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Variations of fine root diameter with root order in Manchurian ash and Dahurian larch plantations

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Abstract Fine root lifespan and turnover play an important role in carbon allocation and nutrient cycling in forest ecosystems. Fine roots are typically defined as less than 1 or 2 mm in diameter. However, when categorizing roots by this diameter size, the position of an individual root on the complex lateral branching pattern has often been ignored, and our knowledge about relationships between branching order and root function thus remains limited. More recently, studies on root survivals found that longevity was remarkably different in the same branching level due to diameter variations. The objectives of this study were: (1) To examine variations of fine root diameter from the first- to fifth-orders in *Fraxinus mandshurica* Rupr and *Larix gmelinii* Rupr roots; and (2) To reveal how the season, soil nutrient, and water availability affect root diameter in different branch order in two species. This study was conducted at Maoershan Forest Research Station (45°21′–45°25′ N, 127°30′–127°34′ E) owned by Northeast Forestry University in Harbin, northeast China. Both *F. mandshurica* and *L. gmelinii* were planted in 1986. In each plantation, fine roots of two species by sampling up to five fine root branch orders three times during the 2003 growing season from two soil depths (i.e., 0–10 and 10–20 cm) were obtained. The results showed that average diameters of fine roots were significantly different among the five branch orders. The first-order had the thinner roots and the fifth order had the thickest roots, the diameter increasing regularly with the ascending branch orders in both species. If the diameter of fine roots was defined as being smaller than 0.5 mm, the first

three orders of *F. mandshurica* roots and the first two orders of *L. gmelinii* roots would be included in the fine root population. The diameter ranges of the fine roots from first-order to fifth-order were 0.15–0.58, 0.18–0.70, 0.26–1.05, 0.36–1.43, and 0.71–2.96 mm for *F. mandshurica*, and 0.17–0.76, 0.23–1.02, 0.26–1.10, 0.38–1.77, and 0.84–2.80 mm for *L. gmelinii*. The average coefficient of variation in first-order roots was less than 10%, second- and third-order was 10–20%, and fourth- and fifth-order was 20–30%. Thus, variation in root diameter also increased with the ascending root order. These results suggest that “fine roots”, which are traditionally defined as an arbitrary diameter class (i.e., <2 mm in diameter) may be too large a size class when compared with the finest roots. The finest roots have much shorter lifespan than larger diameter roots; however, the larger roots are still considered a component of the fine root system. Differences in the lifespan between root diameter and root order affect estimates of root turnover. Therefore, based on this study, it has been concluded that both diameter and branch order should be considered in the estimation of root lifespan and turnover.

Keywords fine root diameter, root order, lifespan, turnover, *Fraxinus mandshurica*, *Larix gmelinii*

1 Introduction

Fine root (≤ 2 mm in diameter) production and turnover play a key role in carbon allocation and nutrient cycling in forest ecosystems (Fahey and Hughes, 1994; Eissenstat and Yanai, 1997; Gill and Jackson, 2000). In previous studies, roots less than 1 or 2 mm in diameter were considered as fine roots. However, this diameter class approach neglected the position of fine roots on the complex lateral branching system (i.e. root branching order), so the accuracy of estimating fine root lifespan and turnover was limited (Pregitzer et al., 1997). Pregitzer et al. (1997, 2002) and Wells et al. (2002) reported that fine root longevity within the diameter ≤ 2 mm was remarkably different due to the heterogeneity of root branching position in root networks.

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The primary function of the first-order roots at the distal end of the root system was to absorb water and nutrients from the soil, which has important morphological and physiological properties, such as thinner diameter, higher N concentration, lower lignification level, and a shorter lifespan; however, the higher order roots were thicker in diameter with higher lignification level, and mainly had a function of transportation and longer lifespan (Eissenstat and Yanai, 2002; Mei et al., 2004). For example, Wells et al. (2002) reported in *Prunus persica* (Rosaceae) that the average median lifespan of the first-order roots (mean diameter: 0.33 mm) was 100 days, and that of the higher order roots (mean diameter: 0.47 mm) was 242 days. Obviously, the differences in fine root lifespan estimated were mainly caused by variation of root diameter size and branching order (Eissenstat and Yanai, 2002). Therefore, the relationship between root order and root lifespan had been recognized as a key in the study of the fine root turnover mechanism (Wells and Eissenstat, 2003), and was a great challenge in estimating fine root turnover in the traditional approach based on diameter size.

Root branching was the most primary characteristic in root system (Fitter and Stickland, 1992) and linkage root functions, which represented the various developmental stages in root system. Because the spatial heterogeneity of soil water and nutrients might result in plasticity in root architecture, morphology, and function, root diameter could exhibit great variations even within the same root order (Pregitzer et al., 1997; Guo et al., 2004); yet the diameter variations among the root orders was still unclear and the integrative effect of diameter and root order on root longevity was poorly understood. The objectives of this study were: (1) To examine variations of fine root diameter from the first- to fifth-order in *Fraxinus mandshurica* Rupr and *Larix gmelinii* Rupr roots; and (2) To reveal how the soil nutrient and water availability affect root diameter in different branch orders in two species.

2 Materials and methods

2.1 Study site

This study was carried out at Maoershan Forest Research Station (45°21′–45°25′ N, 127°30′–127°34′ E) of Northeast Forestry University, in Heilongjiang, north China. The study area has a continental temperate monsoon climate with mean January, July, and annual temperatures of –19.6°C, 20.9°C and 2.8°C respectively. The mean annual precipitation is 723 mm with 477 mm distributed in June, July, and August. The accumulated temperature $\geq 10^\circ\text{C}$ amounts to 2,526°C. The length of growing season ranges from 120 to 140 days. Soils are Hap-Boric Luvisols that exceeds 50 cm in depth and with high a content of organic matters, have well-developed horizons, and are well drained. Two plantations, *L. gmelinii* and *F. mandshurica*, were selected on a southwest-facing slope of approximately 13 degrees, with an elevation ranging

from 450 to 500 m above the sea level. Both plantations were established in 1986 by planting two-year-old seedlings using a 1.5 m \times 2.0 m planting grid. Three 20 m \times 30 m plots were randomly placed in each plantation in May 2002.

2.2 Root and soil sampling

Root sampling was conducted on May 15th, July 15th, and September 15th of 2003. On each sampling date, three (*F. mandshurica*) and four (*L. gmelinii*) subplots were randomly located within each of the three plots established in *L. gmelinii* and *F. mandshurica* plantation, respectively. At each subplot, intact root networks consisting of more than five branch orders were sampled at two depths (0–10 cm and 10–20 cm), following the procedure described in Pregitzer et al. (2002). Thus, a total of 18 and 24 soil blocks (20 cm (W) \times 20 cm (L) \times 10 cm (D)) were excavated for each species. Once excavated, the intact soil blocks were put on plastic cloth, the intact fine roots were very carefully picked up, numbered, and cased in a plastic bag and placed in a cooler on ice and transported to the lab within several hours and frozen for subsequent root processing. At the same time, soil sample (about 200 g) in each block was collected and cold-stored, and then carried back to the laboratory for chemical analysis. The soil temperature of about 5 cm and 15 cm depths were recorded at each sampling time.

2.3 Root processing and soil analysis

In the lab, large intact root branches and all root segments were carefully brushed and washed with deionized water (2–3°C) to clean attached soil particles, and then dissected following the procedure described in Pregitzer et al. (2002): the most distal root tips were labeled as the first-order, two first-order roots joined to form a second-order root, and two second-order roots joined to form a third-order root, and so on. Some, but not all soil blocks contained up to six root orders, and only the first five orders were studied in following analysis. The numbers of each order of fine roots were counted, and the diameter and length of each individual root were measured under a 10 \times stereomicroscope with an ocular micrometer (precision to 0.01 mm). Once dissected, all individual roots of a given order were oven-dried (70°C for 48 h), weighed (0.000, 1 g,) finely ground, and collected on the plot basis. Soil moisture and nutrients were analyzed according to the methods provided by Liu et al. (1996).

2.4 Data analysis

In this study, means of the sum of root number ranged from the first- to fifth-order of *F. mandshurica* in one block (20 cm \times 20 cm \times 10 cm) at each sampling time was 16,176 (soil depth: 0–10 cm) and 4,522 (soil depth: 10–20 cm), respectively; that of *L. gmelinii* was 4,900 (soil depth: 0–10 cm) and 1,249 (soil depth: 10–20 cm), respectively. Within the average root number, first-order roots accounted for 85%, and the second, third, fourth, and fifth accounted for 10%, 3%,

1.8%, and 0.2%, respectively. Then, means of diameter, coefficients of variation (CV) and minimum and maximum of diameter in each root order were calculated for both species in different seasons and depths. One-way analysis of variation (one-way ANOVA) was applied to test the difference between fine root diameter in the first five orders, and differences between two soil depths (0–10 cm and 10–20 cm) within a root order was noted. In addition, the effect of soil nutrients and soil water availability on the variation of fine root diameter was also examined.

3 Results

3.1 Mean diameter of each root order

For both species, average diameter of the first-order roots were the thinnest (0.26 mm for *F. mandshurica* and 0.34 mm for *L. gmelinii*), and the fifth-order roots were the thickest (1.54 mm for *F. mandshurica* and 1.70 mm for *L. gmelinii*). The average root diameters increased with the ascending root-order (Table 1), and their discrepancy of diameter from the first- to fifth-orders was about 4–5 folds. Even the narrowest definition of fine roots, that is, all roots <0.5 mm in diameter, encompassed at least three branch orders for *F. mandshurica* and two branch orders for *L. gmelinii*, and the first four-order roots was <1 mm in diameter for both species (excepting for *L. gmelinii* in depth of 10–20 cm sampled in May). There were significant differences among the five root orders ($P < 0.001$) and in two soil depths ($P < 0.001$) for root diameters. Average diameter of the first three order roots of *F. mandshurica* and the first-order roots of *L. gmelinii* in summer (July) were smaller than that in spring (May) and autumn (September), but the significant differences only yielded in the first-order roots ($P < 0.05$) in both species. In the higher order roots such as the fourth or fifth, average

diameter was the thickest in spring (May), and the thinnest in autumn (September). It was particularly noted that the root diameter substantially decreased by a proportion of one of four from the third- to second-order, and second to the first-order roots for both species across soil depths and seasons (Table 1).

3.2 Range of diameter within each root order

Despite the fact that the root diameter increased with the ascending root orders, the variation of diameter was greater in each branching levels (Table 2). Among the first four order roots, the low end of diameter range was <0.2 mm in diameter, and the high end of diameter range was over 1.9 mm, and the differences between the minimum and maximum was up to 3–4 folds. For both species, the diameter range of the first-order roots was 0.2–0.5 mm for *F. mandshurica* and 0.2–0.7 mm for *L. gmelinii*, respectively. The second- and third-order roots were 0.2–0.3 mm for the low end of diameter range, and less or equal 1 mm for the high end of diameter range. The variation of diameter within the fifth-order roots was 1–3 mm. Higher order roots had a greater variations than lower order roots (Table 3) and as such, the average of CV for diameter were less than 10% in the first, 10–15% in the second and third, and 20–30% for the fourth- and fifth-order roots (Table 3).

3.3 Effect of soil resource availability on root diameter

Soil temperature (excepting in September), moisture, and N availability in topsoil (0–10 cm) were significantly higher ($P < 0.05$) than those in deep soil (10–20 cm) in two species sites, especially soil available N concentration in topsoil was twice as much as in deep soil (Table 4). Higher soil resource availability in topsoil could benefit root growth and development. Average diameter in each branching level was different

Table 1 Average diameter of fine roots among the first five orders in *Fraxinus mandshurica* and *Larix gmelinii* plantations

Species	Month	Soil depth /cm	Mean diameters of fine roots				
			First-order	Second-order	Third-order	Fourth-order	Fifth-order
<i>Fraxinus mandshurica</i>	May	0–10	0.266 (0.005)	0.363 (0.020)	0.468 (0.018)	0.862 (0.051)	1.788 (0.106)
		10–20	0.269 (0.009)	0.349 (0.013)	0.493 (0.026)	0.930 (0.063)	2.317 (0.398)
	July	0–10	0.242 (0.006)	0.326 (0.025)	0.410 (0.020)	0.673 (0.045)	1.287 (0.108)
		10–20	0.245 (0.006)	0.337 (0.015)	0.417 (0.028)	0.663 (0.046)	1.408 (0.039)
	Sept	0–10	0.276 (0.008)	0.384 (0.010)	0.470 (0.019)	0.642 (0.025)	1.190 (0.026)
		10–20	0.277 (0.009)	0.376 (0.014)	0.461 (0.015)	0.645 (0.021)	1.290 (0.055)
	Mean	0–10	0.261 (0.006)	0.358 (0.019)	0.449 (0.019)	0.726 (0.040)	1.422 (0.087)
		10–20	0.264 (0.008)	0.354 (0.014)	0.457 (0.023)	0.746 (0.043)	1.672 (0.164)
<i>Larix gmelinii</i>	May	0–10	0.328 (0.008)	0.417 (0.018)	0.533 (0.020)	0.868 (0.047)	2.103 (0.206)
		10–20	0.330 (0.005)	0.430 (0.021)	0.659 (0.027)	1.029 (0.040)	2.105 (0.151)
	July	0–10	0.308 (0.005)	0.450 (0.017)	0.530 (0.027)	0.813 (0.045)	1.551 (0.104)
		10–20	0.312 (0.007)	0.434 (0.013)	0.576 (0.031)	0.965 (0.089)	1.759 (0.157)
	Sept	0–10	0.369 (0.007)	0.424 (0.009)	0.507 (0.015)	0.647 (0.025)	1.140 (0.051)
		10–20	0.389 (0.006)	0.467 (0.010)	0.597 (0.026)	0.831 (0.047)	1.559 (0.103)
	Mean	0–10	0.335 (0.007)	0.431 (0.015)	0.532 (0.020)	0.776 (0.039)	1.598 (0.120)
		10–20	0.344 (0.006)	0.443 (0.015)	0.610 (0.028)	0.942 (0.059)	1.808 (0.137)

Note: values in parentheses are standard errors.

Table 2 Diameter (mm) range (min-max) of fine roots among the first five orders in *Fraxinus mandshurica* and *Larix gmelinii* plantations

Species	Month	Soil depth /cm	Diameter range (min-max) among the first five orders				
			First-order	Second-order	Third-order	Fourth-order	Fifth-order
<i>Fraxinus mandshurica</i>	May	0–10	0.15–0.78	0.21–0.78	0.27–0.83	0.38–1.73	0.96–3.31
		10–20	0.19–0.47	0.19–0.66	0.27–0.94	0.43–1.51	1.30–4.16
	July	0–10	0.12–0.47	0.14–0.64	0.22–0.78	0.33–1.31	0.60–2.23
		10–20	0.14–0.47	0.15–0.67	0.22–1.37	0.32–1.37	0.62–2.46
	Sept	0–10	0.16–0.49	0.22–0.68	0.29–0.88	0.36–1.24	0.58–2.12
		10–20	0.15–0.49	0.20–0.69	0.32–0.84	0.39–1.46	0.64–2.27
Mean	0–10	0.15–0.58	0.19–0.70	0.26–0.83	0.36–1.43	0.71–2.56	
	10–20	0.16–0.48	0.18–0.67	0.27–1.05	0.38–1.45	0.85–2.96	
<i>Larix gmelinii</i>	May	0–10	0.18–0.65	0.17–1.10	0.24–1.07	0.42–1.55	1.13–3.29
		10–20	0.18–0.58	0.23–0.81	0.35–1.06	0.50–1.90	1.01–3.44
	July	0–10	0.19–0.81	0.25–1.17	0.26–1.01	0.40–1.56	0.84–2.52
		10–20	0.15–0.69	0.23–0.84	0.28–1.06	0.45–1.81	0.95–2.63
	Sept	0–10	0.17–0.82	0.26–0.77	0.27–0.95	0.33–1.25	0.54–2.10
		10–20	0.19–0.80	0.22–0.89	0.30–1.16	0.40–1.60	0.98–2.32
	Mean	0–10	0.18–0.76	0.23–1.02	0.26–1.01	0.38–1.45	0.84–2.64
		10–20	0.17–0.69	0.23–0.85	0.31–1.10	0.45–1.77	0.98–2.80

Table 3 Coefficients of variations in fine root diameters among the first five orders in *Fraxinus mandshurica* and *Larix gmelinii* plantations

Species	Month	Soil depth /cm	Coefficients of variations in fine root diameters				
			First-order	Second-order	Third-order	Fourth-order	Fifth-order
<i>Fraxinus mandshurica</i>	May	0–10	0.058	0.167	0.106	0.178	0.195
		10–20	0.104	0.108	0.157	0.204	0.515
	July	0–10	0.073	0.233	0.145	0.199	0.275
		10–20	0.074	0.129	0.201	0.208	0.082
	Sept	0–10	0.086	0.079	0.109	0.106	0.066
		10–20	0.095	0.101	0.097	0.099	0.128
Mean	0–10	0.072	0.159	0.127	0.165	0.179	
	10–20	0.091	0.106	0.152	0.170	0.242	
<i>Larix gmelinii</i>	May	0–10	0.084	0.150	0.128	0.188	0.338
		10–20	0.048	0.170	0.142	0.133	0.249
	July	0–10	0.056	0.130	0.176	0.193	0.233
		10–20	0.073	0.104	0.189	0.321	0.309
	Sept	0–10	0.047	0.138	0.184	0.242	0.316
		10–20	0.055	0.078	0.149	0.195	0.229
	Mean	0–10	0.062	0.139	0.163	0.208	0.296
		10–20	0.059	0.107	0.160	0.216	0.262

Table 4 Soil temperature, moisture, and nitrogen availability of different soil depths in *Fraxinus mandshurica* and *Larix gmelinii* plantations

Species	Month	Soil depth /cm	Soil temperature /°C	Soil moisture /%	Soil nitrogen content /(mg · kg ⁻¹)
<i>Fraxinus mandshurica</i>	May	0–10	9.93 (0.65) ^a	0.55 (0.02) ^a	24.69 (1.36) ^a
		10–20	8.87 (0.42) ^b	0.63 (0.01) ^b	10.39 (0.71) ^b
	July	0–10	16.95 (0.45) ^a	0.52 (0.01) ^a	26.75 (1.33) ^a
		10–20	16.01 (0.47) ^b	0.59 (0.02) ^b	12.57 (0.89) ^b
	Sept	0–10	10.05 (0.08) ^a	0.57 (0.01) ^a	18.99 (1.41) ^a
		10–20	10.50 (0.09) ^a	0.67 (0.01) ^b	9.81 (0.74) ^b
<i>Larix gmelinii</i>	May	0–10	8.43 (0.44) ^a	0.58 (0.01) ^a	21.38 (3.18) ^a
		10–20	7.73 (0.18) ^b	0.65 (0.01) ^b	13.15 (0.76) ^b
	July	0–10	17.10 (0.58) ^a	0.61 (0.06) ^a	21.05 (1.37) ^a
		10–20	16.25 (0.31) ^b	0.62 (0.01) ^a	10.33 (0.84) ^b
	Sept	0–10	9.85 (0.42) ^a	0.65 (0.01) ^a	18.88 (1.99) ^a
		10–20	10.13 (0.41) ^b	0.70 (0.01) ^b	10.64 (0.92) ^b

Note: values in parentheses are standard errors, a, b are shown significant differences, $P < 0.05$.

between two soil depths (Table 1), but not significant ($P > 0.05$), excepting for *L. gmelinii* roots in September ($P < 0.05$). Moreover, there were also no significant differences between the minimum and maximum diameters among the five order roots in both soil depths ($P > 0.05$). However, the diameter of individual roots had significant differences ($P < 0.001$), suggesting that the diameter of individual roots had a higher variation in soil.

4 Discussion

Diameter was recognized as a key parameter in root morphology, and different diameter size reflects different physiological function in root system (Fitter, 1996). In contrast to coarse roots, fine roots always had a higher N concentration (Pregitzer et al., 2002) and lower C content (Gordon and Jackson, 2000). Many previous studies found that on one hand, small diameter roots with a greater specific root length had a maximum efficiency in absorbing nutrients and water from soil, and had a lower construction cost and maintenance efforts (Eissenstat, 1992). On the other hand, coarse roots with a smaller specific root length (usually lignified) invested more C for root building, had a higher efficiency of transportation, and higher resistance to environmental stress, such as below-ground pathogens and herbivores (e.g. nematodes) (Eissenstat and Yanai, 1997; Forde and Lorenzo, 2001). However, the root diameter size and variations were affected by the spatial and temporal heterogeneity of soil resources availability, many roots would exhibit their diameter plasticity to adapt to different environmental conditions (Fitter, 1996; Eissenstat et al., 2000; Forde and Lorenzo, 2001). In this study, soil resource availability (e.g., soil temperature, available N) varied with soil depths (Table 4), diameter of the individual root was significantly different to each other in both *F. mandshurica* and *L. gmelinii* ($P < 0.001$), and the average diameter in topsoil (0–10 cm) was slightly, but not significantly thinner than that in deep soil (10–20 cm, $P > 0.05$, Table 1). From this study, we found that individual roots in root system had a greater plasticity in soil with a higher heterogeneity of resources availability than root population, alternatively, root system adapted to different soil conditions via individual root plasticity in root morphology (Eissenstat and Caldwell, 1988; Friend et al., 1990; Eissenstat, 1992; Wu et al., 2004).

Root function was reflected not only by diameter but mainly by branching order (Fitter, 1996; Pregitzer et al., 1997). Based on the root position of lateral branching networks, Pregitzer et al. (2002) studied the first three order roots of four hardwoods and five conifers species in north America, they found that the root diameter and C concentration increased but N concentration decreased with ascending root orders. Therefore, lower order roots appeared to die more easily than higher order roots (Pregitzer et al., 2002; Wells et al., 2002). In root branching networks, the aging sequence was perhaps reverse to root development stage (Burton et al.,

2000; Pregitzer et al., 1997, 2002), suggesting that a large error might be obtained in the estimation fine root turnover and longevity when using traditional diameter class approach (e.g. < 2 mm or 1 mm). This study for *L. gmelinii* and *F. mandshurica* roots showed that fine root pool would encompass the first five order roots in ≤ 2 mm diameter class (Table 1); however, these the first five order roots differed in their developmental stage, position of branching networks, and functions. In a specific diameter size, such as < 0.5 mm, the first three order roots in *F. mandshurica* and the first two order roots in *L. gmelinii* was to be sampled, when diameter was < 1 mm, the first four order roots could be yielded (Table 1). Root diameter increased with the ascending root orders in this study for both species. However, variations of average root diameter exhibited several folds among the five root orders, and as well as individual roots in the same order (Table 2). Particularly in this study, the diameter range was 0.2–0.7 mm in the first-order roots, 0.2–1 mm in the second-order roots, and 1–3 mm in the fifth-order roots, although in the same branching level, root life span could greatly differ. Wells et al. (2002) had studied fine root survivals of California peach (*Prunus persica*), and they found that median lifespan of the first-order roots ≤ 0.25 mm in diameter was 74 days, while that of roots 0.25–0.5 mm in diameter was 121 days, and that of the first-order roots > 0.5 mm in diameter was 213 days. Despite the fact that the same branching level was the same in root networks, the discrepancy of median root life span was three folds higher than expected. Therefore, there might be a large error in estimating fine root longevity and turnover if we only considered root order regardless root diameter (Tables 1 and 2).

While considering root developmental stage, root senescence processes and physiological functions, applying branch order in studying fine root turnover seemed to be more reasonable than applying diameter. However, it was too difficult to sample individual roots in branching networks, due to the huge individual roots in soil. In addition to separating each individual roots and determining its branching position one by one was impossible in forests. The question now was how to develop an integrative approach based on the diameter method and branch order method in root study? This study provided clear evidence that the root diameter substantially decreased with branch order descending (Tables 1 and 2), while the root diameter decreased to < 0.5 mm; Fine-root pool was composed of the first-three order roots for *F. mandshurica* or the first two order roots for *L. gmelinii*, the numbers, length, and biomass of the first-order roots would account for a predominant proportion in fine root pool sampled. Applying small diameter size (e.g., < 0.5 mm in diameter) to estimate fine root longevity and production, estimating errors of longevity and turnover might be substantially decreased. However, few studies had revealed the effects of integrative of fine root diameter and branch order on fine root longevity and turnover in forests. In a further root study, relationship between fine root diameter and branch order required attention.

5 Conclusions

Average root diameter of *F. mandshurica* and *L. gmelinii* increased with ascending branch order, fine roots <2 mm in diameter encompassed the first five order roots, and fine roots <0.5 mm in diameter also encompassed the first three order roots for *F. mandshurica* and the first two order roots for *L. gmelinii* in this study. There were greater variations of diameter in two species roots, the low end of diameter range was <0.2 mm, and the high end was 0.5 mm for *F. mandshurica* and 0.7 mm for *L. gmelinii* in the first-order roots. Average diameter range was 0.2–1 mm for the second- and third-order roots, and 1–2 mm or 3 mm for the fifth-order roots.

Coefficients of variation in diameter increased with the ascending branch order. Average of CV were less than 10% for the first-order roots, 10–15% for the second- and third-order roots, and 20–30% for the fourth and fifth-order roots, respectively. Soil temperature, moisture, and N availability in upper (0–10 cm) and lower (10–20 cm) soil depth had significant effect on the individual root diameters, rather than an average for a given specific branch order roots.

Fine-root life span was closely associated with fine-root diameter as well as branch order, suggesting that the thinner diameter would have a shorter life span. On the other hand, life span of the first-order roots would be shorter than that of higher order roots. Even within the same branching level, roots had different life span due to diameter variations. Therefore, both root diameter and branch order should be considered in estimating fine root longevity and turnover.

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