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# Short-Term Effects of Low Intensity Thinning on the Fine Root Dynamics of *Pinus massoniana* Plantations in the Three Gorges Reservoir Area, China

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**Abstract:** Fine roots play an important role in plant growth as well as carbon (C) and nutrient cycling in terrestrial ecosystems. Fine roots are important for understanding the contribution of forests to the global C cycle. Knowledge about this topic is still limited, especially regarding the effects of different forest management practices. This study investigated the seasonal dynamics of fine roots (<2 mm) in *masson pine* (*P. massoniana*) plantations for one year after low intensity thinning by using a sequential soil coring method. The fine roots showed pronounced seasonal dynamics, with a peak of fine root biomass (FRB) occurring in September. Significant differences were noted in the seasonal dynamics of FRB for the different diameter size sub-classes ( $\leq 0.5$  mm, 0.5–1 mm and 1–2 mm); also FRB was inversely related to soil depth. Moreover, the FRB ( $\leq 0.5$  mm and 0.5–1 mm except 1–2 mm) in the thinning plots was greater than that in the control only in the upper soil layer (0–10 cm). Furthermore, the FRB varied significantly with soil temperature, moisture and nutrients depended on the diameter sub-class considered. Significant differences in the soil temperature and moisture levels were noted between low-intensity thinned and control plots. Soil nutrient levels slightly decreased after low-intensity thinning. In addition, there was a more sensitive relationship between the very fine roots (diameter < 0.5 mm) and soil nutrients. Our results showed an influence of low-intensity thinning on the fine root dynamics with a different magnitude according to fine root diameter sub-classes. These results provide a theoretical basis to promote the benefits of C cycling in the management of *P. massoniana* forests.

**Keywords:** fine root biomass; seasonal dynamics; diameter sub-classes; The Three Gorges Reservoir area; *Pinus massoniana*

## 1. Introduction

Forests are an important component of the global carbon (C) budget as a major C sink because they store approximately 80% of all terrestrial aboveground C and about 44% of all soil organic C [1–3]. Furthermore, the roots of forest trees are a vital source of soil C [4–6], especially fine roots (i.e., <2 mm in diameter), which have a shorter life span and higher metabolic activity compared with coarse roots [7–9], and their turnover represents up to 33–67% of the total net primary production in most ecosystems [10]. Hence, it is widely recognized that fine root dynamics is essential to the understanding of their role as C-stores and sources of soil litter input in terrestrial ecosystems.

Fine root biomass (FRB) typically shows a regular vertical distribution, with most of the fine roots distributed above a soil depth of 30 cm, especially at a depth of about 10 cm in the mineral soil layer [11]. However, FRB was reported to be affected by plant configuration, density, and soil properties; therefore, the vertical distribution of FRB shows significant differences based on these factors. For example, FRB decreases strongly as the soil depth increases and is higher in mixed forests than in pure forests [12]. In addition, FRB shows obvious seasonal dynamics and has a significant seasonal pattern [13]. In general, FRB has unimodal or bimodal variations throughout the year [14–16], with the maximum value often occurring in mid to late summer, and the minimum value in late autumn to early winter [17,18]. Many studies have shown that the biomass of the fine roots of *P. massoniana* often shows only one peak, although the timing thereof varies, under natural conditions [19].

Fine roots, even those that are <0.5 mm, have been shown to be extremely sensitive to environmental changes and are dependent on factors such as forest stand characteristics [14] (life form, tree species, stand age, stand density, basal area, and understory vegetation), environmental cues (soil moisture, soil temperature, precipitation, and soil nutrient availability) [14,20–23]. However, the results of previously published studies are inconsistent. Helmisaari et al. [21] found that the FRB had a positive relationship with the C:N ratio of the soil, and a negative relationship with temperature in a Norway spruce (*Picea abies* L. Karst) stand. Mei et al. [20] described a positive relationship between the FRB and the average soil temperature at a depth of 10 cm in the Manchurian ash, *Fraxinus mandshurica*. Finér L. et al. [11] and Montagnoli et al. [15] reported that the FRB decreased with stand age in European beech (*Fagus sylvatica* L.), but increased in Scots pine (*Pinus sylvestris*) stands. Moreover, they found that the mean basal area was more important than environmental factors or forest stand factors in determining the total FRB [21].

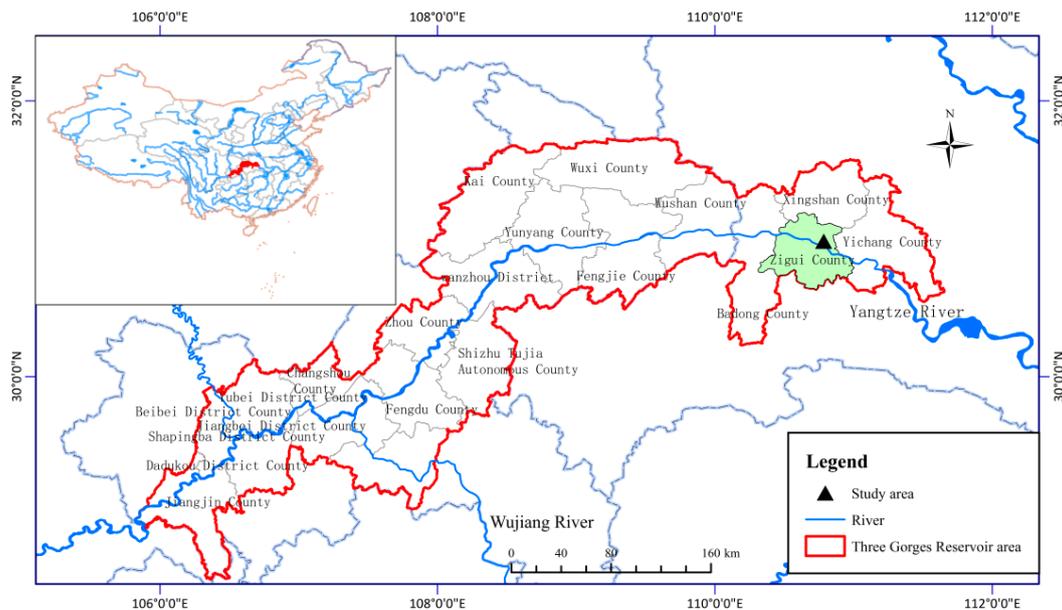
Thinning is an essential forestry practice. Numerous studies have shown that, after thinning, the succession and recovery of vegetation, stand structure, species composition, soil nutrient content, soil temperature and moisture undergo a corresponding change [24–29]. Soil C content in the forest ecological system also changes after thinning [30–32]. Considering that plant configuration, density, and soil properties might change after thinning, understanding the dynamics of fine root responses to forest thinning is important [33,34]. *P. massoniana* is an important species in southern China and is also the most widely distributed forest type in the Three Gorges Reservoir area [35]. Few studies have investigated the dynamics of the fine roots of *P. massoniana* under natural or human management conditions in the Three Gorges Reservoir area [19,36]. We hypothesized that thinning will affect the fine root biomass. To test our hypothesis, we used sequential coring to determine (1) the effects of low intensity thinning on the FRB of *P. massoniana* plantations and (2) the relationship between the seasonal dynamics of the biomass of fine roots and soil temperature, moisture, and nutrients. The aim of our study was to provide the theoretical basis to increase C sequestration in managed *P. massoniana* forests.

## 2. Materials and Methods

### 2.1. Study Site

The experimental site is located at the Jiulingtou Forest Farm (30°59' N, 110°47' E) in the Three Gorges Reservoir area, Zigui County, Hubei Province, China (Figure 1). The climate is subtropical temperate continental monsoon climate, with an annual mean temperature of 16.9 °C, and an annual precipitation of 1000 to 1250 mm falling mainly from April to September. The monospecific plantations of *P. massoniana* were aerially seeded in the 1970s, this species is the most commonly used indigenous species for reforestation in this area, evenly distributed in Jiulingtou Forest Farm. The mean height, DBH, density of *P. massoniana* was 8.33 m, 11.10 cm and 1688 tree ha<sup>-1</sup>, respectively. The soils are classified as Haplic Luvisol based on Chinese soil classification [37]. The experimental stand was relatively steep, with a northwest slope of 34°. The average diameter at breast height (DBH) of understory shrubs was 5 cm, and the average height was 5.60 m. Understory shrubs included mainly shrubby bushclover, *Lespedeza bicolor* (Turcz.), Chinese firethorn, *Pyracantha fortuneana* (Maxim.),

and *Litsea pungens* (Hemsl.) Herbs in the study area included mainly *Woodwardia japonica* (L.f.), *Carex tristachya* (Thunb.), *Aster ageratoides* (Turcz.), and *Parathelypteris nipponica* (Franchet and Savatier) Ching. A total of 6 plots (each 20 m × 20 m) were randomly selected for sampling at an elevation of 1225 m above sea level in an area of >1 ha. Each treatment included three replicates. The experiment was conducted at the middle of October 2013 and included a control intact forest and a forest subjected to low-intensity thinning (15% of the basal area of *P. massoniana* removed) using chain saw. Only the harvested trunks were removed and the residues produced by the harvest was not cleared from the plots; each plot was surrounded by 5-m wide buffer zones.



**Figure 1.** Location of the study area. The study area is indicated by a triangle, and Zigui County is marked in green. The Yangtze River (blue line) flows through the Three Gorges Reservoir area (red line).

## 2.2. Fine Root Biomass

Sequential soil coring was used to sample fine roots at the control and thinned sites in September 2013; the samples were collected at an interval of not more than 40 days from March to November 2014. The sampling was conducted a total of nine times; no samples were collected in January because the Jiulingtou Forest Farm was closed due to low temperatures. Ten randomly placed replicate soil samples were collected from each subplot at depths of 0–10, 10–20, and 20–30 cm yielding 360 (12 subplots × 10 replicates per subplot × 3 soil layers) samples; the sampling was conducted using a soil sampler with a length of 30 cm. All samples were immediately transferred to the laboratory and processed. In the laboratory, the roots were washed on a sieve (pore size of 0.40 mm) to remove soil, and while still fresh, the roots of *P. massoniana* were identified based on their colour, toughness, and flotation properties [38]. Clean live roots were immediately put into a plastic bag and stored at low temperature (−25 °C), hence, this approach can avoid fine roots dehydrated. The roots were measured using a Vernier caliper and sorted into three fine root diameter sub-classes: ≤0.5 mm, 0.5–1 mm, and 1–2 mm. The sorted fresh roots were air-dried and categorized into three sub-classes: ≤0.5 mm, 0.5–1 mm, and 1–2 mm diameter. The roots were weighed after drying to a constant weight at 80 °C for 24 h. The following formula was used to calculate the biomass of fine roots:

$$\text{Fine root biomass (t}\cdot\text{ha}^{-1}) = 100A/[\pi (D/2)^2] \quad (1)$$

where A and D are the average soil core root dry weight (g) and diameter of the root auger (cm), respectively. D = 10 cm in this formula.

### 2.3. Environmental Factors

#### 2.3.1. Soil Temperature and Moisture

Soil moisture and temperature were measured using WatchDog 2000-series weather stations (Spectrum Technologies, Plainfield, IL, USA) in the six plots. Sensors were placed at the centre of each site at depths of 5 and 15 cm. The soil temperature and moisture were recorded at hourly resolution.

#### 2.3.2. Soil Samples and Chemical Analysis

The concentrations of soil nutrients were measured in control and thinned plots. To collect soil samples and mix them better, soil sampling points were allocated in an S-shaped track in each plot. Ten sample points were randomly selected near the soil core point in each plot. Samples were obtained from depths of 0–10, 10–20, and 20–30 cm, and those from the same soil layer were mixed and sealed in plastic bags.

The samples were returned to the laboratory and further mixed before the removal of visible plant roots and debris. Once mixed, the samples were spread evenly on a clean sheet of paper to air dry in a cool and ventilated location. After air-drying and the removal of roots, stones, and other debris from the soil, the soil samples were sieved through 2-mm mesh sieves. A portion of the samples was sieved through a 0.149 mm mesh sieve. The soil organic C (SOC) content was analysed using the dichromate oxidation method [39], and total N (TN) was analysed using the Kjeldahl method [40]. Total P (TP) and K (TK) were determined using the HF-HClO<sub>4</sub>-HNO<sub>3</sub> digestion-ICP Act method; available P (AP) was analysed using the bicarbonate extraction method; and available K (AK) was analysed using the 1 mol·L<sup>-1</sup> ammonium acetate extraction-ICP method [41].

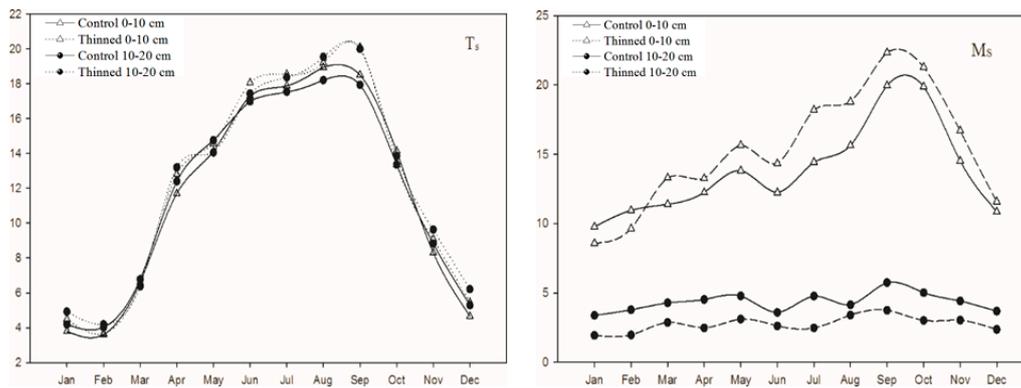
### 2.4. Statistical Analysis

All data were statistically analysed using SPSS software v. 22.0 (SPSS Inc., Chicago, IL, USA). Student's *t*-test was used to determine the differences in FRB between the experimental sites or between the soil layers and to determine the differences in soil temperature and moisture at the same soil depth between the experimental sites. One-way ANOVA was used to analyse the seasonal dynamics of the FRB at different soil depths at both sites. When the differences were significant according to ANOVA, comparisons among the means were performed using the least-significant difference (LSD) test. Univariate analysis of variance was used to test the traits of fine roots by diameter sub-classes, including the following fixed factors: site (S), soil depth (D), and month (M). The relationships between FRB and soil variables (soil temperature, soil moisture, and soil nutrients) were determined using Pearson correlation analysis, and then linear regression was used to investigate the comprehensive effects of soil factors on the biomass of fine roots.

## 3. Results

### 3.1. Soil Temperature and Moisture

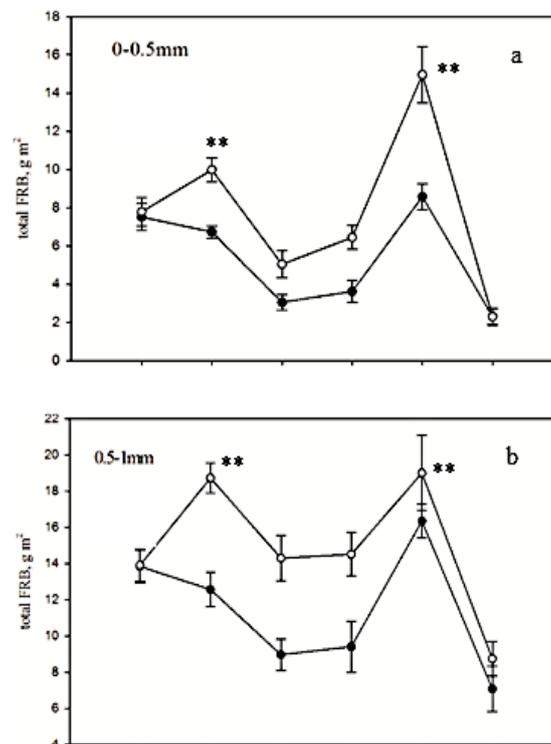
Seasonal patterns of soil temperature and moisture were similar for both control and thinned plots. Soil temperature increased from February to September 2014 and rapidly decreased until December 2014. In particular, soil temperature was higher in thinned plots at both soil depths from June to September (Figure 2, Ts). Soil moisture pattern was detectable in the upper soil layer increasing from June to October. At deepest soil layer soil moisture remained stable during the whole year. Soil moisture was higher in thinned plots than in control at 0–10 cm soil depth. The opposite was detected at deeper soil layer (10–20 cm) with higher values in control plots than in thinned ones.



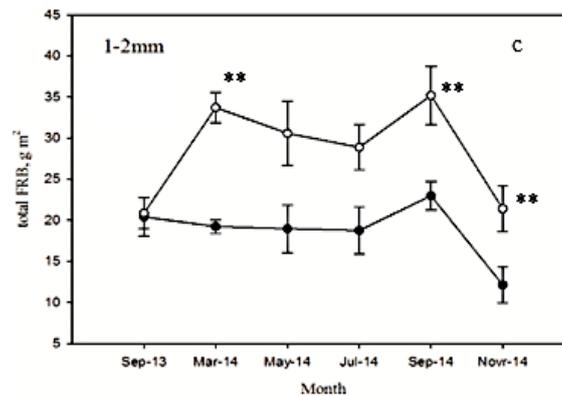
**Figure 2.** Soil temperature (°C) and moisture (% volume) at depths of 0–10 and 10–20 cm in the control and thinned plots (Ts and Ms are soil temperature and soil moisture, respectively). Solid and dashed lines represent control and thinned plots, respectively. Open triangles and closed circles represent 0–10 and 10–20 cm soil depths, respectively.

### 3.2. Seasonal Dynamics of FRB after Low Intensity Thinning

In the control and thinned plots, the FRB of the three diameter sub-classes ( $\leq 0.5$ , 0.5–1, and 1–2 mm) showed similar seasonal patterns between thinned and control plots (Figure 3). The maximum and the minimum FRB for all the diameter sub-classes in both thinned and control plots were detected in September and November, respectively; the maximum FRB of the  $\leq 0.5$ , 0.5–1, and 1–2 mm sub-classes were 14.9, 19.0, and 35.2  $\text{g}\cdot\text{m}^{-2}$ , respectively, in thinned plots, and 8.6, 16.3, and 23.0  $\text{g}\cdot\text{m}^{-2}$ , respectively, in the control plots. Furthermore, the greatest amplitude of FRB variation across different months was measured in the roots with 0–0.5 mm diameter. Significant differences in the FRB of the three diameter sub-classes ( $\leq 0.5$ , 0.5–1, and 1–2 mm) after low intensity thinning were noted across the different months ( $p < 0.01$ ) between March and September.



**Figure 3.** Cont.



**Figure 3.** Seasonal variation of *P. massoniana* fine root ( $\leq 0.5$ , 0.5–1, and 1–2 mm) biomass ( $\text{g m}^{-2}$ ) in the control and thinned plots (at 0–30 cm soil depth). Closed and open circles represent the fine root biomass in the control and thinned plots, respectively. Error bars denote standard errors.  $p < 0.01$  represents a significant difference. \*\*  $p < 0.01$ .

The total FRB for the three diameter sub-classes ( $\leq 0.5$ , 0.5–1, and 1–2 mm) was significantly higher in thinned plots than the control ones ( $p < 0.01$ ). In the thinned plots, the total FRB of the three diameter sub-classes was 46.1, 88.9, and 170.9  $\text{g m}^{-2}$ , significantly increase of 59.5%, 35.4%, and 47.8%, in comparison with control plots.

### 3.3. Seasonal Dynamics of FRB at Different Depths after Low Intensity Thinning

The seasonal trends of FRB in the three diameter sub-classes ( $\leq 0.5$ , 0.5–1, and 1–2 mm) at soil depths of 0–10, 10–20, and 20–30 cm in the control and thinned plots were almost identical (Figure 4). In November, the FRB at the depths of 10–20 and 20–30 cm was slightly larger than that at a 0–10 cm depth for both control and thinned plots. However, no significant differences ( $p > 0.05$ ) were noted between the FRB of each soil layer in the same size sub-class.

The FRB of the  $\leq 0.5$  mm size sub-class was significantly affected by depth ( $p = 0.000$ ) and depth  $\times$  month interaction ( $p = 0.001$ ). The FRB of the  $\leq 0.5$  mm diameter sub-class at each soil depth in the thinned plots was larger than that in the control plots (Figure 4). At depths of 0–10 and 10–20 cm, the FRB of the  $\leq 0.5$  mm size sub-class in the control and thinned plots was significantly different ( $p < 0.05$ ). The seasonal dynamics of the FRB of the  $\leq 0.5$  mm size sub-class at depths of 0–10 and 10–20 cm was significantly different in the control and thinned plots, respectively (Table 1).

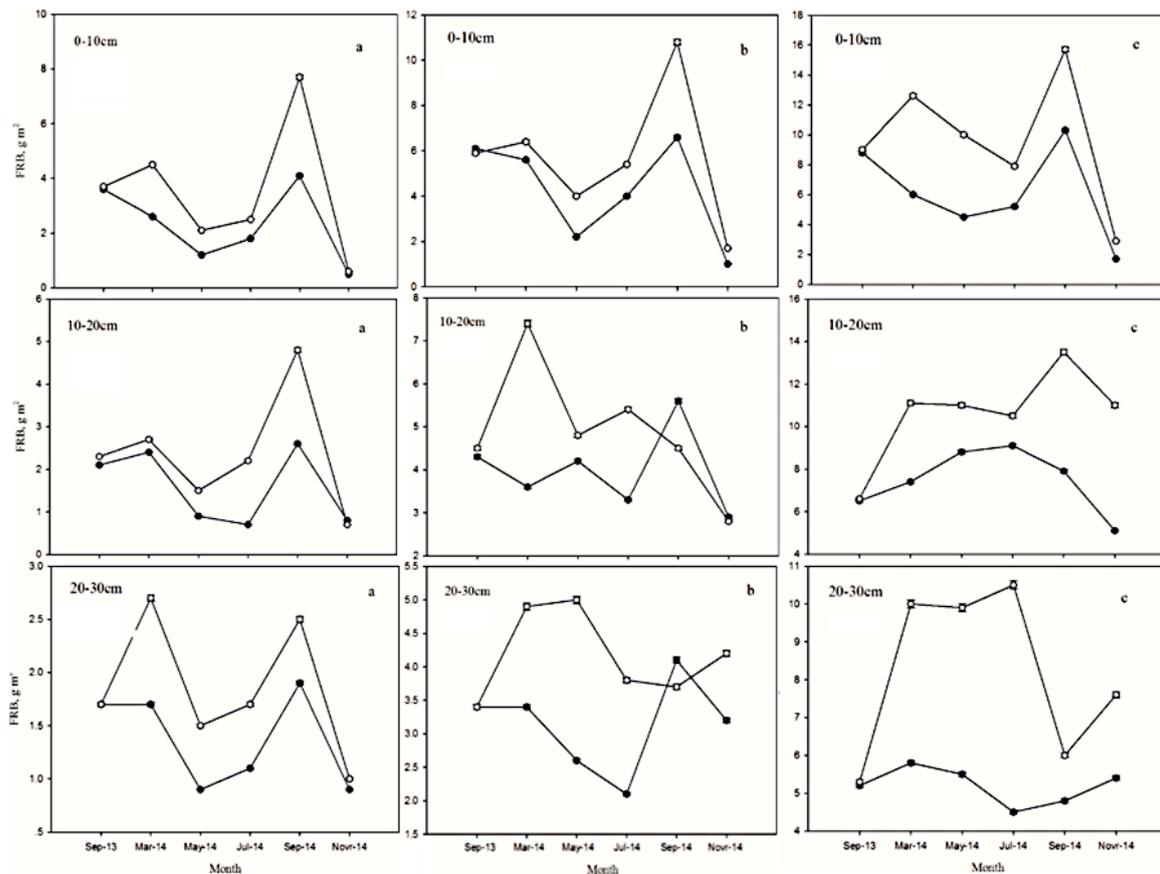
**Table 1.**  $p$  values for one-way ANOVA of the seasonal dynamics of *P. massoniana* fine root biomass at depth intervals of 0–10, 10–20, and 20–30 cm.

Soil Depth (cm)	Control				Thinned			
	$\leq 0.5$ mm	0.5–1 mm	1–2 mm	Sum of the Size Sub-Classes	$\leq 0.5$ mm	0.5–1 mm	1–2 mm	Sum of the Size Sub-Classes
0–10	0.020	0.102	0.143	0.109	0.003	0.014	0.283	0.154
10–20	0.018	0.210	0.678	0.268	0.006	0.115	0.889	0.547
20–30	0.461	0.605	0.990	0.621	0.291	0.555	0.429	0.401

The FRB of the  $\leq 0.5$  mm size sub-class was significantly affected by the depth  $\times$  month interaction ( $p = 0.001$ ), but not by depth alone ( $p = 0.107$ , Table 1). The FRB of the  $\leq 0.5$  mm size sub-class at each soil depth in thinned plots exceeded the biomass in almost fine root diameter sub-classes in the control plots. The FRB in the  $\leq 0.5$  mm size sub-class between the control and thinned plots was significantly different ( $p = 0.004$ ), at the depth of 0–10 cm, but not at the other depths ( $p > 0.05$ ).

(Figure 4). The seasonal dynamics of FRB in the  $\leq 0.5$  mm size sub-class  $p$  values for one-way ANOVA in thinned plots was significantly different from that in the control plots at the same sampling time.

The FRB in the 1–2 mm size sub-class was not significantly affected by depth, month, or the depth  $\times$  month interaction (Table 1). The FRB in the 1–2 mm size sub-class at each soil depth in thinned plots was larger than that in the control plots (Figure 4). At each depth, no significant differences ( $p > 0.05$ ) were noted in the FRB of the 1–2 mm size sub-class between the control and thinned plots. The seasonal dynamics of the FRB in the 1–2 mm size sub-class at each depth was also not significantly different between the control and thinned plots (Table 1).



**Figure 4.** Seasonal variation of *P. massoniana* fine root biomass (FRB) ( $\text{g m}^{-2}$ ) of roots with diameter  $\leq 0.5$  (a,d,g), 0.5–1 (b,e,h), and 1–2 mm (c,f,i) at depth intervals of 0–10, 10–20, and 20–30 cm in the control and thinned plots. Closed and open circles represent the FRB in the control and thinned plots, respectively. Error bars denote standard errors.

### 3.4. Relationships between Soil Environmental Factors and FRB

In the present study, soil TN, TP, AP, AK, TK, and SOC content decreased with increasing soil depth. In the 0–10, 10–20 and 20–30 cm soil layers, the SOC, TN, TP, and AK content was lower in the treatment plots than in the control plots while AP was greater in treatment plots than in the control plots. Pearson correlation analysis and linear regression were used to determine how the measured soil environment variables (i.e., SOC, TN, TP, TK, AP, AK), and soil moisture and temperature, were related to FRB (Table 2). The biomass of roots in diameter sub-class  $< 0.5$  mm was significantly and positively correlated with SOC, TN, and AP ( $r = 0.332$ ,  $p < 0.05$ ;  $r = 0.492$ ,  $p < 0.05$ ;  $r = 0.619$ ,  $p < 0.05$ , respectively; Table 2). Moreover, the biomass of roots in the diameter class 0.5–1 mm was also significantly positively correlated with SOC, TN, and AP ( $r = 0.583$ ,  $p < 0.01$ ;  $r = 0.563$ ,  $p < 0.01$ ;  $r = 0.597$ ,  $p < 0.01$ , respectively). The combined effect of soil nutrients on the FRB in the  $\leq 0.5$  mm and 0.5–1 mm size sub-classes were

of great magnitude (70.1% and 79.7%, respectively), but their effect on the FRB in the 1–2 mm size sub-class was relatively small (29.9%).

**Table 2.** Correlation coefficients for the relationship between the fine root biomass of *P. massoniana* and soil nutrients at a depth of 0–30 cm and soil temperature and moisture at depths of 0–10 and 10–20 cm. \*\* and \* indicate that the correlation is significant at the 0.01 and 0.05 levels, respectively.

Parameter	Correlation Coefficient								
	r <sub>OC</sub>	r <sub>TN</sub>	r <sub>TP</sub>	r <sub>AP</sub>	r <sub>TK</sub>	r <sub>AK</sub>	r <sub>OC+TN+TK+TP+AK+AP</sub>		
Fine root ≤0.5 mm biomass/(t·ha <sup>-1</sup> )	0.332 *	0.492 *	0.289	0.619 *	0.357	0.094	0.701 **		
Fine root 0.5–1 mm biomass/(t·ha <sup>-1</sup> )	0.583 *	0.563 *	0.316	0.597 *	0.085	0.063	0.797 **		
Fine root 1–2 mm biomass/(t·ha <sup>-1</sup> )	0.124	0.165	0.248	0.276	0.072	0.183	0.299		
Soil Depth (cm)	r <sub>T</sub>	r <sub>W</sub>	r <sub>T+W</sub>	r <sub>T</sub>	r <sub>W</sub>	r <sub>T+W</sub>	r <sub>T</sub>	r <sub>W</sub>	r <sub>T+W</sub>
	Fine Root ≤0.5 mm Biomass/(t·ha <sup>-1</sup> )			Fine Root 0.5–1 mm Biomass/(t·ha <sup>-1</sup> )			Fine Root 1–2 mm Biomass/(t·ha <sup>-1</sup> )		
0–10	0.701 *	0.831 **	0.749 **	0.685 *	0.814 **	0.643 *	0.501 *	0.662 **	0.497 *
10–20	0.521 *	0.552 *	0.516 *	0.503 *	0.101	0.467 *	0.287	0.194	0.196

The correlations of FRB with soil temperature and moisture at the 0–10 cm depth were stronger than those in the 10–20 cm soil layer (Table 2). At the 0–10 cm soil depth, the FRB of all fine root sub-classes was positively correlated with soil temperature and moisture. At the 10–20 cm soil depth, the FRB of the ≤0.5 mm sub-class was positively correlated with soil temperature and moisture ( $r = 0.521$ ,  $p < 0.05$  and  $r = 0.552$ ,  $p < 0.05$ , respectively) and that of the 0.5–1 mm sub-class was positively correlated with soil temperature ( $r = 0.503$ ,  $p < 0.05$ ).

## 4. Discussion

### 4.1. Changes in FRB Dynamics in Response to Thinning

There are conflicting reports about the effect of thinning on the growth of fine roots. López et al. [42] reported that thinning can boost the growth of fine roots (<2 mm) while Noguchi et al. [43] reported the opposite. In this study, we found that the FRB in the three diameter sub-classes (≤0.5, 0.5–1, and 1–2 mm) increased significantly after thinning. This might be due to the increase of fine root productions stimulated by the cutting. Compared with that in thinned plots, the fine root distribution in control plots was relatively complex, with a competition for space and nutrients in the above and below ground parts of the forest [44]. *P. massoniana* is a taproot tree, which ensures that the fine root (<2 mm) biomass is located largely at a depth of 0–30 cm under conditions of high stand density and complex community structure [45]. However, the growth of fine roots in the subsoil might be promoted to a certain extent [46]. In addition, canopy closure decreases with thinning, allowing more light to reach *P. massoniana* trees in thinned plots. This, in turn, increases leaf photosynthesis and accumulation of photosynthetic products, which are then allocated to fine roots, thereby promoting their growth [23].

FRB has clear seasonal patterns [12,47] and typically peaks in summer [48]. In this study, we found that the seasonal patterns of the FRB of *P. massoniana* had a peak in September 2014 in the control and thinned plots. In March, the soil temperature increases, surface snow melts, and soil moisture increases, resulting in increased availability of soil nutrients, which provided large amounts of carbohydrates for fine root growth [42,49,50]. This may explain the FRB peak in March of lower magnitude. During foliage production and photosynthesis, trees and understory plants produce extensive fine root networks to satisfy their high demands for soil water and nutrients [45]. The fine roots fill a greater space and occupy different niches in the soil because of the contrasting rooting traits of the component species in the mixed stands [51]. *P. massoniana* is a non-fibrous tree, and its fine roots have a relatively weak ability to compete in the upper soil compared with that of fibrous

plants. The intense competition in the upper soil between different plant populations may restrict the fine root growth of *P. massoniana*. This explains the general increase in the FRB in thinned plots rather than in control plots. In summer, temperature and humidity conditions are suitable for plant growth, and plants have a high demand for nutrients and water [44]. This may promote the growth of fine roots, which would explain the second FRB peak in September in both the control and thinned plots.

#### 4.2. Changes in FRB Dynamics at Different Soil Depths in Response to Thinning

Thinning affects the FRB at different soil depths [22,42]. In thinned plots, the FRB of *P. massoniana* at depths of 0–10, 10–20, and 20–30 cm increased compared with that in control plots (Figure 4). Thinning had a more significant effect on the FRB in the 0–10 cm soil layer than it did at other depth intervals, with the exception of the FRB of the  $\leq 0.5$  mm size sub-class in the 10–20 cm soil layer. This is related to the diameter of the fine roots, with roots with smaller diameters being more affected [17]. In thinned plots, the FRB of all diameter sub-classes ( $\leq 0.5$ , 0.5–1, and 1–2 mm) increased at a depth of 0–10 cm, by 71%, 46%, and 75%, respectively, compared with that in control plots. Differences in the FRB of the different diameter sub-classes at different soil depths had no pronounced patterns after thinning. In this study, the time at which the samples were obtained had a significant effect on the seasonal dynamics of the FRB in the  $\leq 0.5$  mm size sub-class at a depth of 0–20 cm in the thinned and control plots, but not at a depth of 20–30 cm. These results suggest that time was not the key factor affecting the seasonal dynamics of FRB in the  $\leq 0.5$  mm size sub-class. Thinning did not change the effects of soil depth and time on the seasonal dynamics of FRB in the 0.5–1 and 1–2 mm size sub-classes, which were similar to those of control plots. Thinning intensity, as a forest management practice, may significantly affect the growth of fine roots of trees [33,43,44], such as fine root number and fine root density [52]. Liu et al. [44] showed that FRB increased as thinning intensity increased, and different thinning intensities also affected the allocation of FRB at different soil depths. The mild thinning used in our study can largely explain the above results.

#### 4.3. Correlations of FRB and Soil Factors in Response to Thinning

Fine roots are primarily responsible for nutrient and water acquisition from the soil [45,53,54]. The relationships of fine root dynamics and soil temperature, moisture, and nutrients have been widely reported, but the results of these studies are not consistent [20,55–59]. In our study, thinning had a more significant effect on soil moisture than on temperature at the 0–20 cm depth, mainly because different tree species can affect soil moisture levels due to their canopy structure and canopy interactions with the atmosphere [60]. The results of this study were similar to those of Bréda et al. [26] who showed that soil moisture increased in thinned plots owing to the reduction of transpiration, which was in contrast to the findings of Mattson and Smith [24].

Soil moisture and temperature in the top soil were positively correlated with fine root ( $< 2$  mm) biomass in both control and thinned plots. The correlations were significant probably because the water availability and temperature influenced nutrient uptake and C allocation to the belowground compartment [61]. Therefore, soil surface moisture and temperature were important for the dynamics of the FRB at the 0–10 cm depth in this study. Our results are consistent with those of Mei et al. [20] and Cheng et al. [58]. The correlation between soil moisture and FRB changes at different soil depths [58]. At the depth of 10–20 cm, a sharp decline in soil moisture is noted, and the correlation of soil moisture and FRB of the 1–2 mm sub-class was not significant, suggesting that moisture was not the most important factor controlling FRB under low moisture conditions. This indirectly explained the reason why fine roots were more concentrated in the surface soil [18].

In this study, no significant differences were found in soil nutrients between thinned and control plots, but the nutrient content in the thinned plots was slightly lower, probably because the removal of vegetation increased soil erosion and decreased the organic matter content, thereby affecting other soil nutrients [62]. This result was in contrast to those of Serrasolses [63] and Zhang et al. [64].

Both N and P are essential elements for tree growth, and their contents in soil have been experimentally shown to have an important effect on the growth of roots [65]. A significant positive correlation was noted between TN and AP and the FRB (<1 mm) in the control and thinned plots. TK and AK were positively, but not significantly, correlated with the FRB. Taken together, these findings suggest that the seasonal dynamics of fine root (<1 mm) biomass was controlled by the combined effects of multiple soil nutrients. Consequently, the fine roots with a diameter <1 mm were more sensitive to environmental conditions and soil nutrient status in forest fields.

## 5. Conclusions

We found significant differences in the FRB of the same diameter sub-classes between the low-intensity thinned and control plots. Low-intensity thinning increased the fine root (<2 mm) biomass and produced a seasonal pattern of the FRB. In addition, it increased the FRB of the three diameter sub-classes in the vertical direction. Soil temperature, moisture, and nutrients were affected by low-intensity thinning. Significant differences in the soil temperature and moisture levels were noted between low-intensity thinned and control plots. Soil nutrient levels slightly decreased after low-intensity thinning, but no significant differences were observed between thinned and control plots. In addition, the fine roots with diameters <1 mm were more sensitive to environmental characteristics and soil nutrient status in forest fields. These results clearly indicate seasonal dynamics among fine roots of different diameters, explain the differences in important mechanisms of root dynamics after short-term low-intensity thinning, and improve our understanding of the mechanisms related to soil C fluxes and the quantification.

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