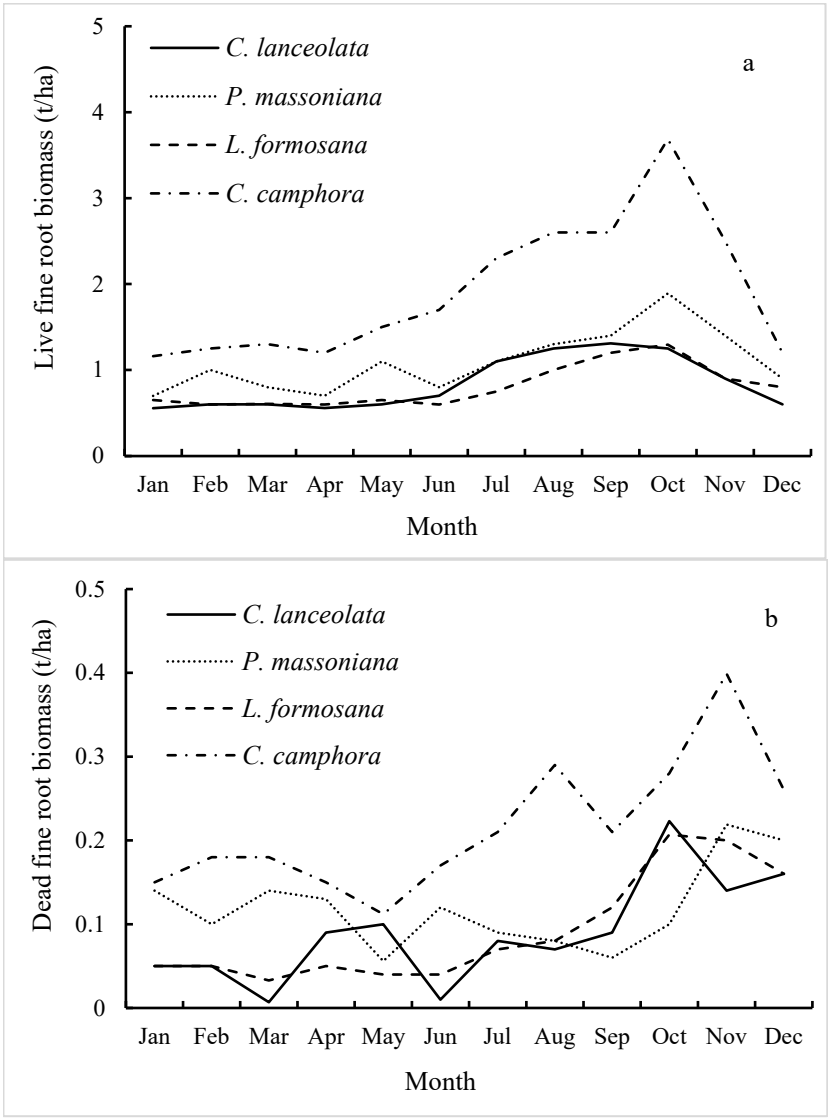
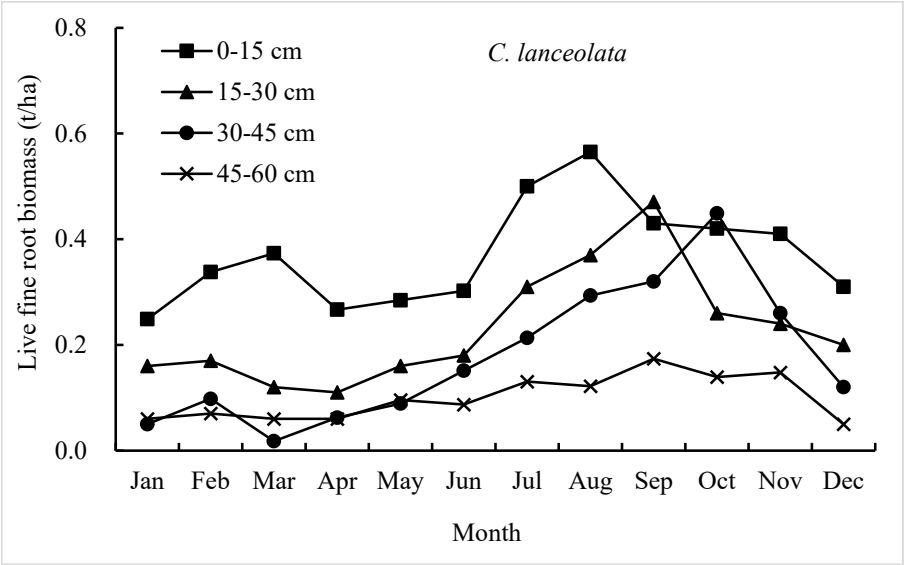


Figure 2. Monthly changes of fine root biomass in the four plantation forests at the study site: live fine root biomass (**a**) and dead fine root biomass (**b**).

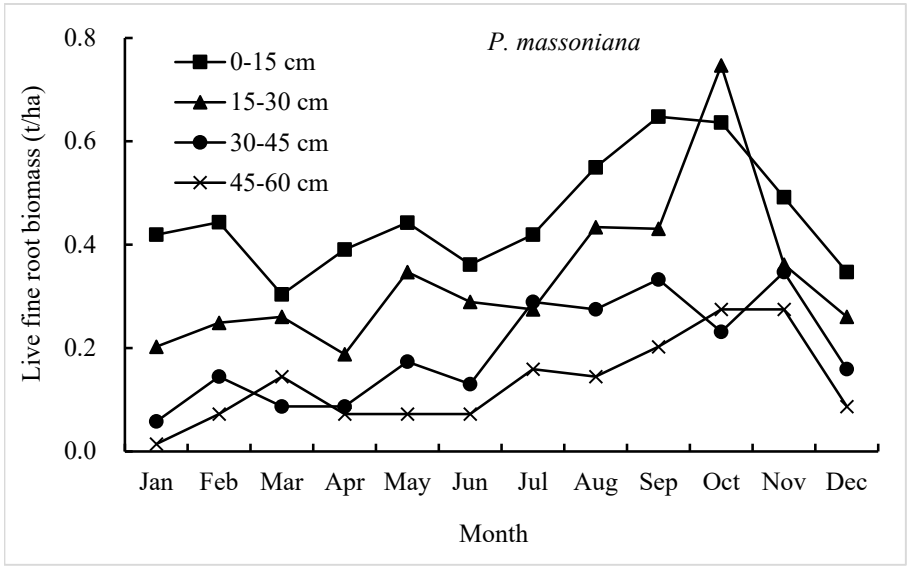
The seasonal changes in dead fine root biomass among the four forests exhibited irregular fluctuations, with varying peak and minimum values across different months. The peak value for the CFF forest was 0.22 t/hm^2 in October, while the lowest value was 0.01 t/hm^2 in March. In MPF, the peak value of 0.22 t/hm^2 occurred in November, with the lowest value of 0.06 t/hm^2 in May. A peak value of 0.21 t/hm^2 in October and a minimum value of 0.03 t/hm^2 in March were found in CGF. For CTF, the peak value was 0.40 t/hm^2 in November, while the lowest value was 0.11 t/hm^2 in May (Figure 2b, $p < 0.05$).

There were significant differences in live fine root biomass among the four types of forests across various soil layers ($p < 0.05$) (Figure 3). In CFF, live fine root biomass varied noticeably across the 0–15, 15–30, and 30–45 cm soil layers, with peaks observed in August (0.57 t/hm^2), September (0.47 t/hm^2), and October (0.45 t/hm^2), respectively (Figure 3a). For MPF, the 0–15 cm soil layer showed peaks in February (0.44 t/hm^2), May (0.44 t/hm^2), and September (0.65 t/hm^2). In the 15–30 cm layer, peaks occurred in March (0.26 t/hm^2), May (0.35 t/hm^2), and October (0.75 t/hm^2), with October values surpassing those in the 0–15 cm layer (Figure 3b). Seasonal changes were minor in the 0–15 cm and 45–60 cm layers in CGF, but more pronounced in the 15–30 cm and 30–45 cm layers, peaking in October (0.41 t/hm^2) and September (0.28 t/hm^2), respectively (Figure 3c). In the CTF, live fine root biomass exhibited significant seasonal fluctuations across all layers, with more than three peaks annually. The highest peak in the 0–15 cm layer occurred in June (1.50 t/hm^2), while other layers showed lower biomass during this period. Subsequent months saw varied biomass trends across layers, with notable increases in October, particularly in the 0–15 cm (1.61 t/hm^2), 15–30 cm (1.08 t/hm^2), and 30–45 cm (0.64 t/hm^2) layers, and a peak of 0.54 t/hm^2 in the 45–60 cm layer in August (Figure 3d).



(**a**)

Figure 3. *Cont.*



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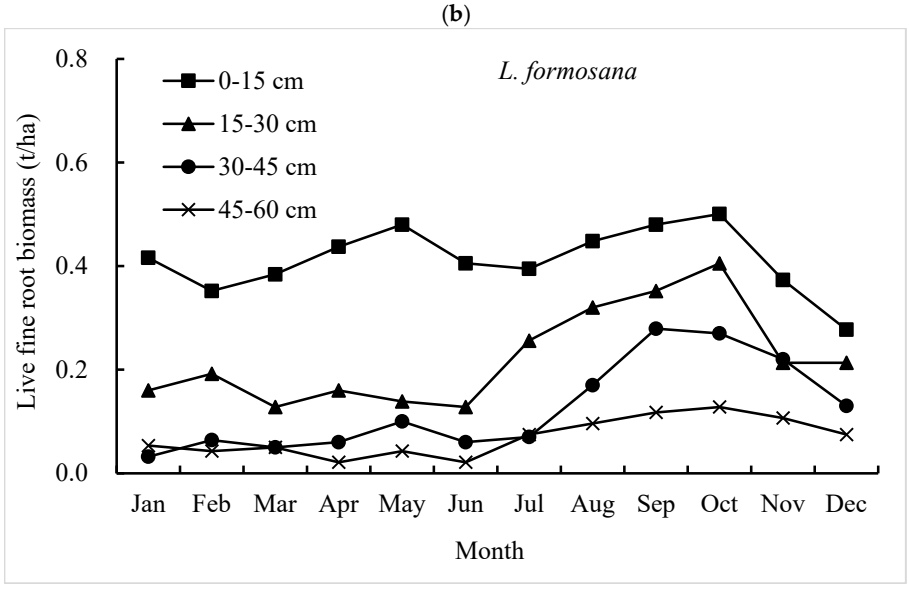

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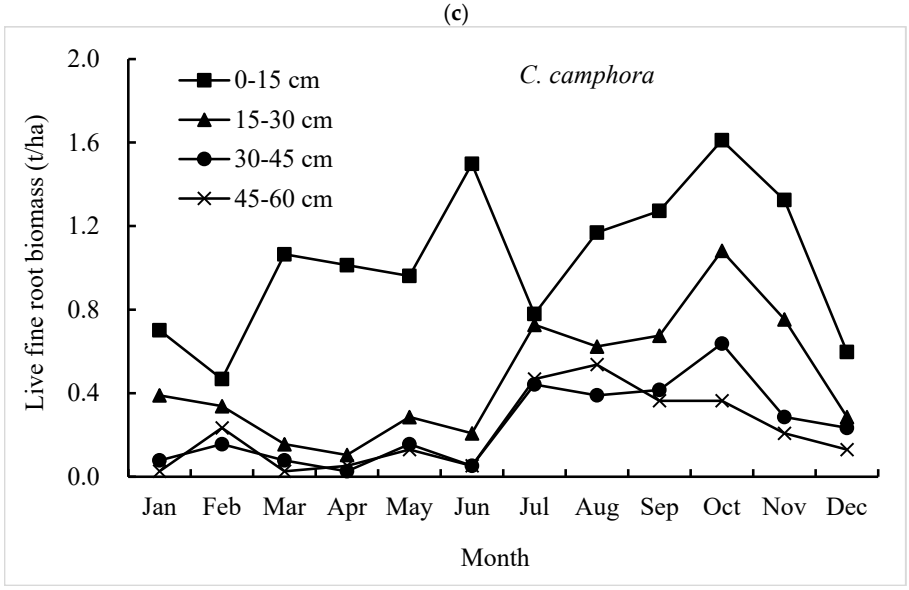
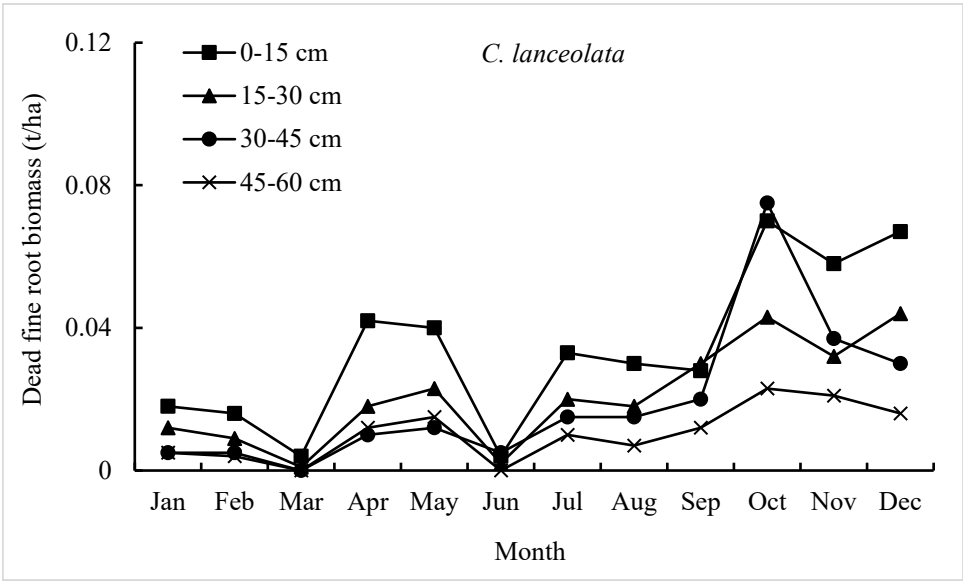


(**d**)

Figure 3. Monthly changes of live fine root biomass at different soil layers in the four plantation forests at the study site: *C. lanceolate* (**a**), *P. massoniana* (**b**), *L. formosana* (**c**) and *C. camphora* (**d**).

There were significant differences in dead fine root biomass among the four forest types across different soil layers ($p < 0.05$) (Figure 4). The distribution of dead fine root biomass in CFF fluctuated significantly across the four soil layers, reaching its lowest values in March and June (Figure 4a). Interestingly, the biomass of dead fine roots in the 30–45 cm layer was higher than in the 0–15 cm layer, while changes in dead fine root biomass in the 45–60 cm layer were relatively insignificant. In MPF, dead fine root biomass exhibited noticeable seasonal changes across the four soil layers (Figure 4b), peaking in January, November, and December, with low levels throughout the year from May to October. The seasonal variation of dead fine root biomass in each soil layer remained relatively stable from January to August, with minimal changes, and then increased rapidly from August to November in CGF (Figure 4c). In CTF, the maximum peaks of dead fine root biomass in the 0–15 cm and 15–30 cm layers occurred in November, while the maximum peaks in the 30–45 cm and 45–60 cm layers occurred in August (Figure 4d).



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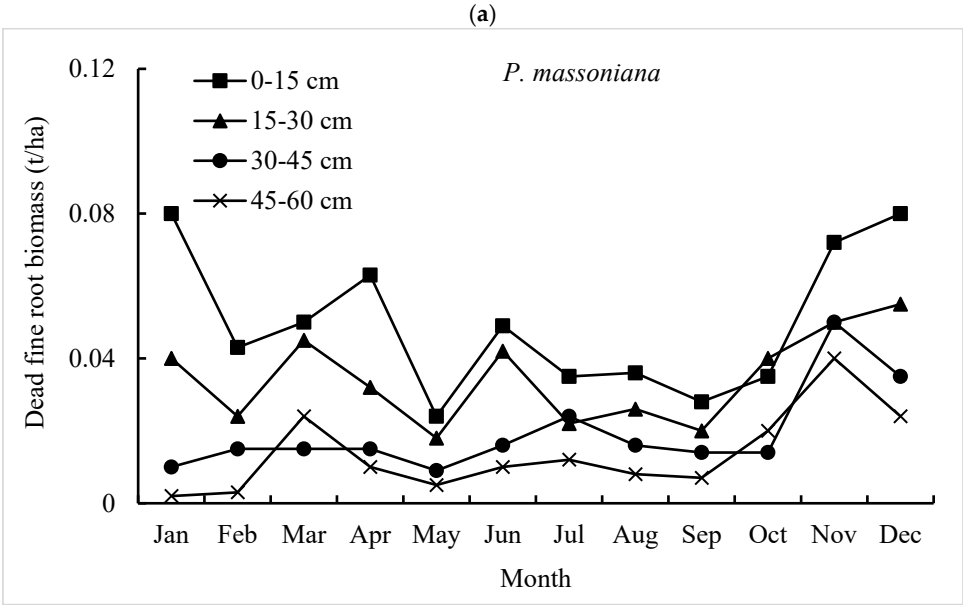

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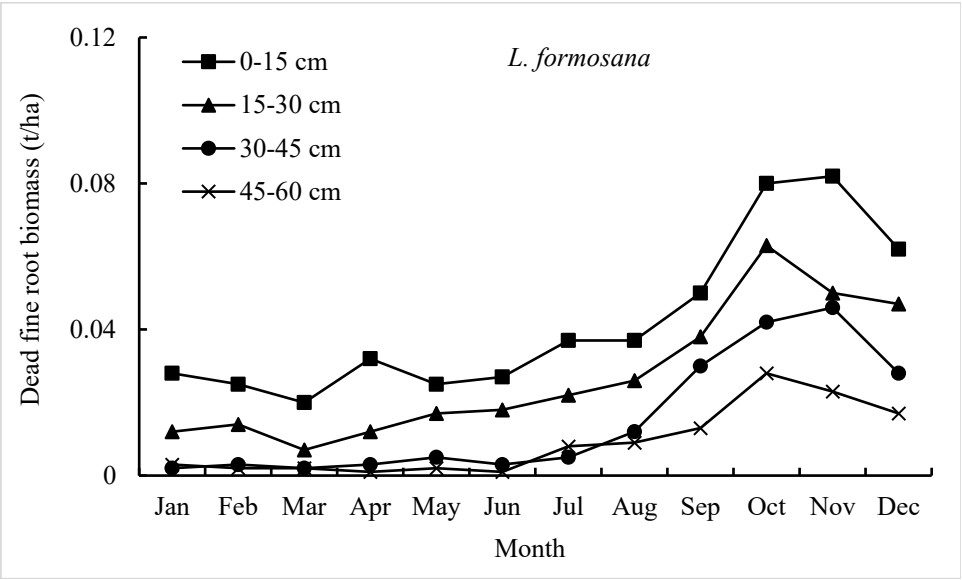
Figure 4. *Cont.*



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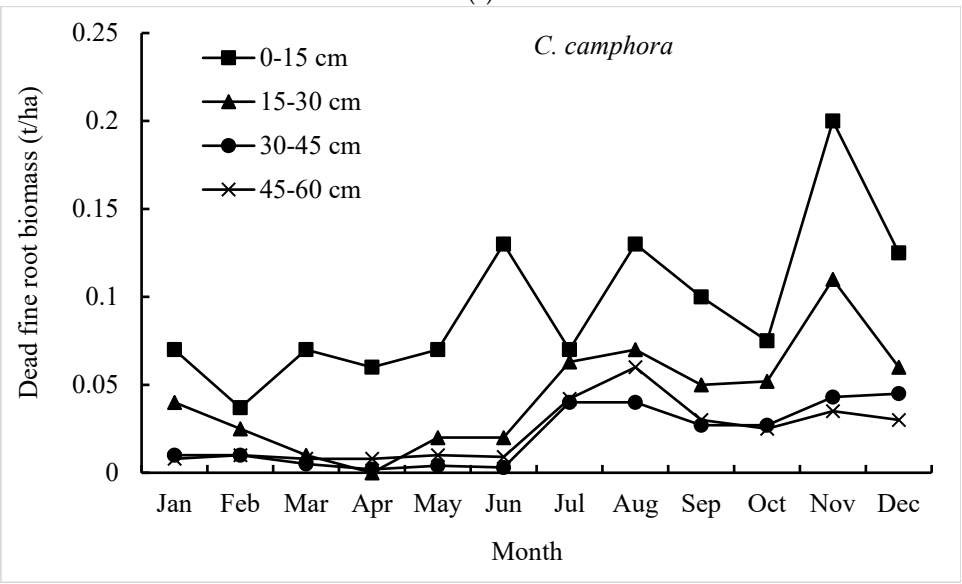
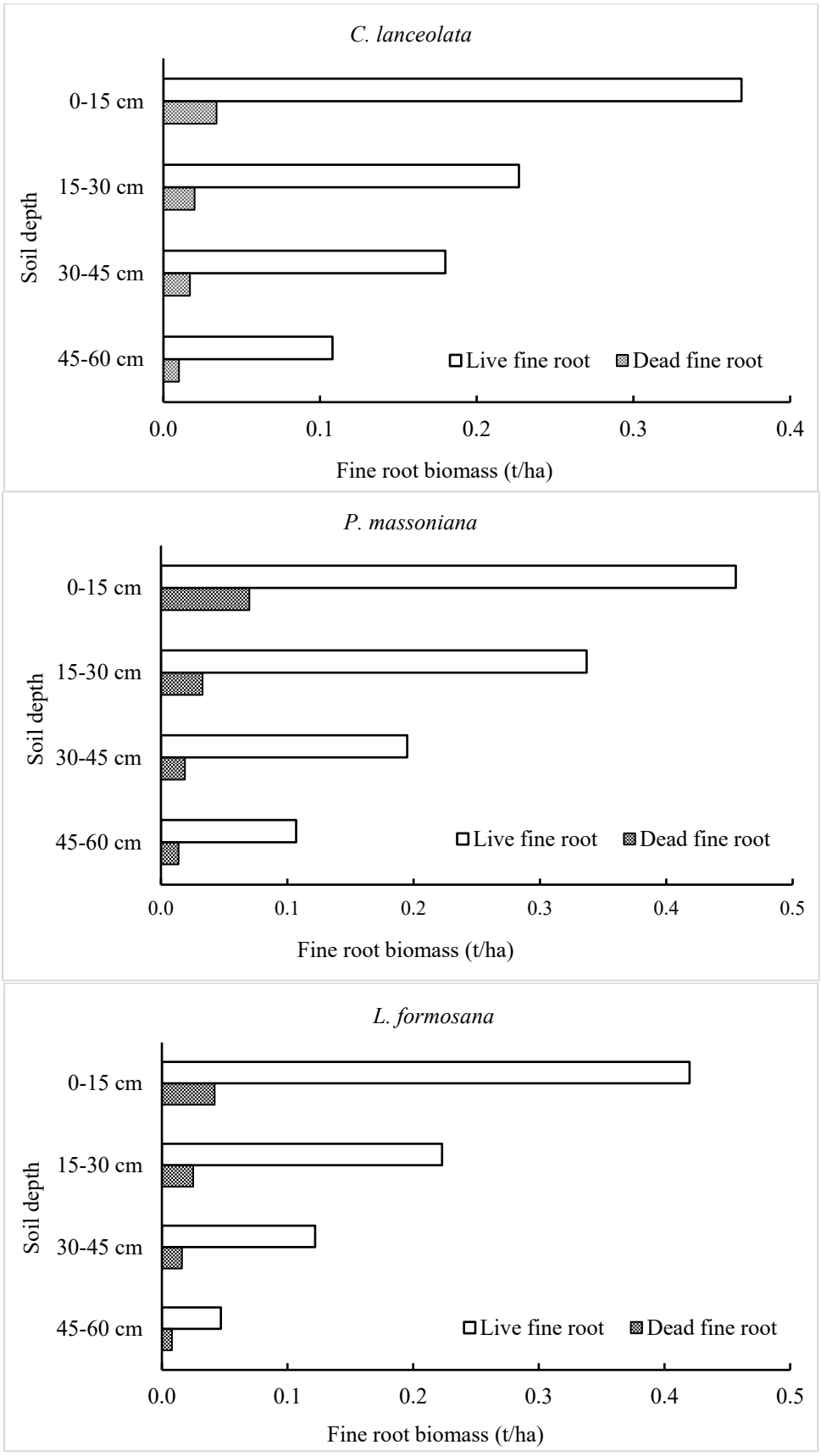


(**d**)

Figure 4. Monthly changes of dead fine root biomass at different soil layers in the four plantation forests at the study site: *C. lanceolate* (**a**), *P. massoniana* (**b**), *L. formosana* (**c**) and *C. camphora* (**d**).

There was a clear similarity in the distribution pattern of live and dead fine root biomass across different soil layers for the four forest types (Figure 5). The fine root biomass was primarily concentrated in the upper soil layers (0–30 cm), with biomass decreasing in deeper soil layers. The live and dead fine root biomass accounted for 42.2%, 25.6%, 20.1%, and 12.1% and 41.4%, 24.6%, 21.9%, and 12.1% at depths of 0–15 cm, 15–30 cm, 30–45 cm, and 45–60 cm in CFF, MPF, CGF, and CTF, respectively.



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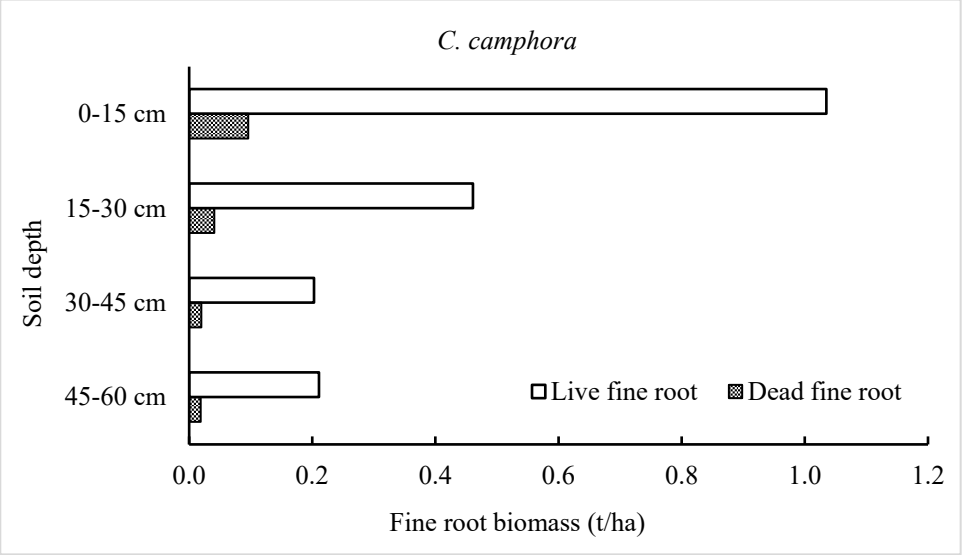

Figure 5. Vertical distribution of live and dead fine root biomass in the four plantation forests at the study site.

The estimations of FBP and FBT rate for the four plantation forests are presented in Table 4, using three different methods: Max–Min, Integral, and Decision Matrix. In terms of FBP, CFF exhibited the lowest FBP across all methods, with values ranging from 0.866 to 0.966 t/ha. On the other hand, MPF demonstrated the highest FBP, with values ranging from 1.162 to 1.833 t/ha. The other two forest types, CGF and CTF, showed intermediate FBP values. For CGF, FBP ranged from 0.865 to 0.930 t/ha, while CTF had the highest FBP estimates, ranging from 2.655 to 2.903 t/ha (Table 4). Regarding FBT rate, CFF exhibited turnover rates ranging from 0.94 to 1.045 a^{-1}, with the lowest values among the studied forests. MPF displayed FBT values ranging from 0.96 to 1.514 a^{-1}, indicating a moderate turnover rate. CGF had turnover rates between 0.97 and 1.038 a^{-1}. In contrast, CTF showed the highest turnover rates, with values ranging from 1.25 to 1.361 a^{-1} across the three methods (Table 4).

Table 4. Estimations of fine root biomass production (FBP) and fine root biomass turnover rate (FBT) in the four plantation forests at the study site.

Forest Type	FBP (t/ha)			FBT (a^{-1})		
	Max–Min Method	Integral Method	Decision Matrix Method	Max–Min Method	Integral Method	Decision Matrix Method
C. lanceolata	0.866	0.909	0.966	0.94	0.983	1.045
P. massoniana	1.162	1.659	1.833	0.96	1.371	1.514
L. formosana	0.865	0.915	0.930	0.97	1.021	1.038
C. camphora	2.655	2.845	2.903	1.25	1.334	1.361

4. Discussion

Our study highlights significant variations in seasonal live and dead fine root biomass among CFF, MPF, CGF, and CTF in the subtropical region of China. We found that CFF exhibited a clear unimodal pattern in live fine root biomass, peaking in September and reaching its lowest value in January, which aligns with findings regarding optimal root growth conditions during late summer [21,22]. For MPF, we observed a more complex growth pattern with three peaks, the most pronounced occurring in October. Our results are consistent with previous studies indicating sporadic root growth driven by variable climatic

conditions [23–25]. The October peak in MPF is typical of deciduous species maximizing nutrient absorption in autumn [26–28]. CTF exhibited substantial root biomass with a peak in October and a significant decrease in January, reflecting vigorous growth and competitive nutrient acquisition common in broadleaf evergreens in subtropical regions [29,30].

The irregular fluctuations observed, such as the peak in dead fine root biomass for CFF in October and the subsequent low in March, suggest that root turnover is heavily influenced by species-specific phenological cycles and environmental conditions [21,31]. These patterns indicate the trees' adaptive strategies to seasonal changes, where higher root mortality in autumn may correlate with nutrient resorption and allocation for future growth [23,25]. The significant peak in CTF dead fine root biomass in November, notably higher than that of the other species, underscores the impact of broadleaf evergreen trees' root dynamics on ecosystem carbon cycling and soil nutrient availability [29,30]. Such pronounced peaks in dead root biomass are likely a result of increased root senescence triggered by physiological stress or seasonal shifts in resource allocation [21,26]. Understanding these variations is crucial for improving forest management practices, as it provides insights into belowground carbon dynamics and nutrient cycling processes that underpin forest productivity and resilience to climatic changes [32,33]. These findings emphasize the importance of considering species-specific root turnover patterns in modeling carbon sequestration and developing sustainable forest management strategies [28,34].

The observed significant variations in live fine root biomass among the four studied forest types across different soil layers underscore the complex interplay between plant physiology, soil properties, and seasonal environmental changes [21,22]. The distinct seasonal peaks in live fine root biomass highlight species-specific root dynamics and adaptive responses to environmental conditions, which have important implications for forest management and ecological sustainability [25,29]. For CFF, the peaks in live fine root biomass across different soil layers during late summer and early autumn suggest an active period of root growth and nutrient acquisition before the onset of winter dormancy [23,30]. The delayed peak in deeper soil layers, compared to the surface layers, could be attributed to soil moisture gradients and root competition for water and nutrients, as deeper roots may have better access to stable moisture reserves during dry periods [32,33]. In MPF, the occurrence of three distinct peaks in live fine root biomass in the upper soil layers reflects a high degree of root turnover and adaptability to fluctuating environmental conditions, such as temperature and soil moisture variations [26,31]. The higher biomass observed in October in deeper soil layers indicates a strategic response to drought stress, with roots penetrating deeper into the soil to access residual moisture [28,34]. This finding aligns with previous studies suggesting that pine species tend to develop deeper root systems in response to prolonged drought conditions [33,35]. The relatively minor seasonal changes in live fine root biomass in CGF's upper and lower soil layers, compared to the more pronounced variations in the mid-soil layers, suggest that maple trees may prioritize root growth in intermediate depths where nutrient availability is optimal [21,23]. The rapid increase in fine root biomass during the wetter months indicates a strategic allocation of resources to capitalize on improved soil moisture conditions, which is critical for supporting the tree's growth and metabolic activities [25,31]. CTF demonstrated significant seasonal fluctuations in live fine root biomass across all soil layers, with multiple peaks observed annually. The highest biomass in the 0–15 cm soil layer in June highlights the importance of shallow roots in capturing nutrient pulses and responding to rapid environmental changes [29,30]. The subsequent increase in biomass in deeper soil layers suggests a strategic shift in resource allocation, possibly to exploit water reserves during dry periods, which is critical for sustaining growth during adverse conditions [22,26]. This dynamic

root growth pattern underscores CTF's ability to adapt to varying soil moisture conditions and optimize nutrient uptake throughout the year [32,34].

The similarities in the distribution patterns of live and dead fine roots across different soil layers among the four forests highlight the consistent influence of soil depth on fine root biomass allocation. The concentration of both live and dead fine roots in the upper 0–30 cm soil layer indicates the critical role of this zone in nutrient uptake and root turnover processes. This trend aligns with previous findings that suggest a greater accumulation of fine roots in the topsoil due to higher nutrient availability and more favorable moisture conditions [19,25]. In MPF, the relatively higher proportion of live fine roots in the 15–30 cm soil layer compared to other species suggests a deeper rooting strategy, potentially as an adaptation to access water and nutrients during dry periods [23]. The similar proportions of live and dead fine roots across soil layers in CGF and CTF reflect their respective rooting habits and the influence of soil properties on root mortality [31]. CTF, in particular, demonstrated a higher concentration of both live and dead fine roots in the 0–15 cm soil layer, which may indicate a shallow rooting system adapted to rapidly exploit surface nutrients and moisture [32]. This pattern suggests that camphor trees might be more susceptible to surface soil disturbances, emphasizing the need for careful management practices to maintain soil health and forest productivity [28].

The data presented underscore the importance of soil layer stratification in understanding root dynamics and their implications for forest ecosystem functioning. The pronounced accumulation of fine roots in the topsoil layers emphasizes the significance of this zone in nutrient cycling and carbon sequestration processes [33,34]. Future studies should focus on the long-term impacts of root dynamics on soil properties and forest health under changing climatic conditions [22,26]. Additionally, research should continue exploring how species-specific root dynamics influence overall forest health and carbon storage capacity, integrating these insights into sustainable forest management strategies [27,36]. By advancing our understanding of fine root biomass dynamics, we can better predict and mitigate the impacts of climate change on forest ecosystems, ensuring their long-term sustainability and ecological integrity [33,34].

This study provides valuable insights into fine root dynamics in four subtropical plantation forests, focusing on FBP and FBT. The results in Table 4 highlight significant differences in fine root dynamics between species, suggesting species-specific strategies in response to environmental conditions and resource availability.

The variation in FBP and FBT observed across the forest types is consistent with previous studies suggesting that fine root dynamics are influenced by both intrinsic species traits and external factors such as soil properties, climate, and forest management practices [12,15]. For instance, coniferous species, such as MPF, tend to exhibit higher fine root biomass production, which may be linked to their ability to quickly exploit available resources in the soil, a trait commonly observed in fast-growing, nutrient-demanding species [18]. In contrast, broad-leaf species like CGF and CTF may allocate fewer resources to root biomass production, potentially as a strategy to conserve nutrients and water, particularly in subtropical conditions where moisture stress can limit root growth [14].

The observed differences in FBT rates further emphasize species-specific adaptation strategies. Fast turnover rates, particularly in species like CTF, are likely a response to the highly dynamic nutrient cycling in subtropical forest ecosystems. Rapid turnover allows these species to maintain efficient nutrient uptake and ensure survival in environments where nutrient availability can fluctuate seasonally [16]. On the other hand, species like CFF, with slower turnover rates, may invest in longer-lived roots, which could be more advantageous under conditions where nutrient limitations are less frequent. Our study's findings expand the understanding of fine root dynamics by incorporating new data on

FBP and FBT rates in subtropical forest ecosystems, where such information has been limited [37]. The different estimation methods used in this study further contribute to the robustness of our results and offer a comprehensive understanding of how fine root dynamics may vary across different forest types.

This research adds to the growing body of literature highlighting the importance of fine root systems in forest carbon and nutrient cycling [12,13]. Understanding the variation in fine root dynamics among species is crucial for improving forest management strategies, particularly in the context of climate change, as different species respond differently to changing environmental conditions.

Future research could explore the underlying mechanisms driving differences in fine root dynamics, particularly the role of soil properties, environmental stressors, and nutrient availability. Additionally, integrating data on root nutrient uptake and its relationship to turnover rates would further elucidate the ecological role of fine roots in subtropical forest ecosystems. While our study provides valuable insights into fine root dynamics in subtropical plantation forests, there are several limitations to consider. First, our study was conducted over a single year, which may not fully capture the long-term fluctuations in fine root biomass and turnover rates that could vary across multiple years, especially under changing climatic conditions. Second, the study only included four forest types, which may not fully represent the diversity of species and soil types found in subtropical ecosystems. Future studies should include a broader range of species and forest types to provide a more comprehensive understanding of fine root dynamics. Third, although we employed a standard sampling method, the challenge of accurately quantifying fine roots, especially in deeper soil layers, remains an inherent limitation of root sampling techniques. Improving sampling methods, such as increasing the frequency of measurements or integrating complementary techniques, could help mitigate this issue. Lastly, while this study focused on seasonal variations, longer-term studies that incorporate the impacts of forest management practices and environmental stressors would provide further insights into the ecological role of fine roots in subtropical forests.

5. Conclusions

This study illuminates the significant spatiotemporal variability in fine root dynamics across four main subtropical forest types in China: CFF, MPF, CGF, and CTF. The biomass of live and dead fine roots was predominantly concentrated in the upper 0–30 cm soil layer, with distinct patterns of decline observed in deeper layers. Live fine roots accounted for over 90% of total biomass in these forest types, underscoring their critical role in nutrient uptake. Seasonal variations revealed that both live and dead fine root biomass exhibited notable fluctuations, reflecting the dynamic nature of root turnover influenced by seasonal conditions. These distinct distribution patterns among the forest types highlight the importance of species-specific adaptations in root dynamics, particularly in the CTF, which demonstrated superior nutrient cycling capabilities. The results of FBP and FBT rates further deepen our understanding of these dynamics. The estimations for FBP revealed that Cinnamomum lanceolata had the lowest production across all methods, with values ranging from 0.866 to 0.966 t/ha, while MPF exhibited the highest FBP, with values ranging from 1.162 to 1.833 t/ha. The other forest types, CGF and CTF, showed intermediate FBP values, with CTF having the highest estimates, ranging from 2.655 to 2.903 t/ha. In terms of fine root turnover, CFF exhibited the lowest turnover rates (0.94 to 1.045 a^{-1}), while CTF displayed the highest rates, ranging from 1.25 to 1.361 a^{-1}. These variations in FBP and FBT reflect species-specific strategies in response to environmental conditions and resource availability. This study highlights the role of fine root systems in forest carbon and nutrient cycling, emphasizing the need for effective forest management. Understanding

fine root dynamics across species and forest types can optimize reforestation, enhance carbon sequestration, and improve ecosystem resilience under climate change.

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