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Root inclusion net method: novel approach to determine fine root production and turnover in *Larix principis-rupprechtii* Mayr plantation in North China

Xiyang WANG[1], Lvyi MA[1,2,*], Zhongkui JIA[1], Liming JIA[1]
[1]Key Laboratory for Silviculture and Conservation, Beijing Forestry University, Beijing, P.R. China
[2]National Energy R&D Center for Non-Food Biomass, Beijing Forestry University, Beijing, P.R. China

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Abstract: A novel root inclusion net method was designed to determine the fine root productions and turnover rates of 13-, 22-, and 38-year-old *Larix principis-rupprechtii* plantations in the whole growing season of 2012, and it was compared with the results of the sequential coring method and in-growth core method. All following values are reported in order for 13-, 22-, and 38-year-old *L. principis-rupprechtii* plantations. The mean values of fine root biomasses were 103, 261, and 356 g m^{-2}, about 76–78% of which were live fine root biomasses. The fine root productions were 86–118 g m^{-2} $year^{-1}$, 124–138 g m^{-2} $year^{-1}$, and 134–160 g m^{-2} $year^{-1}$, respectively. The fine root turnover rates were 1.12, 0.61, and 0.51 times $year^{-1}$, respectively, suggesting a relative slow fine root turnover in *L. principis-rupprechtii* plantations. The carbon inputs into soil accompanying fine root turnover were 52, 58, and 94 g C m^{-2} $year^{-1}$. This organic carbon is a sizeable pool in the forest ecosystem. The results suggest that our new modified root inclusion net method is suitable for field-based assessment of fine root production and turnover.

Key words: Fine root turnover, plantation, root inclusion net method, soil organic carbon

1. Introduction

Fine root turnover is a major pathway where carbon enters into the underground ecosystem. A large part of the soil organic carbon pool may be derived from fine roots (Richter et al., 1999; Gill and Jackson, 2000). Fine roots are the most active part of the root system. Fine root biomass, which is about 3%–30% of the stand biomass (Vogt et al., 1981; Jackson et al., 1996; Jackson et al., 1997) in forest ecosystems, contributes to 33%–67% of annual primary productivity (Jackson et al., 1996; Brunner and Godbold, 2007; Godbold and Brunner, 2007). The nutrients and organic matter that enter into the soil through fine root turnover are an important source for soil carbon and carbon cycles. Forest fine root turnover occupies an important position in the energy and material cycles of the biosphere and plays an important role in soil resource utilization (Stewart and Frank, 2008). Fine roots play an important role in the global carbon cycle (Godbold et al., 2003; Jha and Mohapatra, 2010). On the one hand, the fine root provides a channel for the transport of carbon and energy from overground parts of the plants to the soil. Guo et al. (2008) and Xia et al. (2010) indicated that some fine roots can undergo secondary development, which is important for better understanding of soil carbon turnover. However, due to the rapid growth, short life cycle, and fast turnover, fine roots have an important impact on carbon allocation and nutrient cycling of below-ground ecosystems (Godbold et al., 2006; Sah et al., 2011). Thus, fine root production and turnover have a direct impact on biogeochemical cycles in terrestrial ecosystems (Lukac et al., 2003; Jha and Mohapatra, 2010). On the other hand, since the fine roots are used by plants to absorb water and nutrients to grow, they are the most important part of the plant root system (Brunner and Godbold, 2007; Godbold and Brunner, 2007). The fine root system, which is a major source of underground organic carbon, has important effects on the physical and chemical processes and biological properties of the soil (Jackson et al., 1997; Godbold et al., 2006; Lukac and Godbold, 2011). The quantity of organic carbon that enters the soil through fine root turnover is one to several times as much as that of litter (Vogt et al., 1981; Wallander, 2006). If the material cycle of fine root production, mortality, and decomposition is ignored, the nutrient turnover in the soil will be underestimated by 20%–80% (Vogt et al., 1995). To estimate fine root production and turnover is one of the primary focuses in the studies of the underground carbon cycle and carbon dynamic in different ecosystems (Ruess et al., 2003; Helmisaari et al., 2007).

* Correspondence: maluyi@bjfu.edu.cn

Two of the most commonly used methods that determine the fine root production are the in-growth core method and minirhizotrons method (Majdi et al., 2005; Milchunas, 2012). Both have drawbacks that influence the reliability of the observations, mostly related to the fact that a certain degree of soil environment disturbance is unavoidable before commencing the measurement. Lukac and Godbold (2010) suggested an improved method that does not cause interference to the soil profile. However, in their paper, the methods of mesh placement and lifting are neither well developed nor well documented.

Larix principis-rupprechtii Mayr is a unique species in China. It is a major dominant species of the community composition of coniferous forests (Cheng et al., 2006; Mei et al., 2010) and a major species for afforestation in North China mountainous areas existing in the cold temperate zone (Zhang and Meng, 2007). *L. principis-rupprechtii* plantations, as a green, great wall for metropolises such as Beijing and Tianjin, play an important part in wood production, water and soil conservation, and ecological environment regulation in North China (Xue et al., 1997; Zhang et al., 2001). A lot of work about the biomass, spatial distribution, and seasonal variations of fine roots of *L. principis-rupprechtii* plantations has been done (Sun et al., 2006; Yang and Han, 2008; Yang et al., 2008, 2012a, 2012b). The total fine root biomass typically ranges from 97 to 156 g m^{-2}. *L. principis-rupprechtii* is a species with a root system mainly in shallow soil (Yang and Han, 2008). Fine roots in the 0–10 cm topsoil are about 31%–49% and in the 0–30 cm soil layer are 60%–90% of total fine root biomass. Only 0.4%–5.3% of the total fine root biomass occurs in the soil layers under depths of 30 cm (Yang and Han, 2008). The seasonal variation of fine root biomass in the 0–10 cm soil layer had a significant difference ($P < 0.05$). From the 0–30 cm soil layer, the total fine root biomasses range from 170 to 263 g m^{-2} in different seasons (Yang et al., 2008). As far as we know, fine root turnover in *L. principis-rupprechtii* plantations and its contributions to soil organic carbon have not been reported.

In this research, we first test the validity of a modified root inclusion net method for the determination of fine root production and turnover in this research region and other similar high mountainous regions. Second, we try to obtain the fine root biomass and fine root turnover rate to learn the effect of fine root turnover on soil organic carbon and to provide a basis for the understanding of soil organic carbon dynamic at the ecosystem level.

2. Materials and methods

2.1. Site description

The study area is located in the Saihanba National Forest Park (SNFP) of Weichang Manchu and Mongolian Autonomous County in northeastern Hebei Province (42°02′N to 42°36′N and 116°51′E to 117°39′E), 460 km north-northeast of Beijing (Figure 1). The gray forest soils or brown soils with pH values of 6.32–6.71 are deeper than

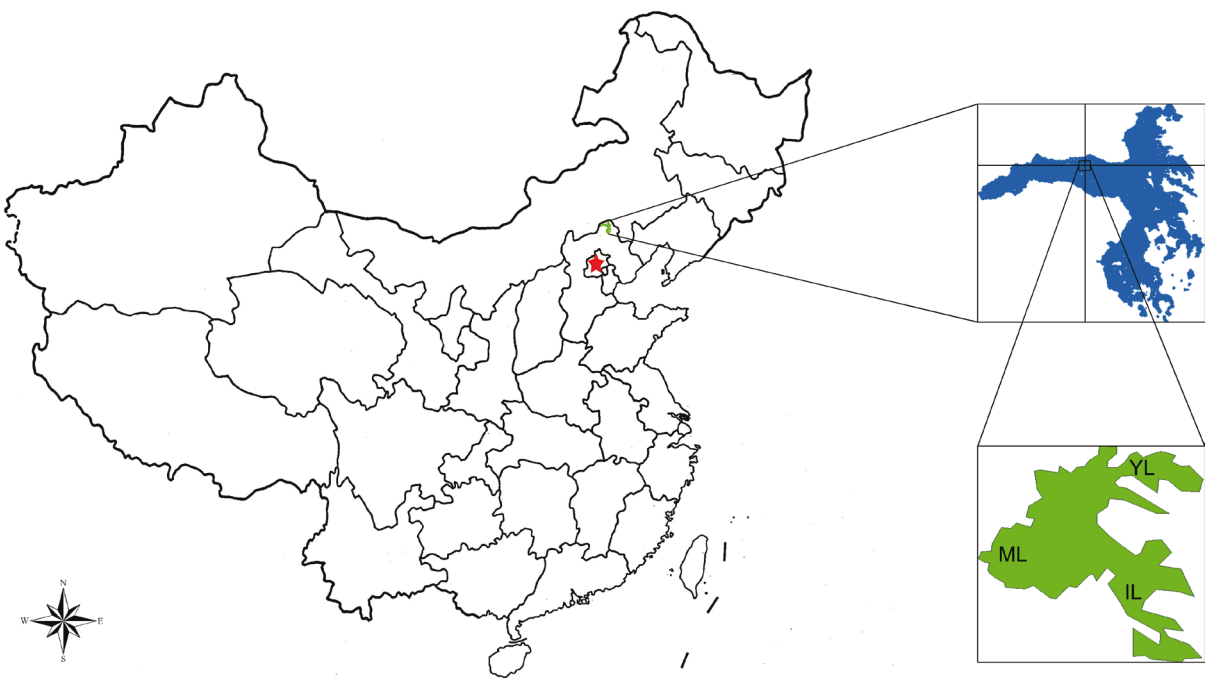

Figure 1. Location of the SNFP, Hebei, China (42°02′N to 42°36′N, 116°51′E to 117°39′E). YL = 13-year-old stand, IL = 22-year-old stand, ML = 38-year-old-stand.

1.5 m. Soil parent materials are eluvium, saprolite, and alluvium. The thickness of the surface organic horizon is about 3–8 cm in stands of all ages. Before the establishment of first generation stands, our site was used as farmland and then was abandoned to form a wild grass ground.

L. principis-rupprechtii, having a plantation with a single stand structure and simple composition, is a dominant species in the SNFP. In addition, there are Scots pine (*Pinus sylvestris var. mongolica* Litv.), spruce (*Picea asperata* Mast.), birch (*Betula platyphylla* Buk.), and oak (*Quercus mongolica* Miq.) in the SNFP. The forest's understory herbaceous vegetation mainly comprise sparse Maizuru grass [*Maianthemum bifolium* (Linn.) F.W.Schmidt], saussurea (*Saussurea japonica* Kom.), and thalictrum (*Thalictrum aquilegifolium*).

Generally trees and undergrowth are harvested after 40 or more years of growth in the SNFP. The new seedlings are then manually replanted. The area with *L. principis-rupprechtii* plantation older than 40 years is very small. In our study, we selected a young larch stand (abbreviated as YL, 13 years old in 2010), middle-aged stand (abbreviated as IL, 22 years old in 2010), and mature stand (abbreviated as ML, 38 years old in 2010) for a total of 3 *L. principis-rupprechtii* stands of different growth stages that basically have the same site conditions and stand conditions. Within each site at least 2 crown lengths apart, 3 replicate plots were selected. Each plot has an area of 20 × 20 m^2. A total of 9 permanent standard plots were set in 3 stands. Plot conditions are shown in Table 1. Topographically, this region is a transitional area between the Yan Mountain and the Inner Mongolia Plateau. The annual precipitation is 530.9 mm. The precipitation in June and August is 68% of the total annual precipitation (Figure 2). With its high altitude of 1400–1734 m, the annual mean temperature at our site is –1.4 °C, extreme maximum temperature is 30.9 °C, and extreme minimum is –43.2 °C . The duration of snowpack can last 7 months (from November to May). The depths of snowpack are about 20–120 cm in different months and places.

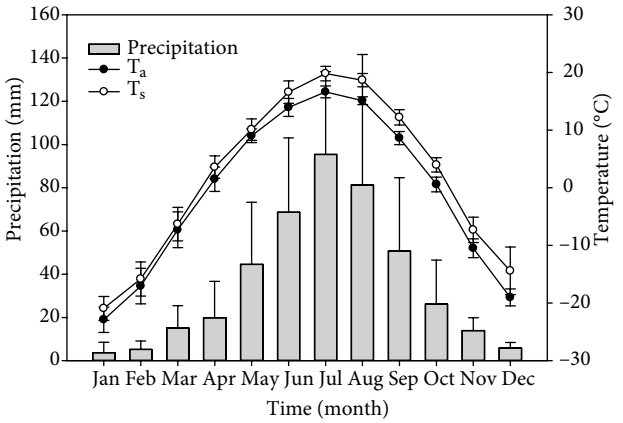

Figure 2. Monthly mean air temperature (T_a), soil temperature, (T_s) and precipitation recorded in the SNFP from 1996 to 2012. Bars are means ± SE, n = 7.

2.2. Experimental design and sampling

2.2.1. Soil organic carbon

In May and September 2012, 3 soil cores were chosen at random and taken using a auger of 10 cm in diameter in each replicate plot, causing as little disturbance of the surrounding soil as possible. Each core was taken to a depth of 60 cm, which was divided into 4 layers (0–10 cm, 10–20 cm, 20–40 cm, and 40–60 cm). The mixture of obtained soils in the same layer as a soil sample was packed into a labeled resealable plastic bag. In laboratory, the samples were placed in a shady place to dry naturally. The air-dried soil was used to determinate soil organic carbon content.

2.2.2. Soil temperature and water content

A temperature thermistor and a soil moisture probe, which are parts of the LI-8100A Automated Soil CO_2 Flux System (LI-COR Bioscience, Lincoln, NE, USA), were used to determine the soil temperature and soil moisture of each sampling point at 5 cm.

2.2.3. Fine root biomass

To determine biomass and necromass (dead root biomass) of the fine root (<2 mm), 3 soil cores were taken using a 10 cm diameter auger in each replicate plot. The core

Table 1. Stand characteristics of *L. principis-rupprechtii* plantations.

Plot no.	Stem density (stems ha^{-1})	Canopy density	Mean height (m)	Mean DBH (cm)	Aboveground biomass (Mg ha^{-1})
YL (13)	3600	0.83	6.9	7.7	29.42
IL (22)	2775	0.76	9.4	9.9	83.80
ML (38)	925	0.77	19.3	23.0	173.3

DBH: Diameter at breast height.

position was chosen at random in each replicate plot. Only 10%–14% of the fine root biomass was found at depths of greater than 30 cm in testing cores at all sites (taken to a depth of 100 cm). Each core was taken to a depth of 30 cm, which was divided into 3 layers (0–10 cm, 10–20 cm, and 20–30 cm). We took samples once each month in May–October 2012. The soil samples were put into a simple refrigerator and were taken back to the lab. A sieve (0.2 mm opening) was used to wash fine roots with fresh water, to separate roots from soil particles and organic materials. After washing, all roots were put in fresh water and live fine roots were picked from the residual soil particles and organic material using forceps and filters. Live fine roots were distinguished from dead fine roots by their lighter color and greater resilience. Fine roots were dried at 85 °C to a constant weight in a drying oven.

2.2.4. Fine root production, mortality, and turnover rate

A sequential coring method was used to measure fine root biomass and dead fine root biomass data in this study. These data were used to calculate the fine root production, mortality, turnover rate, and mortality rate. Fine root turnover rate is the ratio of the annual root production to the annual mean of live fine root biomass (Makkonen and Helmisaari, 1999). Fine root mortality rate is defined as the ratio of the amount of fine root mortality to the average fine root biomass. Fine root production includes annual and monthly fine root production. The monthly fine root production and mortality can be calculated by the decision matrix method and formulas in Table 2.

The maximum–minimum method, decision matrix method, and in-growth core method were employed to estimate annual fine root production. At the same time, we proposed a novel approach for both placing and lifting root nets to estimate fine root production and to compare with the in-growth core method. In October 2011, 3 individual nylon nets (10 cm × 30 cm, 1 mm opening) were inserted vertically into the soil in each replicate plot, with the help of a thicker blade (10 cm × 30 cm, 2 mm thick) along its bottom cutting edge and 2 similar thin blades (10 cm × 30 cm, 1 mm thick) attached to a single handle. First, the thicker stainless blade was inserted vertically into the soil to a depth of 30 cm. After lifting the blade, a deep slit was left in the soil. Second, a nylon net, which was clamped in the 2 thinner blades, was inserted into the slit. Third, the nylon net was left in the slit after the successive extraction of the 2 thinner blades. At last the root inclusion nets were marked. One year later (October 2012), the nylon nets were extracted. At first, 2 curvilinear lines against both mesh edges were cut in the soil to a depth of 30 cm using a garden spade. Two curvilinear lines parallel to the mesh at a distance of about 5 cm were then cut to a depth of 30 cm. Second, the soil around the soil block, which contained the nylon net, was removed with the garden spade until the soil block appeared totally. Third, the soil block, which had an approximate size of 10 cm in length, 10 cm in width, and 30 cm in height, was cut out by the garden spade. Finally, the soil clods attached to fine root nylon net were removed carefully to get to the nylon nets attached to the fine roots.. The fine roots were removed from the net and then put into resealable plastic bags. The fine roots were dried to a constant weight in laboratory. The root production can be calculated by the result of root biomass in this soil block with certain ground area.

2.2.5. Soil organic carbon pool and fine root organic carbon pool

The size of a soil organic carbon pool is the product of soil organic carbon in each soil layer (0–60 cm) multiplied by soil bulk density in the corresponding soil layer. The fine root biomasses in each soil layer (0–10 cm, 10–20 cm, and 20–30 cm) and the percentage composition of fine root organic carbon were used to estimate the fine root organic carbon pool. Fine root organic carbon was determined by using an improved Walkley–Black wet digestion method. Fine root carbon pool was calculated as: fine root carbon pool (g C m^{-2}) = fine root biomass (g m^{-2}) × C%.

Table 2. Formulas of monthly fine root production and mortality.

	Live fine root		
	Increase	Decrease	
Dead fine root		$\Delta B^{dead} > \Delta B^{live}$	$\Delta B^{live} > \Delta B^{dead}$
Increase	$P = \Delta B^{live} + \Delta B^{dead}$	$P = \Delta B^{live} + \Delta B^{dead}$	$P = 0$
	$M = \Delta B^{dead}$	$M = \Delta B^{dead}$	$M = -\Delta B^{live}$
Decrease	$P = \Delta B^{live}$	$P = 0$	
	$M = 0$	$M = -\Delta B^{live}$	

B: biomass; M: mortality; P: production of fine roots.

2.3. Statistics

Analysis of variance was performed to identify statistical differences in the estimates of soil organic carbon, fine root biomass and fine root production by different sampling times, sampling methods, soil layers, soil temperatures, soil water contents, and stands of different ages. All statistics were calculated using PASW Statistics 18 (IBM, Armonk, NY, USA) with a level of significance of $P < 0.05$. All figures were made using SigmaPlot 12 (Systat Software Inc., San Jose, CA, US).

3. Results

3.1. Fine root biomass and its dynamics

Stand age significantly affected fine root biomass ($P < 0.001$). The mean values of fine root biomasses were 103, 261, and 356 g m^{-2} in 13-, 22-, and 38-year-old plantations, respectively. Live fine root biomasses were 79, 205, and 269 g m^{-2}, or 76.7%, 78.5%, and 75.8% of the total fine root biomass, respectively. Fine root biomass and live fine root biomass both increased with increasing stand age.

Fine root biomass had a significant monthly variation ($P < 0.001$). Live fine root biomasses increased gradually from May to September and reached peaks of 109, 261, and 311 g m^{-2}, respectively, then started to decrease. Dead biomass only in the 22-year-old stand was in accord with this pattern. Both dead biomasses in 13- and 38-year-old stands kept increasing (Figure 3).

Fine root biomasses also had significant differences ($P < 0.001$) among different soil layers. Fine root biomass declined gradually with the increasing soil depth. Fine root biomasses in 0–10, 10–20, and 20–30 cm separately were 70.1%, 20.4%, and 9.5% of total fine root biomass in the 13-year-old stand. In the 22- and 38-year-old stands, the regular pattern mentioned above was still valid (Figure 4).

3.2. Fine root production and mortality

The seasonal variation of monthly fine root production was significant ($P < 0.001$) in stands of all ages. Fine root production increased gradually from April to August, and then declined after September. The maximum appeared between July and August (Figure 5a). The fine

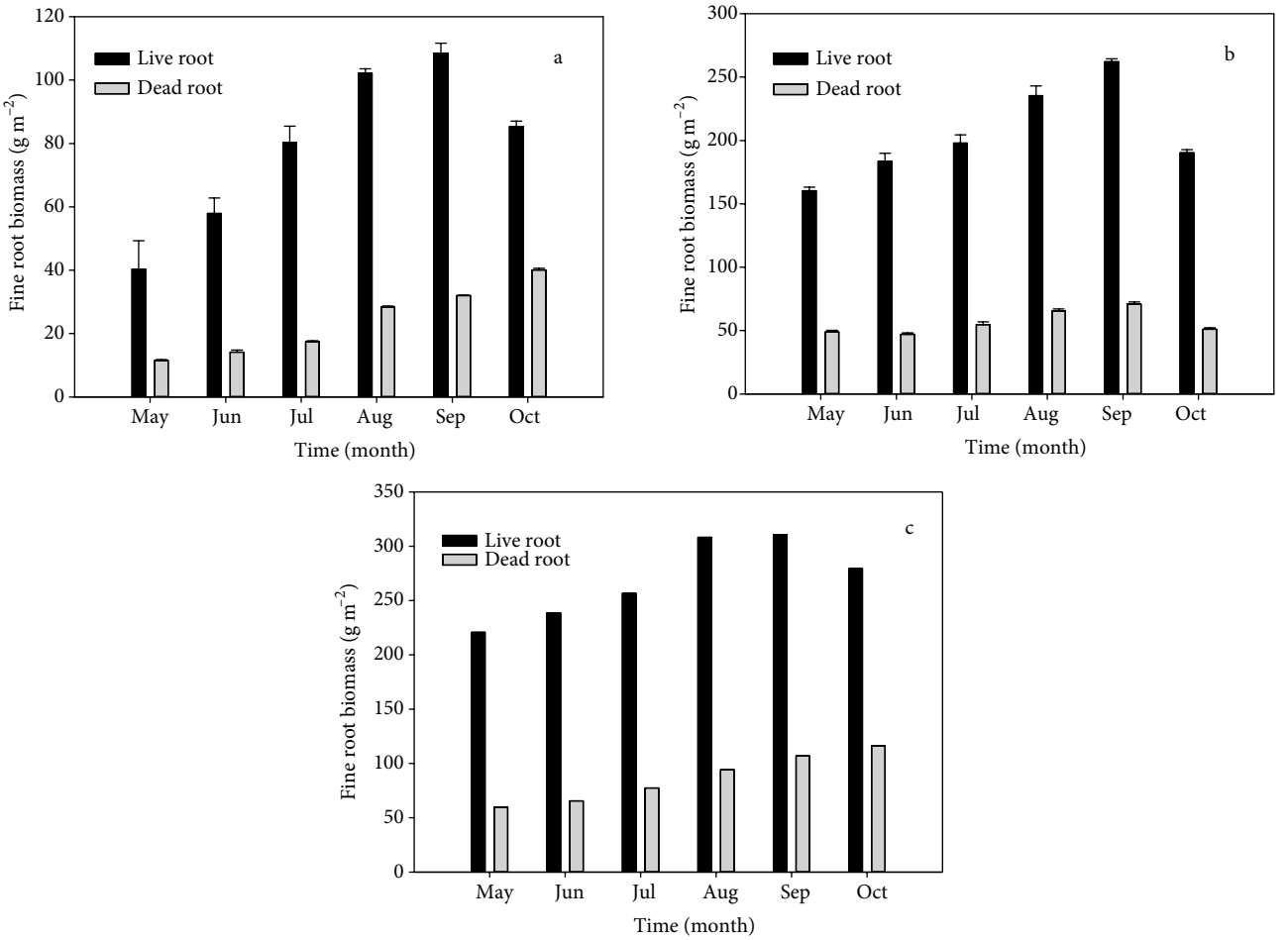

Figure 3. Monthly variations of fine root biomass in (a) 13-, (b) 22-, and (c) 38-year-old *L. principis-rupprechtii* stand. Bars are means ± SE, n = 9.

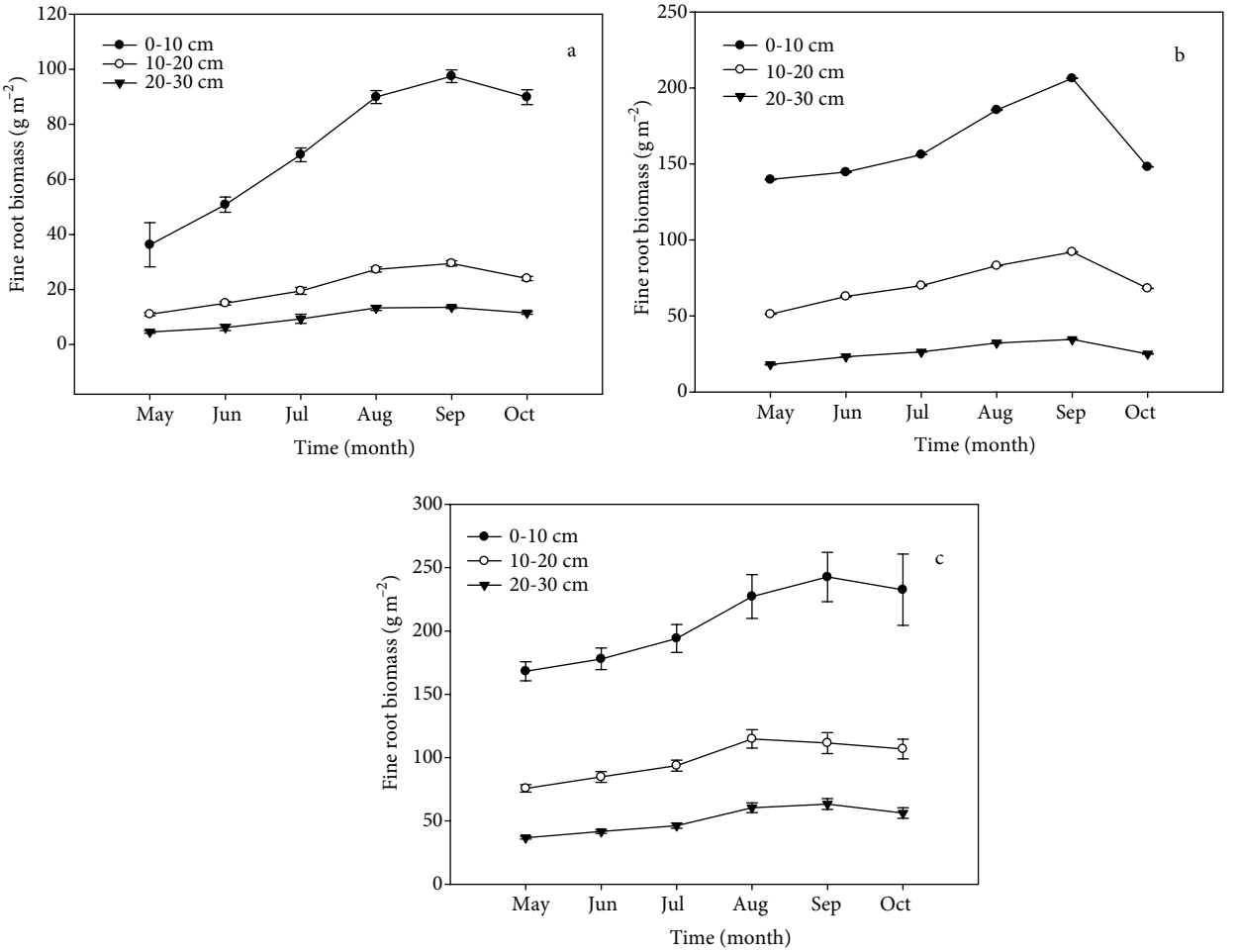

Figure 4. Monthly variations of fine root biomass in 3 soil layers (0–10 cm, 10–2 cm, and 20–30 cm) in (a) 13-, (b) 22-, and (c) 38-year-old *L. principis-rupprechtii* stands. Bars are means ± SE, n = 9.

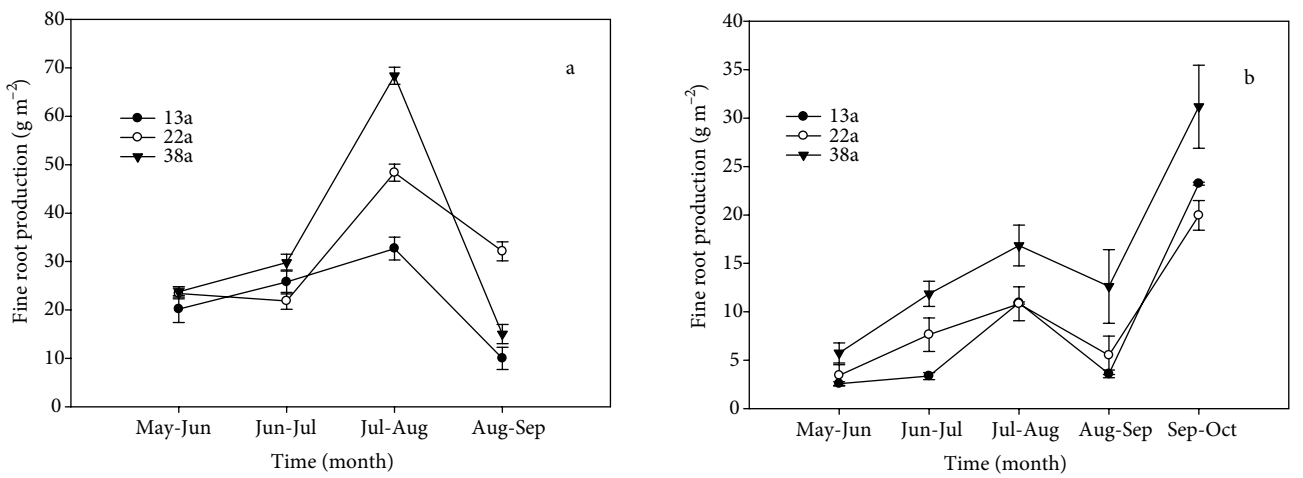

Figure 5. Monthly variations of (a) fine root production and (b) fine root mortality of *L. principis-rupprechtii* stands of 3 different ages. Bars are means ± SE, n = 9.

root productions calculated by different methods in 3 *L. principis-rupprechtii* plantations are shown in Table 3.

The monthly mean values of fine root mortality were 9, 10, and 16 g m^{-2}, respectively, in 3 *L. principis-rupprechtii* plantations. The monthly variation of the fine root mortality had a similar pattern, such that the fine root mortality ascended from May to August, decreased between August and September, and then increased sharply in October (Figure 5b). The fine root mortality rates in different soil layers differed significantly ($P < 0.05$).

The fine root productions had no significant difference at a $P = 0.05$ significance level between the in-growth cores method and inclusion net method ($P = 0.056$), while there was a significant difference between the decision matrix method and maximum–minimum method ($P = 0.009$, $P = 0.0074$) (Figure 6a). The fine root productions measured by the in-growth core method and inclusion net method were higher than the those of the other 2 methods in the 0–30 cm soil layer. Fine root productions in different soil layers differed significantly ($P < 0.001$). There was a peak value of fine root production in the 0–10 cm soil layer that was 54.1%–69.0% of the total fine root production (Figure 6b).

3.3. Fine root turnover rate and mortality rate

The fine root turnover rates were 1.12, 0.61, and 0.51 times $year^{-1}$, respectively, in 13-, 22-, and 38-year-old *L. principis-rupprechtii* plantations. The fine root turnover rate increased with soil depth (Figure 7a). The maximum fine root mortality rate occurred in 0–10 cm and differed significantly between soil layers ($P < 0.001$). It then decreased with the increasing soil depth (Figure 7b).

3.4. Soil organic carbon pool and fine root biomass carbon

The mean values of organic carbon respectively were 45, 47, and 39 g C kg^{-1} in the 0–60 cm soil layer of 3 different *L. principis-rupprechtii* plantations. The organic carbon contents differed significantly between soil layers. The highest organic carbon content in the surface soil declined gradually with increasing soil depth (Figure 8a).

The mean values of soil bulk density in 0–60 cm of 3 *L. Principis-rupprechtii* plantations were 1.23, 1.18, and 1.27 g kg^{-1}, respectively. Soil bulk densities ascended with increase of the soil depth, with a minimum value in the 1–10 cm soil layer and the greatest soil bulk density in the lowest layer (Figure 8b).

The soil organic carbon pools correspondingly were 0.55, 0.52, and 0.49 Mg C m^{-2} in 3 *L. Principis-rupprechtii* plantations. The fine root biomass carbon pools were 52, 131, and 178 g C m^{-2}, respectively. The fine root carbon pool was only a very small portion of the soil organic carbon pool (<0.01%). The organic carbon of dead fine roots that entered the soil was 52, 58, and 94 g C m^{-2} $year^{-1}$, respectively.

Table 3. Annual fine root production (g m^{-2} $year^{-1}$) calculated by different methods.

Stand age (years)	Minimum–maximum method	Decision matrix method	In-growth core method	Root inclusion net method
13	89	84	118	111
22	124	126	138	128
38	137	130	160	150

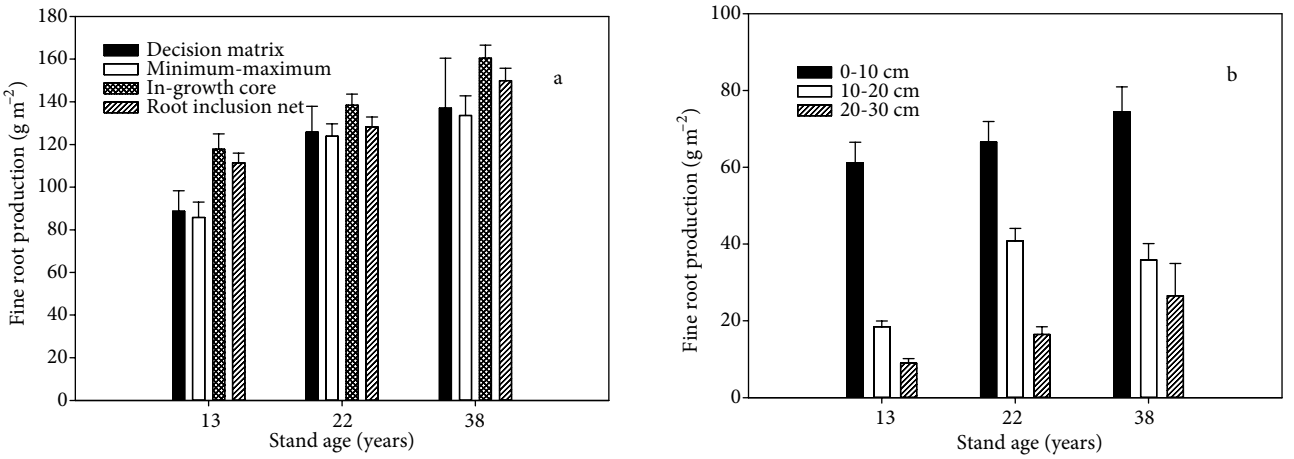

Figure 6. Annual fine root production calculated (a) by different methods and (b) in different soil layers by sequential coring method in 3 stands. Bars are means ± SE, n = 3.

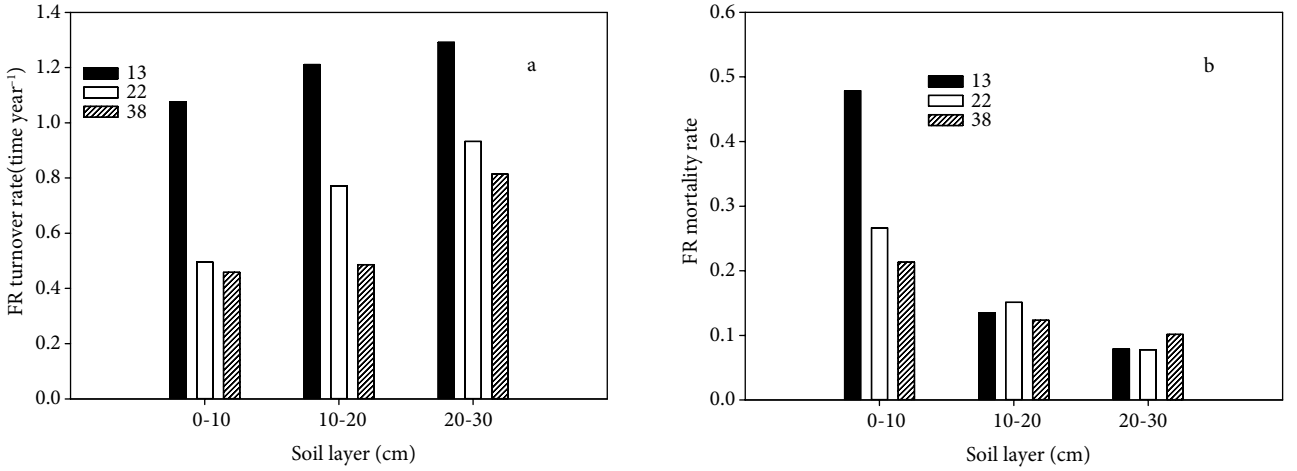

Figure 7. (a) Fine root turnover rates and (b) fine root mortality rates in each soil layer in 13-, 22-, and 38-year-old *L. Principis-rupprechtii* plantations.

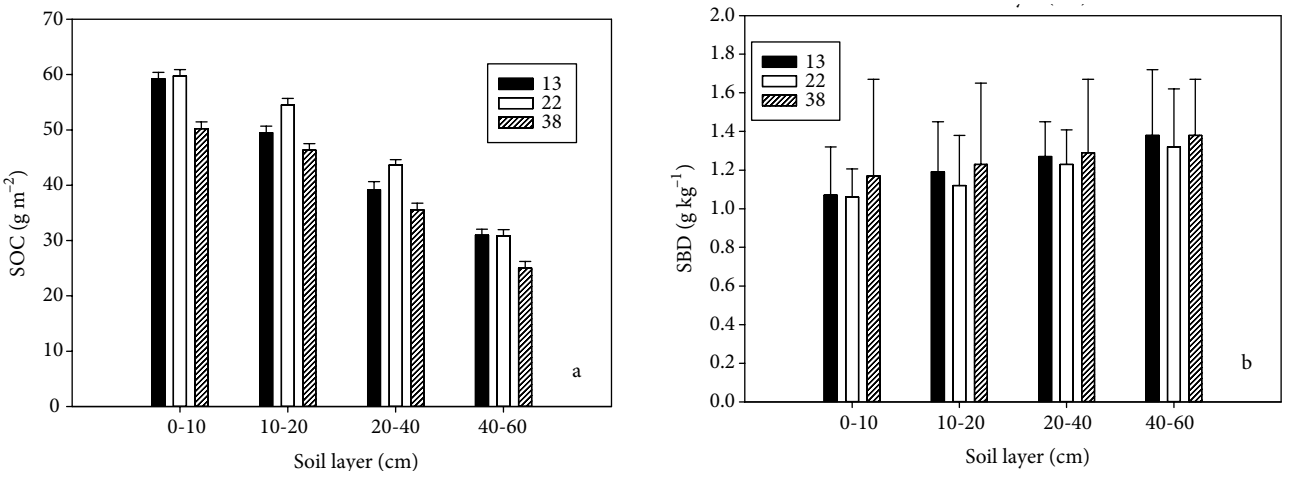

Figure 8. (a) Soil organic carbon (SOC) content and (b) soil bulk density (SBD) of *L. principis-rupprechtii* stands in different soil layers. Bars are means ± SE, n = 3.

4. Discussion

4.1. Fine root biomass and its spatial distribution

Vanninen and Mäkelä (1999) reported that Scots pine fine root biomass varied between 118 and 412 g m^{-2} in 23 to 178 years old Scots pine stands in Southern Finland, which is comparable to our range of 103-356 g m^{-2} in 13- to 38-year-old stands. Our fine root biomass values of 103–356 g m^{-2} were greater than the range reported in China (97–156 g m^{-2}) by Yang et al. (2012a) and Yang and Han (2008). Our higher values of fine root biomass came from having a more suitable growing environment in our site than Yang's in Shanxi Province. The soil in our study site is deeper and more fertile and is in favor of the growth of fine root.

Fine root biomass, following increasing stand ages, increases to a maximum and then decreases gradually to a stable state (Vogt et al., 1995). Because no mature stands exist in our studying site, our results can only support the lower half of this regular pattern. Fine root biomass has various seasonal patterns (McClaugherty et al., 1982; Fogel, 1983; Joslin and Henderson, 1987; Kavanagh and Kellman, 1992; Burke and Raynal, 1994; Liao et al., 1995; Rytter and Hansson, 1996; Sundarapandian and Swamy, 1996). Accompanying the tree growth, fine root biomass peaked in September and then started to decrease. Fine root biomasses were not different significantly at different soil temperatures ($P = 0.24$) but were significantly different under the conditions of different soil water contents ($P < 0.01$).

In our 13-, 22-, and 38-year-old *L. principis-rupprechtii* stands, fine root biomass in the 0–10 cm soil layer contributed 58%–70% to total fine root biomass. Only

10%–14% of the fine root biomass was found in soil deeper than 30 cm. The rich nutrients and higher soil temperature in the upper soil layer are in favor of fine root growth. The high fertility and soil temperature in the upper soil layer may be a vital factor affecting the shallow distribution of fine roots in *L. principis-rupprechtii* plantations.

4.2. The contribution of fine root turnover to soil carbon pool

Our study began in October 2011 and ended in October 2012, covering the entire growing season of 2012. From late autumn to early spring, the frozen soil and snow cover restricted the fine root study in the SNFP. The start and cease of fine root growth is closely related to soil temperature (Barber et al., 1988; Cheng et al., 2006). When the soil temperature drops to 4 °C, the fine roots stop growing. The ground in the SNFP is covered by snow from October to March, when the monthly average temperature is lower than 0 °C. Although some plants that adapt to this harsh local climate still can have a certain amount of fine root growth, we neglected this part of fine root production. The results of fine root turnover obtained by the in-growth core method and root inclusion net method had no significant difference.

The fine root turnover rates were 1.12, 0.61, and 0.51 times year^{-1} in 13-, 22-, and 38-year-old stands in the high mountainous area, and were relatively lower as compared to 3.1 times year^{-1} of fine root turnover in a *Larix gmelinii* (Rupr.) Rupr. forest in Northeast China (Shi et al., 2008). After summarizing studies on fine roots of pines worldwide, Schoettle et al. (1994) suggested that fine root turnover rates range from 0.2 to 5.0 times year^{-1}. Rytter and Rytter (1998) calculated the fine root turnover of *Salix veminalis* L. plantation to be as high as 4.9 to 5.8 times year^{-1}.

Fine root production and turnover both have significant seasonal variations. In temperate needle leaf forests, fine root production peaks in spring or summer. Fine root mortality has a minimum in winter and a maximum in summer or autumn, depending on tree species and local climates (Steele et al., 1997). In our study, the drought in autumn may be the main cause for the increased fine root mortality in October. In temperate deciduous forests, there is a fine root production peak in spring (McClaugherty et al., 1982; Joslin and Henderson, 1987; Hendrick and Pregitzer, 1993) or summer (Burke and Raynal, 1994) and a fine root mortality peak in autumn (Hendrick and Pregitzer, 1993).

Fine root turnover in our 3 *L. principis-rupprechtii* stands respectively contributed 52, 58, and 94 g C m^{-2} year^{-1} to the soil. Fine root turnover is a major route for carbon to enter underground and it takes part in cycles of carbon and nutrients in forest ecosystems. Although fine root turnover contributed only a very small portion of the soil organic carbon to the soil carbon pool in this study, fine root biomass carbon still has an important influence on the soil carbon and nutrient cycles in this region.

4.3. The reliability of our modified root inclusion nets method

We need to confirm a suitable time for nets left in soil to assure that the biomass of dead roots attached to nets is the least. This time is a main factor affecting the accuracy of fine root turnover by using a traditional root inclusion net method (Lukac and Godbold, 2010).

The possible death and decomposition of fine roots attached to nets may cause an underestimation of fine root turnover. In a humid and hot study area, it is necessary to shorten the time for implanted nets, to avoid the appearance of dead fine root. In cold and dry study areas, the implanting time for nets should be extended. In our study, no dead roots were found in either soil cores or nets after a whole year from the implementation of the soil core method and root inclusion net method. This planting period does not cause more errors in estimating the fine root turnover. This suggests that the planted nets can remain for more time than 1 year in the soil of our study area. Persson and Stadenberg (2010) pointed out that in Swedish forests the nets should be implanted into the soil for more than 1 year, while in humid inland areas of Alaska, the fine roots of black fir decomposed relative quickly, starting to disappear 97 days after its production (Ruess et al., 2003).

There was no significant difference ($P = 0.056$) between the fine root productions calculated by the in-growth cores method and root inclusion net method. We used data from the growing season to estimate fine root production by using the sequential coring method but used data from the whole year, including both the growing and nongrowing seasons, to estimate results in the in-growth cores method and root inclusion net method. The value of fine root production of the sequential coring method is only 76% to 94% of the root inclusion net method. In addition, the dead fine roots decompose slowly in our study area, which has an extremely cold winter and a relative low annual mean temperature. These dead but not decomposed fine roots resulted in greater fine root productions in the in-growth cores method and root inclusion net method. The slit in the ground caused by net implantation did not disturb the physicochemical properties of the soil. The relative consistency of fine root productions obtained by using both the in-growth cores method and root inclusion net method indicates that the refilled soil in the in-growth method can be restored to a state similar to the original soil.

There is no analysis of fine root production in different soil layers estimated by the root inclusion net method in this paper. The extracted net maintained original soil

layers, and thus the fine root production in different soil layers can also be calculated by using the root inclusion net method, like in-growth cores method.

Thus, we can draw the conclusion that our novel root inclusion net method is a reliable and widely applicative method to estimate fine root production and turnover. It is also the most suitable method for fine root study in high mountainous regions in North China. This method is easy to carry out and is labor-saving. Many duplicates can be set into the soil in a shorter time and cause little disturbance to soil physicochemical properties. In addition, this method can play a role in remote areas where the use of special instruments is restricted.

In our study region, the fine root biomass is relatively greater, but the turnover rate is lower than results in other studies on fine roots of *L. principis-rupprechtii* plantations in Shanxi Province, China. Organic carbon entering the soil carbon pool through fine root turnover is an important source of underground carbon and nutrients cycles. In the recent several decades, the constructions of ecological forestry projects and plantation production bases led to a sharp decline of soil fertility. Therefore, more research on effects of fine root turnover in the decline of site productivity on plantations and on how to regain forests' productivity needs to be carried out urgently.

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