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Fine root biomass and production regarding root diameter in *Pinus densiflora* and *Quercus serrata* forests: Soil depth effects and the relationship with net primary production

Seung Hyun HAN[1,2], **Seongjun KIM**[1,3], **Hanna CHANG**[1,4], **Hyun-Jun KIM**[1,5], **Jiae AN**[1,3], **Yowhan SON**[1,*]
[1]Department of Environmental Science and Ecological Engineering, Graduate School, Korea University, Seoul, Republic of Korea
[2]Division of Restoration Strategy, Research Center for Endangered Species, National Institute of Ecology, Yeongyang, Republic of Korea
[3]Division of Restoration Research, Research Center for Endangered Species, National Institute of Ecology, Yeongyang, Republic of Korea
[4]Urban Forests Research Center, National Institute of Forest Science, Seoul, Republic of Korea
[5]Department of Forest Resources, College of Agriculture and Life Sciences, Chonnam National University, Gwangju, Republic of Korea

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Abstract: This study aimed to examine the effects of soil depth on fine root biomass (FRB) and production (FRP), and determine the relationship between FRP and net primary production (NPP) across two root diameter classes (<1 and 1–2 mm) in *Pinus densiflora* and *Quercus serrata* forests. FRB and FRP were investigated from April 2016 to March 2017 using the soil sequential coring and ingrowth core methods. In *P. densiflora* and *Q. serrata* forests, mean FRB < 1 mm (2.22 ± 0.23 and 2.63 ± 0.23 Mg ha^{-1}) and annual FRP < 1 mm (0.97 ± 0.09 and 1.55 ± 0.16 Mg ha^{-1} year^{-1}) were higher than mean FRB 1–2 mm (0.63 ± 0.12 and 1.72 ± 0.38 Mg ha^{-1}) and annual FRP 1–2 mm (0.26 ± 0.14 and 0.20 ± 0.06 Mg ha^{-1} year^{-1}) at 0–30 cm depth. Soil properties, such as soil moisture, organic matter, and inorganic nitrogen, decreased with soil depth (0–30 cm). The gradient of soil properties corresponding with soil depth could directly and indirectly influence FRP <1 mm, resulting in higher FRB <1 mm and FRP <1 mm at topsoil (0–10 cm). Additionally, only FRP <1 mm showed significant relationships with NPP and litter production. Although very fine roots (<1 mm in diameter) occupied a small percentage of NPP (7.5%), they may be an important factor for predicting forest NPP, since NPP would be regulated by the capability of roots to absorb water and nutrients. Our findings indicate that finer roots are more sensitive to soil conditions than thicker roots, and they could be a forest productivity indicator.

Key words: Environmental condition, productivity indicator, soil depth, very fine root

1. Introduction

Fine roots are generally categorized as roots less than 2 mm in diameter (Strand et al., 2008), and their production accounts for 4–70% of the total net primary production (NPP) in temperate forests (Vogt, 1991). In addition, fine root dynamics might be associated with patterns of the above-ground physiological processes and changes in litter production (Block et al., 2006; Satomura et al., 2006). The positive relationships of fine root production (FRP) with NPP and above-ground litter production have been reported in temperate forest ecosystems (Newman et al., 2006; Van Do et al., 2015; An et al., 2017).

Fine root dynamics, such as fine root biomass (FRB), FRP, and turnover rate, are affected by the soil's environmental conditions. In general, soil physical properties (bulk density and clay content), soil chemical properties (soil organic matter and inorganic nitrogen), and soil microclimate (soil temperature and moisture) directly and indirectly affect fine root dynamics (Joslin et al., 2006; Quan et al., 2010; Finér et al., 2011). Cai et al. (2019) found that FRB and turnover rate were reduced by increasing soil nitrogen availability in forest ecosystems. In the metaanalysis, FRB, FRP, and turnover rate were controlled by air temperature, precipitation, soil nitrogen concentration, and soil phosphorus concentration in forest ecosystems globally (Yuan and Chen, 2010; Finér et al., 2011). In particular, soil microclimate and soil chemical properties showed differences along the soil depth, because topsoil is directly affected by climate and above-ground activity such as litterfall (An et al., 2017). These soil environmental conditions can differentiate FRB and FRP along the soil depth gradients (Makita et al., 2011). In previous studies, FRB and FRP at topsoil occupied over 50% of the total biomass and production in temperate forests (Noguchi et al., 2005; Han et al., 2006).

Approximately 90% of previous studies about fine root dynamics were conducted on roots defined as 0–2 mm in diameter (Finér et al., 2011). However, fine roots may

* Correspondence: yson@korea.ac.kr

show functional differences with root diameter and root branch order (Guo et al., 2008b; Makita et al., 2011). The functions of fine roots are divided into the absorption of water and nutrients, and the transport capacity according to the root diameter and root branch order (de Kroon and Visser, 2003; Makita et al., 2011). Very fine roots and lower-order roots were characterized by fast metabolic activities (Makita et al., 2011). Water and nutrient absorption mainly occurs in very fine roots defined as <1 mm diameter (Strand et al., 2008). Also, very fine roots were sensitive to status of soil resources such as water and nutrients because of vulnerability to soil environmental conditions (Konôpka et al., 2013). As a result, biomass, production, and turnover rate of very fine roots are more susceptible to respond to the changing soil environment compared to those of fine roots (<2 mm) (Joslin et al., 2006; Guo et al., 2008a). Because of this, studies on more detailed diameter classification of fine roots such as less than 0.5 mm or 1 mm are necessary (Finér et al., 2011; Mucha et al., 2019). Many previous studies have focused on the changes in root morphology and nutrient content according to the functional difference. Very fine roots showed high potential for nutrient and water uptake, and mycorrhizal colonization (Guo et al., 2008b; McCormack et al., 2015), resulting in changes in root morphology, such as specific root length and thickness (Guo et al., 2008b; Makita et al., 2011). Doi et al. (2017) found that root morphological traits directly correlated with root nutrient content such as inorganic nitrogen and carbon. However, as yet there have been few studies on the relationships between fine root dynamics (according to root diameter) and surrounding soil conditions in response to soil depth and NPP (An et al., 2017; Doi et al., 2017).

Pinus densiflora (pine) are widely used as timber or fuel (Lee et al., 2017) and *Quercus* spp. (oak) are usually utilized as logs for mushroom cultivation (Lee et al., 2018). Pine and oak are important in forest ecosystem research since these species occupy more than 24.7% and 15.4% of South Korean forest area, respectively (Korea Forest Service, 2018). This study aimed (1) to examine the effect of soil depth on FRB and FRP, and (2) to determine the relationship between FRP and NPP in *P. densiflora* and *Q. serrata* forests. These relationships were evaluated according to root diameter (<1 mm and 1–2 mm). Our primary hypothesis was that biomass and production of very fine root (<1 mm) would decline with soil depth as being more closely related to the soil environmental conditions than those of fine roots (1–2 mm). Secondly, we hypothesized very fine root (<1 mm) production would be more closely related to NPP than fine root (1–2 mm) production, since they play an important role in absorption of water and nutrients which directly influences plant growth as well as above-ground activities.

2. Materials and methods

2.1. Study site

This study was conducted in *P. densiflora* (37°47′01″N, 127°10′37″E, 420 m asl) and *Q. serrata* forests (37°46′39″N, 127°11′08″E, 370 m asl) in the Gwangneung Experimental Forest (GEF), central Korea. The mean annual air temperature and precipitation in GEF were 11.2 °C and 1503.0 mm, respectively, from 1981 to 2010 (Korea Meteorological Administration 2011). The soil of both forests is classified as a slightly dry brown forest soil (mostly Inceptisols, United States Soil Classification System). *P. densiflora* and *Q. serrata* forests had similar stand ages (75 and 85 years), while they differed in aspect (SW 260° and NW 320°) and soil texture (sandy clay loam and loam). Detailed characteristics of the two study forests are described in Table 1. Three 20 m × 20 m plots were established in each forest for the study.

2.2. Fine root biomass

FRB was estimated using the soil sequential coring method with a soil corer (diameter: 7.2 cm, length: 10 cm, volume: 407 cm^3). Three soil sampling points were randomly designated in each plot, and soil from each point was sampled four times, on April 8, August 5, and December 9, 2016, as well as March 27, 2017. Soil sampling was conducted at equal intervals for a year to consider seasonal changes. Soil was separately collected at 0–10, 10–20, and 20–30 cm depths, and individually sealed in zipper bags. Woody roots of dominant species and others in each soil sample were collected, separated from understory plants, sorted by root diameter (<1 and 1–2 mm), and carefully washed. These roots were oven-dried to a constant mass at 65 °C to weigh biomass.

2.3. Fine root production

FRP was estimated by the ingrowth core method using a stainless steel mesh cylinder (diameter: 5 cm, length: 35 cm, pore size: 5 mm). On April 6, 2016, 18 ingrowth cores (2 species × 3 plots × 3 points × 1 collection times) were established by digging a hole (30 cm depth) using an auger (approximately 5 cm in diameter), and then filling the hole with root-free soil collected near the site. The upper section of the cores, which remained above the soil surface (about 5 cm), was covered by litter to correspond with the environmental conditions of the surrounding areas. Three points of establishing ingrowth cores were designated in each plot in coordination with the soil core sampling points, and three ingrowth cores in each plot were collected on March 27, 2017. Ingrowth cores were divided into three soil depths (0–10, 10–20, and 20–30 cm). Woody roots of dominant species and others were separated from understory plants, sorted by root diameter (<1 and 1–2 mm) in each soil sample, and carefully washed. Roots were oven-dried to a constant mass at 65 °C.

Table 1. Site characteristics of *Pinus densiflora* and *Quercus serrata* forests in central Korea.

	P. densiflora	*Q. serrata*
Location	37°47′01″N, 127°10′37″E	37°46′39″N, 127°11′08″E
Altitude (m)	410–420	360–370
Aspect (°)	SW 260	NW 320
Stand age (year)	70–80	80–90
Stand density (trees ha^{-1})	933	741
Mean DBH (cm)	34	41
Understory vegetation	*Q. mongolica, Q. variabilis, Carpinus laxiflora,* and *Styrax obassia*	*Q. serrata*, *C. cordata*, *C. laxiflora*, *S. obassia*, and *Acer pseudosieboldianum*

2.4. Soil moisture, organic matter, and inorganic nitrogen

In April 2016, soil samples at 0–10, 10–20, and 20–30 cm depths were collected from three points in each plot using a coring method. Plant materials >2 mm were removed using a sieve with a 2 mm mesh. Soil moisture was estimated gravimetrically after oven-drying the fresh soil at 105 °C. Soil organic matter (SOM) was estimated after soil samples were air-dried and sieved with a 2 mm mesh using the 0.167 M $K_2Cr_2O_7$ solution (Walkley and Black, 1934) and a factor (1.724) to convert soil organic carbon to SOM (Hudson, 1994).

For the analysis of inorganic nitrogen (NH_4^+ and NO_3^-), mineral soil was collected at 0–10, 10–20, and 20–30 cm depths from five points in each plot during the growing season (August 2017). The soil was sampled after removing the litter and humus layers. Each soil sample was individually sealed in a zipper bag and stored at 4 °C until analyses. Plant materials >2 mm were removed using a sieve with a 2 mm mesh. Inorganic soil nitrogen was extracted with 30 mL of 2 M KCl solution from 6 g of fresh soil and was quantified using the colorimetric methods (Miranda et al., 2001; Mulvaney, 1996).

2.5. Net primary production

NPP was calculated as the sum of the above- and below-ground biomass increments, litter production, and FRP. Above- and below-ground biomass increments were calculated using the allometric growth equation from the DBH measured in April 2016 and April 2017. All allometric growth equations which were developed for pine and oak in South Korea were referred to the Korea Forest Research Institute (2014). These equations were in the form of ‘$y = a*(DBH)^b$’. To estimate the above-ground litter production, five litter traps (0.25 m^2) were established in each plot in April 2016. Litter production was collected 3 times when the soil sequential coring was conducted. The collected litterfall was oven-dried to a constant mass at 65 °C and weighed. Annual litter production was determined as the sum of litterfall over the year.

2.6. Statistical analysis

All data, except for soil NH_4^+ and NO_3^-, were normalized by log-transformation prior to statistical analysis. A three-way ANOVA was used to test the effects of species, root diameter, and soil depth on FRB and FRP (n = 3). Tukey’s HSD test was used to determine differences in FRB and FRP within each root diameter class among the soil depths and in soil properties such as SM, SOM, NH_4^+, and NO_3^- among the soil depths in each forest. Pearson correlation analysis was performed to determine the relationship among the soil properties, FRB, and FRP for each soil depth (n = 18). Relationships between NPP and FRP or litter production and between FRP and litter production were tested with linear regression analysis (n = 6). All statistical analyses were conducted with SAS 9.4 (SAS systems, Cary, NC, USA) at the significance level of P = 0.05.

3. Results

3.1. Fine root biomass

Mean FRB significantly differed by species, root diameter, and soil depth during the study period (Table 2). There was a significant interaction between root diameter and soil depth. In *P. densiflora* and *Q. serrata* forests, mean FRB <1 mm (2.22 ± 0.23 and 2.63 ± 0.23 Mg ha^{-1}) was higher than mean FRB 1–2 mm (0.63 ± 0.12 and 1.72 ± 0.38 Mg ha^{-1}) at 0–30 cm soil depth (Figures 1a and 1b). Additionally, mean FRB <1 mm significantly decreased with soil depth, while mean FRB 1–2 mm showed no significant difference among the soil depths (Figures 1a and 1b). Mean FRB <1 mm at 0–10 cm soil depth accounted for 61.6% and 58.2% of FRB <1 mm at 0–30 cm soil depth for *P. densiflora* and *Q. serrata* forests, respectively.

3.2. Fine root production

Annual FRP differed by species, root diameter, and soil depth, and there were also significant interactions between soil depth and the species and root diameter in *P. densiflora* and *Q. serrata* forests (Table 2). In *P. densiflora* and *Q. serrata* forests, annual FRP <1 mm (0.97 ± 0.09 and

Table 2. F ratios of a three-way ANOVA for the effects of species, root diameter, and soil depth on the mean fine root biomass and annual fine root production for *Pinus densiflora* and *Quercus serrata* forests in central Korea.

	Df	Fine root biomass	Fine root production
Species (S)	1	12.8**	6.3*
Diameter (DI)	1	35.6****	24.7****
Depth (DE)	2	34.9****	101.1****
S × DI	1	2.7	0.4
S × DE	2	0.6	9.5**
DI × DE	2	12.2***	13.2***
S × DI × DE	2	1.3	1.1

* P< 0.05; ** P< 0.01; *** P< 0.001; **** P< 0.0001;

1.55 ± 0.16 Mg ha^{-1} year^{-1}) was higher than annual FRP 1–2 mm (0.26 ± 0.14 and 0.20 ± 0.06 Mg ha^{-1} year^{-1}), and there was a significant difference only in annual FRP <1 mm with soil depth (Figures 1c and 1d). Mean FRP <1 mm and FRP 1–2 mm at 0–10 cm soil depth accounted for 58.0 and 53.2% for the *P. densiflora* forest and 53.3 and 40.6% for the *Q. serrata* forest, respectively.

3.3. Relationship between fine root production and soil properties

Changes in soil properties with soil depth are shown in Table 3. The soil moisture, SOM, and NO_3^- concentration decreased with soil depth in *P. densiflora* and *Q. serrata* forests (Table 3). In particular, the effect of soil depth on SOM was significant in both forests, but effects on the soil moisture and NO_3^- concentration were significant only in the *Q. serrata* forest (Table 3). The SOM and NO_3^- concentration at 0–10 cm soil depth were higher than other soil depths, with values of 3.6% and 8.5 mg kg^{-1} for

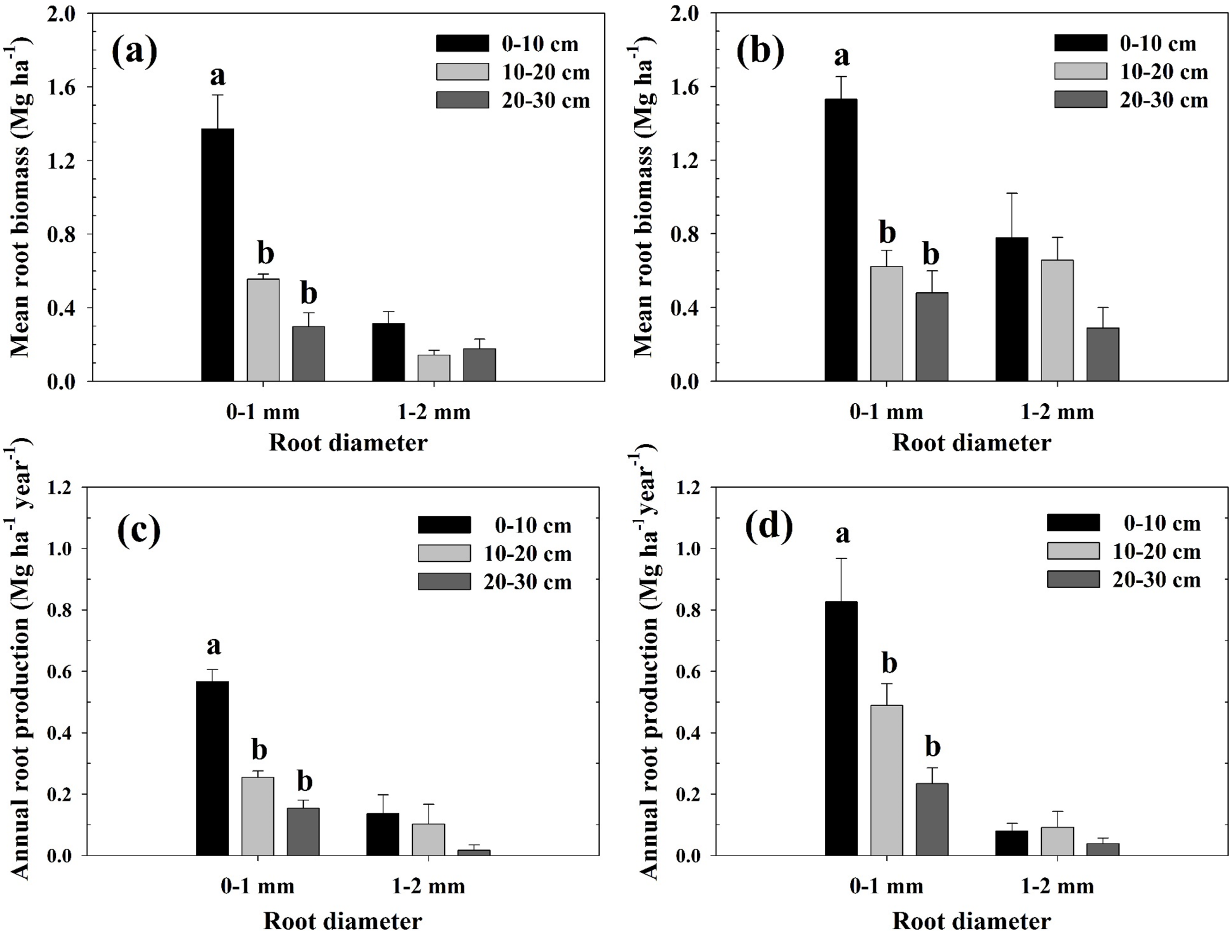

Figure 1. Mean fine root biomass for (a) *Pinus densiflora* and (b) *Quercus serrata* forests and the annual fine root production for (c) *Pinus densiflora* and (d) *Quercus serrata* forests in central Korea. Vertical bars indicate standard error of the mean (n = 3). Values followed by a different letter are significantly different within each root diameter class.

the *P. densiflora* forest and 4.3% and 11.2 mg kg^{-1} for the *Q. serrata* forest, respectively. NH_4^+ concentration did not show a significant difference among the soil depths.

Annual FRP < 1 mm was significantly related to soil moisture (R = 0.52), SOM (R = 0.59), NH_4^+ (R = 0.54), and NO_3^- concentration (R = 0.78), it was also highly correlated with FRB < 1 mm and FRP 1–2 mm (Table 4). However, annual FRP 1–2 mm did not show a significant relationship with soil properties or FRB (Table 4).

3.4. Relationship between fine root production and net primary production

In *P. densiflora* and *Q. serrata* forests, NPP (Mg ha^{-1} $year^{-1}$) was 13.01 ± 1.51 and 20.65 ± 0.93, respectively, and FRP < 1 mm occupied 7.5% of the NPP in both forests (Table 5). There was a significant linear relationship between NPP and either FRP < 1 mm ($P < 0.01$ and $R^2 = 0.91$; Figure 2a) or litter production ($P = 0.01$ and $R^2 = 0.84$; Figure 2c) across the forests. On the other hand, there was no significant relationship between NPP and FRP 1–2 mm ($P > 0.05$; Figure 2b). Also, litter production showed a significant linear relationship with FRP < 1 mm ($P < 0.05$; Figure 2d), but not with FRP 1–2 mm ($P > 0.05$).

4. Discussion

Mean FRB and annual FRP peaked at the topsoil (0–10 cm depth) in both *P. densiflora* and *Q. serrata* forests. These patterns, influenced by soil depth, coincided with previous studies conducted in temperate forests (Noguchi et al., 2005; Han et al., 2016; An et al., 2017). The gradient in soil properties among the soil depths was closely related to FRB and FRP (Table 4). In particular, FRB and FRP strongly reflect soil water and nutrient availability (Noguchi et al., 2005; Makita et al., 2011; Han et al., 2016). Above all, nitrogen availability is an important factor regulating root dynamics such as biomass, production, mortality, and turnover rate (Aber et al., 1985; Yuan and Chen, 2010). Fast decomposition of SOM and the nitrogen input from precipitation could induce the higher nitrogen

Table 3. Soil moisture (SM), soil organic matter (SOM), and concentrations of NH_4^+ and NO_3^- for *Pinus densiflora* and *Quercus serrata* forests in central Korea, expressed as the mean value ± standard error. Different letters for each species indicate significant differences among the soil depths (Tukey's HSD test; n = 3).

	Soil depth (cm)	SM (vol %)	SOM (%)	NH_4^+ (mg kg^{-1})	NO_3^- (mg kg^{-1})
P. densiflora	0–10	20.9 ± 1.0	3.6 ± 0.3a	1.2 ± 0.3	8.5 ± 1.3
	10–20	20.7 ± 1.1	2.7 ± 0.6b	1.5 ± 0.5	7.4 ± 1.0
	20–30	19.2 ± 0.4	1.5 ± 0.1c	0.7 ± 0.1	7.1 ± 0.7
Q. serrata	0–10	33.3 ± 0.2a	4.3 ± 0.0a	3.0 ± 1.0	11.2 ± 1.1a
	10–20	31.0 ± 0.9ab	4.2 ± 0.1a	2.9 ± 1.0	8.9 ± 0.9ab
	20–30	30.5 ± 0.6b	4.1 ± 0.2b	1.4 ± 0.6	7.9 ± 0.3b

Table 4. Pearson correlation coefficients between annual fine root production and soil moisture, soil organic matter, NH_4^+ and NO_3^- concentrations, and fine root biomass at 0–30 cm soil depths (n = 18).

	FRP < 1 mm	FRP 1–2 mm	FRP = 0–2 mm
Soil moisture	0.52*	0.05	0.47*
Soil organic matter	0.59**	0.42	0.63**
NH_4^+ concentration	0.54*	0.04	0.48*
NO_3^- concentration	0.78****	0.39	0.78****
FRB < 1 mm	0.80****	0.30	0.77***
FRB 1–2 mm	0.73***	–0.02	0.63**

FRP t mm: fine root (defined as t mm diameter) production; FRB t mm: fine root (defined as t mm diameter) biomass;
* P < 0.05; ** P < 0.01; *** P < 0.001; **** P < 0.0001.

Table 5. Net primary production (NPP) including biomass increment, litter production, and fine root production for *Pinus densiflora* and *Quercus serrata* forests in central Korea, expressed as mean value ± standard error (n = 3).

		P. densiflora		*Q. serrata*	
		Production (Mg ha^{-1} year^{-1})	Portion (%)	Production (Mg ha^{-1} year^{-1})	Portion (%)
Biomass increment					
Above-ground	Dominant	2.82 ± 0.50	21.7	9.80 ± 0.70	47.5
	Others	1.43 ± 0.37	11.0	0.69 ± 0.01	3.3
Belowground	Dominant	0.68 ± 0.12	5.2	0.95 ± 0.08	4.6
	Others	0.50 ± 0.22	3.8	0.26 ± 0.05	1.3
Subtotal		5.44 ± 1.17	41.8	11.70 ± 0.77	56.7
Litter production		6.34 ± 0.13	48.7	7.19 ± 0.12	34.8
ANPP[1]		10.60 ± 0.99	81.5	17.69 ± 0.64	85.7
FRP	<1mm	0.97 ± 0.09	7.5	1.55 ± 0.16	7.5
	1–2 mm	0.26 ± 0.14	2.0	0.20 ± 0.06	1.0
	Subtotal	1.23 ± 0.22	9.5	1.75 ± 0.22	8.5
NPP[2]		13.01 ± 1.51	100.0	20.65 ± 0.93	100.0

[1]ANPP (above-ground net primary production) = Biomass increment of above-ground + litter production.
[2]NPP (net primary production) = Biomass increment + litter production + FRP (fine root production).

deposition at the topsoil. FRB and FRP at the topsoil would be higher than those at the subsoil, as the carbon allocation to fine roots is closely related to soil nitrogen availability (Nadelhoffer et al., 2000). Furthermore, soil water availability could affect fine root dynamics indirectly by influencing nutrient uptake as well as water uptake of fine roots (Quan et al., 2010). Meanwhile, depth patterns of FRB and FRP were different according to root diameter. FRB < 1 mm and FRP < 1 mm were higher at 0–10 cm depth, while FRB 1–2 mm and FRP 1–2 mm showed no tendencies with soil depth. It appears that only very fine roots were directly affected by soil properties with soil depth, and these results support the first hypothesis. Very fine roots, which conduct the absorption of water and nutrients, have a more pronounced trend compared with the thicker roots, according to the gradient in the soil environmental conditions with soil depth (Makita et al., 2011). Konôpka et al. (2013) have shown that very fine roots (<1 mm) are not fully developed (not yet suberized); thus, are more sensitive to soil water availability than fine roots (<2 mm).

Our findings support the second hypothesis that very fine root production (FRP < 1 mm) shows positive correlations with NPP, but not FRP 1–2 mm (Figure 2). It seemed that NPP was regulated by the capability to absorb soil water and nutrients (Tateno et al., 2004). In general, carbon allocation to fine roots and litter production accounts for a larger proportion of annual NPP in more productive forests (An et al., 2017), and both have a positive correlation (Hendricks and Pregitzer, 1993; Van Do et al., 2015). Higher litterfall could indicate an increase in nutrient input to soils over the long-term in mature forests (Nadelhoffer et al., 1985). The increase in soil nutrients, due to rapid decomposition of SOM, at the topsoil would cause an increase in very fine root production (Han et al., 2019). In this study, although very fine roots occupied a small portion of the NPP (7.5%) compared to litter production (41.8%), very fine roots showed a stronger correlation with NPP than litter production. These results support the notion that very fine roots may be an indicator for estimating the NPP in forests as well as litter production (An et al., 2017). However, our findings can be misinterpreted because of the small number of replicates. To precisely understand and determine the below-ground carbon dynamics, the relationships between fine root dynamics with root diameter and environmental conditions should be determined at multiple sites with varying ranges of soil water and nutrient availabilities (Newman et al., 2006).

Only very fine roots showed a significant difference in the root distribution with soil depth and a significant positive relationship with soil properties. Also, it was found that carbon allocation to very fine roots (<1 mm) could be a predictable factor in NPP and litter production contrary to carbon allocation to fine root (1–2 mm) (Figure 2). In many previous studies, FRP (in general, defined as <2 mm diameter) would be affected by soil

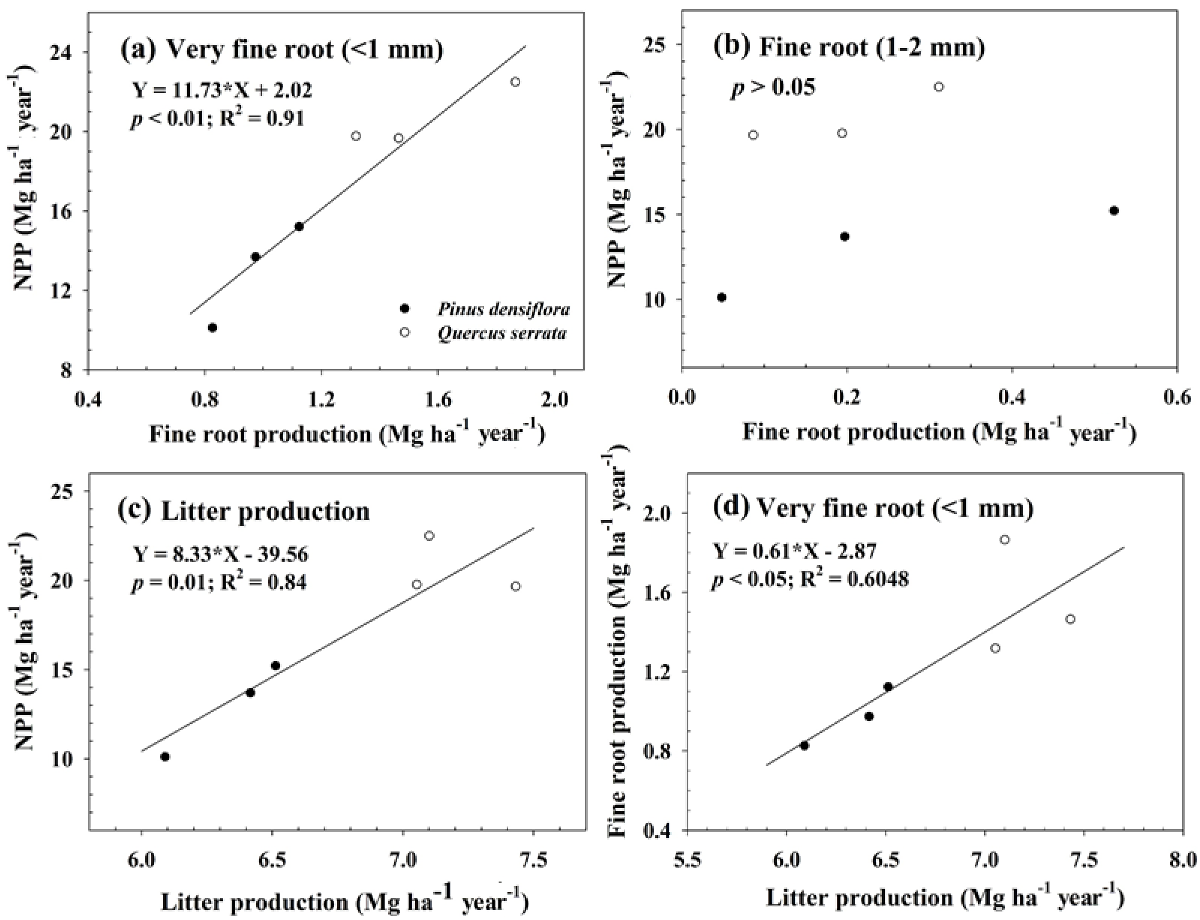

Figure 2. Linear regressions between net primary production (NPP) and (a) very fine root production (<1 mm), (b) fine root production (1–2 mm), and (c) litter production and (d) between very fine root production (<1 mm) and litter production for *Pinus densiflora* and *Quercus serrata* forests in central Korea.

water availability (Newman et al., 2006; Han et al., 2018), soil nutrient availability (Park et al., 2008), NPP, and litter production (Van Do et al., 2015; An et al., 2017). Based on our findings, these results may be a consequence of the fact that very fine roots account for a large proportion of FRB and FRP. Functional divergence among root branch orders or root diameters could cause the differences in nutrient content, uptake capacity, transport capacity, mycorrhizal colonization, and life span (McCormack et al., 2015). The more distal or finer roots, with a faster turnover rate, were more sensitive to environmental variations than relatively thicker roots (Konôpka et al., 2013). The turnover rate of very fine roots was 1.8 times higher than that of fine roots (1–2 mm) in this study (data not shown).

Roots of both species were classified using the same criteria based on their diameter in this study. Recent studies reported that the same root diameter of evergreen-conifers and deciduous hardwoods shows different morphological traits of roots, resulting in different root functions, such as absorption and transport (McCormack et al., 2015; Gu et al., 2017). In contrast to the previous results, our findings show that fine root dynamics and their patterns with soil depth do not vary between two species. However, it is also needed to classify the roots based on root branch order in addition to root diameter, since each species has different root morphological characteristics (Guo et al., 2008b; Gu et al., 2017).

5. Conclusion

The present study shows that the trends in the FRB and FRP with soil depth and the relationship between FRP and NPP were different according to root diameter. Very fine roots occupy a large proportion of FRB and FRP, and they are more sensitive to changes in environmental conditions because of functional divergence among the root diameters. Overall, the findings of the current study support the theory that functional difference regarding root diameter is an important factor in determining the carbon cycling of below-ground and NPP in forest ecosystems.

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