J Soils Sediments (2013) 13:1150–1160
DOI 10.1007/s11368-013-0718-y

SOILS, SEC 2 • GLOBAL CHANGE, ENVIRON RISK ASSESS, SUSTAINABLE LAND USE • RESEARCH ARTICLE

Fine root production, turnover, and decomposition in a fast-growth *Eucalyptus urophylla* plantation in southern China

Weiqiang Xu · Juxiu Liu · Xingzhao Liu · Kun Li · Deqiang Zhang · Junhua Yan

Received: 4 March 2013 / Accepted: 4 May 2013 / Published online: 23 May 2013

Abstract
Purpose A rapid increase of *Eucalyptus* plantation area in southern China has raised widespread attention in the field of ecology and forestry. It might be argued that fast-growth *Eucalyptus* would increase the consumption of resources and thus cause soil degradation. Fine root dynamics could provide insight into nutrient uptake or return. This study therefore focused on fine root production, turnover, and decomposition in a subtropical *Eucalyptus urophylla* plantation.
Materials and methods Sequential coring method was used to estimate fine root production and turnover rate. Root decomposition rate and root nitrogen (N) and phosphorus (P) dynamics were determined using the litterbag method. In this study, roots were divided into three diameter classes: <1, 1–2, and 2–3 mm. We settled litterbags with all three different root diameter classes under the forest floor (0–10 cm) in winter, spring, and summer.
Results and discussion The total production of fine roots at diameter <2 mm was 45.4 g m^{-2} $year^{-1}$, and its turnover rate was 0.58 $year^{-1}$. The roots at diameter <1 mm showed much greater production or turnover rate than those at diameter 1–2 mm. The root mass loss from litterbag across the three diameter classes (<1, 1–2, and 2–3 mm) was similar at the beginning period of 180 days, but significantly different later. The decomposition constant (*k* value) of roots estimated by exponential decay model decreased with increasing diameter class. In addition, the season of litterbag settlement also had effects on root mass loss. In root nutrient dynamics, the fractions of initial N immobilized increased with increasing diameter class. Root P at the three diameter classes showed a similar mineralization pattern.
Conclusions Our studies on fine root production, turnover, and decomposition give some important insights into nutrient cycling between plant and soil in *Eucalyptus* plantations. Our results which show that fine roots had relatively low production and turnover rate partly explain the potential soil degradation under the short rotation systems. The variation of root dynamics among different diameter classes suggests that to accurately assess fine root roles, one should consider the effects of root diameter size.

Keywords Decomposition constant (*k* value) · *Eucalyptus* plantations · Fine roots · Litterbag settlement season · Root diameter class · Soil temperature

Responsible editor: Hailong Wang

W. Xu · J. Liu · X. Liu · K. Li · D. Zhang · J. Yan (✉)
Key Laboratory of Vegetation Restoration and Management of Degraded Ecosystems, South China Botanical Garden, Chinese Academy of Sciences, Xingke Road 723, Tianhe District, Guangzhou 510650, China
e-mail: jhyan@scib.ac.cn

W. Xu · X. Liu · K. Li
Graduate University of Chinese Academy of Sciences, Beijing 100049, China

1 Introduction

Eucalyptus is the most widely planted tree genus in tropical and subtropical regions (FAO 2001; Xu and Dell 2003). As short rotation was employed in *Eucalyptus* plantations, soil nutrient deficiency might arise in these *Eucalyptus* plantations (de Moraes Goncalves et al. 2004; Xu and Dell 2003), just like other tree species plantations under the short rotation system (Fox et al. 2007; Xu et al. 2008). However, the reasons for the potential soil nutrient deficiency in these *Eucalyptus* plantations are still being argued. Hence, understanding the mechanisms of nutrient cycling belowground is important for sustainable management of *Eucalyptus* plantations. The amount of nutrients returned to the soil by fine root mortality was generally considered to be substantial because of the high proportion of plant annual net primary production used for their production and functioning (Jackson et al. 1997) together with their fast turnover rate (Gill and Jackson 2000). Previous studies on fine root in *Eucalyptus* plantations mainly focused on their depth or horizontal distribution (Bouillet et al. 2002; Laclau et al. 2001; O'Grady et al. 2005) or their temporal patterns (i.e., seasonal or tree development) (Katterer et al. 1995; O'Grady et al. 2005), but there were still limited studies on their production and turnover (Jourdan et al. 2008), particularly on their decomposition. Therefore, to assess fine root dynamics, such as production, turnover, and decomposition, may be helpful to explain the potential soil degradation and the nutrient management in these *Eucalyptus* plantations under the short rotation system.

Fine roots were often sorted out less than one selected root diameter size (e.g., <1 or <2 mm) in many studies (Ostonen et al. 2011; Persson 1980). Diameters of fine roots were found to be varied in respiration rates, longevity, specific surface area, or nitrogen (N) concentration (Makita et al. 2009; Pregitzer et al. 1998, 2002; Sun and Mao 2011; Wells and Eissenstat 2001). Such variations could result in their differences in production, turnover, or decomposition (Joslin et al. 2006; Yang et al. 2004). The small-diameter roots (low branching order) were often considered to be with great production or short longevity (i.e., fast turnover rate) (Wells and Eissenstat 2001), but the results from the relationship between root diameter classes with various N concentrations and decomposition rates were inconsistent, where a positive correlation (Silver and Miya 2001) and a negative correlation (Fan and Guo 2010) were both reported. The roots at a small diameter size were usually expected to decompose faster than those at a great diameter size. However, this prediction had recently been questioned. Langley and Hungate (2003) reported that the nutrient-rich finer roots decomposed more slowly than the nutrient-poor larger roots in tree species colonized by ectomycorrhizal fungi. Fan and Guo (2010) also found that the lower-order roots (smaller-diameter class) of two tree species decomposed more slowly than the higher-order roots, which may be due to high N inhibition on decay in lower-order roots. It was because high N (e.g., lower order roots) suppressed the activity of ligninase (a lignin-degrading enzyme) or promoted humus formation (Magill and Aber 1998; Waldrop and Zak 2006). Hence, the root N status should also be considered when studying the effects of root diameter size on root decomposition. In addition, root decomposition is also the process of root nutrient mineralization. Previous studies found that litter N or phosphorus (P) dynamics could be influenced by litter chemical quality, such as N concentration, C/N ratio, or C/P ratio (Manzoni et al. 2008; Moore et al. 2006; Parton et al. 2007). However, such understanding is largely limited to leaf litter nutrient mineralization, and little attention has been paid to root nutrient mineralization (Chen et al. 2002). Therefore, how root diameter size with different chemical qualities would affect both the decomposition rate and root N and P dynamics needs to be further investigated.

In most experiments of litter decomposition, litterbags are placed in the expected season(s) during which most of litter production would occur to reflect the field situation. However, such season(s) when most litters are produced may not be accurately assessed for fine roots mainly for two reasons: Firstly, fine roots were suggested to turn over very fast (Eissenstat et al. 2000), such as several days. Thus, root litter may be produced throughout the year (Hendrick and Pregitzer 1992). In addition, fine root may die abnormally. For example, much root litter may be produced in the unexpected period due to the depression of environmental fluctuation caused by extreme climate events or human disturbance. As mass loss of litter was affected by environmental factors, particularly in early period (Aerts 1997), the season of litterbag settlement may affect fine root decomposition process in regions with significant seasonal variation (e.g., subtropics). However, this potential seasonal effect of litterbag settlement on root decomposition from litterbag is still uncertain.

Since *Eucalyptus* was introduced to China, their area has been rapidly increased. In 2010, the plantation area in China went up to 3.68 million hectares (data cited from China *Eucalyptus* Research Centre). Our study was conducted in an experimental 4.5-year-old *Eucalyptus urophylla* plantation without nutrient fertilization in southern China. This site has a typical subtropical monsoon humid climate with a distinctly hot–wet season (from April to September) and a cold–dry season (from October to March). Many studies had been carried out in this experimental plantation, such as soil microbial community (Chen et al. 2012; Wu et al. 2011a) and soil respiration and its partition (Wu et al. 2011b). As fine root dynamics were closely related to soil microbial activity or soil respiration, studies on fine root dynamics, such as production, turnover, and decomposition, might be helpful to understand the findings of previous studies in this plantation.

In this study, we aimed to get the basal data on fine root production, turnover, and decomposition and then tried to explain the potential nutrient deficiency in *Eucalyptus* plantations in the perspective of fine roots. We hypothesized that production and turnover of fine roots were relatively low in the fast-growth *Eucalyptus* plantation under a short-term rotation system in southern China because soil nutrient deficiency in these plantations was often found in the region (Xu and Dell 2003). The objectives of this study were (1) to estimate the production and turnover rate of roots at different diameter classes, (2) to compare root decomposition rates and N and P dynamics across different diameter classes and then analyze the effects of root chemical quality on these processes, and (3) to evaluate how the season of litterbag settlement would affect root decomposition rates and root N and P dynamics.

2 Materials and methods

2.1 Study site

This study was carried out at the Heshan Hilly Land Interdisciplinary Experimental Station (112°50′ E, 22°34′ N), Chinese Academy of Sciences, Guangdong Province, China. The climate of the region is typical subtropical monsoon with a distinctly wet season (from April to September) and a dry season (from October to March). The mean annual precipitation and temperature are 1,534 mm and 22.5 °C from 2004 to 2009, respectively (Wu et al. 2011a). The lowest mean monthly temperature is 12.8 °C in January, and the highest is 28.5 °C in July. The year could be divided into four seasons: spring (March, April, and May), summer (June, July, and August), autumn (September, October, and November), and winter (December, January, and February). The soil is Acrisol (FAO 2006).

Our experiment was conducted in an about-4.5-year-old *E. urophylla* S. T. Blake plantation. The saplings were planted in 2006 with a spacing of 3 m×2 m. This plantation was without nutrient fertilization and other plantation management after establishment. The understory vegetation was dominated by *Dicranopteris dichotoma* (Thunb.) Bernh. The *Eucalyptus* trees were 10.6 cm in breast-height diameter and 14.4 m in height on average in December 2010. After a year, in December 2011, the average breast-height diameter and the height increased to 11.2 cm and 16.6 m, respectively. Soil pH was 3.84–3.90; soil organic carbon was 13.69–15.21 g kg^{-1}; soil total nitrogen was 0.70–0.87 g kg^{-1} (Wu et al. 2011a).

2.2 Experimental plot design

On November 14, 2010, three experimental plots of 12×8 m were established for root biomass measuring in the plantation. The terrain of the study site is quite hilly, with an altitude varying from 100 to 300 m above sea level in most areas. The three experimental plots were located in different directions of one of these hills. The slope of this hill is about 10°. The buffer zones among the three biomass plots were about 6–8 m. Meanwhile, five plots of 2×4 m were set up for the root decay experiment within the buffer zones. The decay plots were located between two tree rows with a 3-m-width space. The 4-m-length edges of the plots paralleled the tree rows. *D. dichotoma* was very dense in the plantation. For easy litterbag settlement, the understory plants in the decay plots were removed manually, and this treatment may cause some variations of in situ environment in the study.

2.3 Fine root biomass measurement

The sequential coring method (Persson 1978) was used to determine fine root production. Soil cores were sampled on six dates: January 8, March 11, May 16, July 22, September 24, and November 21 in 2011, about every 2 months. The cores were taken to 0–20 cm soil depth with an 8.4-cm-diameter corer (fine roots at diameter <2 mm in 0–20-cm layer constituting 74.6 % of 0–60 cm soil depth). Four soil cores were sampled and combined to one composite sample in each plot. In each sampling time, there were three replicated composite samples from the three plots. The obvious roots (long or large) were carefully picked out by hands, and then the soil was passed through a 2-mm sieve to obtain the remaining roots as much as possible. Roots were taken back to the laboratory immediately and stored in a freezer at 4 °C until further treatment.

In the laboratory, roots were rinsed quickly with tap water to clean away the adhering soil through a 0.147-mm sieve. Distinguishing *E. urophylla* roots from other species was done based on visible root characteristics: morphology, color, and architecture. In order to estimate the production of *E. urophylla* roots at different diameter classes, roots were firstly sorted into two diameter class fractions: <1 and 1–2 mm. After that, roots were further sorted into live and dead fragments by two criteria: color and resilience. Live roots are those of smooth or fresh bark with high resilience. Roots which were of low resilience and easily broken were considered to be dead. Roots were oven-dried to a constant mass at 60 °C and then weighed.

2.4 Root preparation, litterbag sampling, and analysis

Roots in 0–10 cm soil depth were obtained in the *E. urophylla* plantation in November 14 and 17. Soil adhering to roots was washed away by tap water with a 2-mm-mesh-size sieve. Roots of species and vitality were sorted out by the same criteria as described earlier. The live roots of *E. urophylla* were used in our decomposition experiment with the litterbag method. Roots were air-dried and then sorted into three diameter size classes: <1, 1–2, and 2–3 mm. Roots under 2 mm in diameter size were sorted into fine roots in most studies, but we also included roots at 2–3 mm in diameter in our decomposition experiment, mainly for the investigation of the diameter size effect on root decomposition. Roots under the three diameter classes were separately put into nylon litter bags (10×10 cm, 2 g roots per bag). The mesh size was 0.1 mm. Subsamples (five bags for each root diameter class) were randomly collected for initial dry mass and chemical analysis.

Root litterbags were settled on three dates (root decomposition initiated at three seasons): November 21 (winter settlement) in 2010 and March 20 (spring settlement) and June 19 (summer settlement) in 2011. The roots used for the three settlements were collected at one time (at middle of November), and the litterbags of the last two settlements (spring settlement and summer settlement) were separately put into two vacuum bags and were stored in a freezer below

0 °C until settlement. We have analyzed the difference of oven-dried root mass between the initial sample and that which was stored for 7 months. The statistical analysis indicated that there was no significant difference in oven-dried root mass between the fresh and the stored roots (*t*-test, all $P>0.29$). The chemical elements between them were not compared. However, the roots were stored in a vacuum bag and under 0 °C in a freezer. We assumed that the chemical properties of stored roots were the same as the initial roots under the stored conditions. At each settlement, litterbags were placed at 0–10 cm soil depth (at about 45° angles relative to the soil surface) in each plot (six bags per diameter class per plot) with a hoe. The six bags per diameter class were lined up in a row in each plot. There was about 20 cm distance between each two neighboring bags. Five litterbags per diameter class (one per plot) were collected at each sampling. There were six samplings during a period of one year: about 30, 60, 120, 180, 240, and 360 days since each settlement date. At the last settlement (summer settlement), samplings at 60-day decay at diameter 2–3 mm and at 180-day decay at the three diameters were not carried out due to lack of samples. After sampling, litterbags were taken back immediately.

In the laboratory, new roots which grew into the litterbags were removed. Soil adhering to the root samples was carefully washed with a 0.147-mm-mesh-size sieve by tap water. The soil-free root samples were oven-dried to constant mass at 60 °C and weighed. The five root samples per diameter class in each sample time were combined to a mixture sample. Root samples were finely ground and then used for chemical analyses. Carbon (C) concentration was determined by dichromate oxidation. N concentration was measured using the Kjeldahl method (Bremner and Mulvaney 1982). P concentration was measured photometrically after the roots were digested with nitric acid. Each mixture sample was measured three times, and C, N, and P concentrations were the means of three measurements.

Soil temperature at 5-cm depth was recorded every hour with the iButton DS1920 digital thermometer during the study period.

2.5 Data analyses

Root production estimated by the sequential coring method was calculated in the following way: the significant difference between the maximum and minimum live root biomass among the six samplings in 2011 (Vogt et al. 1986). The production of roots at diameter 1–2 mm was the difference between the roots at diameter <1 and <2 mm. The turnover rate was calculated by the production divided by the mean standing biomass of live roots.

The root decomposition constant (*k* value) was estimated by the exponential decay model (Olson 1963): $X/X_0=\exp(-kt)$, X_0 is the initial root mass, X is the remaining mass at time t, and k is the root decomposition constant. Two-way ANOVA was used to determine the effects of root diameter class and litterbag settlement on the mass remaining during 360 days of decomposition. Statistical significance was accepted at $P<0.05$. Statistical analyses were performed in SPSS 16.0 for Windows (SPSS Inc., Chicago, IL, USA).

3 Results

3.1 Fine root production and turnover rate

The biomass of total live fine roots at diameter <2 mm showed a strongly seasonal pattern with a single peak in September (the end of wet season). The growth rates of fine roots were the largest in the period from May to September (Fig. 1a). The periods of the largest growth rate of roots with diameter <1 and 1–2 mm were different, which were from July to September and from May to July, respectively. However, the biomass of dead roots showed two peaks in May (the second month of the wet season) and November (the second month of the dry season), respectively (see Fig. 1b). Based on the sequential coring method, the total production of fine roots at diameter <2 mm was 45.4 g m^{-2} $year^{-1}$, and its turnover rate was 0.58 $year^{-1}$. The fine roots at diameter <1 mm showed much greater production or turnover rate than those at diameter 1–2 mm. The annual production was 34.6 g m^{-2} $year^{-1}$ for the roots at diameter <1 mm and only 10.8 g m^{-2} $year^{-1}$ for the roots at diameter 1–2 mm. The turnover rates were 0.69 and 0.39 $year^{-1}$ for the roots at diameter <1 and 1–2 mm, respectively.

3.2 Root decomposition rate

The root mass loss across the three diameter classes (<1, 1–2, and 2–3 mm) from litterbag showed a similar pattern in each litterbag settlement, particularly in the summer settlement (Fig. 2). The diameter class had no effect on the root mass loss from litterbag at the beginning period of 180 days ($P>0.05$) but with a significant effect at a later period of 181–360 days ($P<0.05$; Table 1). In contrast, the patterns of root mass loss from litterbag among the three litterbag settlements were significantly different, which showed the fastest in the summer settlement, followed by the spring settlement and the winter settlement ($P<0.01$; Table 1; Fig. 2).

The regression results showed that the exponential decay model had a good fit for the relationship between the root mass remaining from litterbag and decay time for each root diameter class and each litterbag settlement (all $r^2>0.80$, all $P<0.05$; Table 2). The root decomposition constant (*k* values) estimated by the exponent decay model seemed to decrease with increasing diameter class in each litterbag settlement. The *k* values were the highest in the summer settlement, followed by

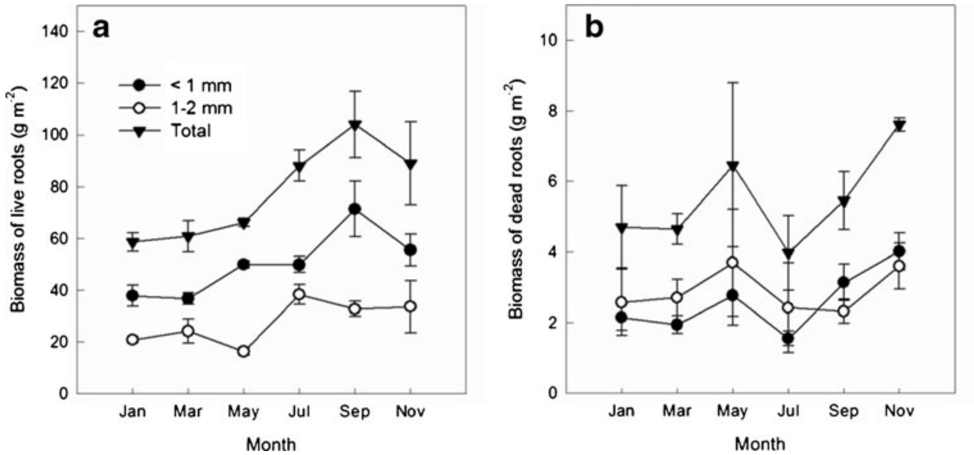

Fig. 1 The seasonal dynamics of the biomass of live (**a**) and dead (**b**) fine roots in the *E. urophylla* plantation in 2011. *Error bars* represent standard errors of means

the spring settlement and the winter settlement (see Table 2). The variations of decomposition *k* values caused by diameter class were high in the winter settlement (CV=13.3 %) and in the spring settlement (CV=14.8 %), but that in the summer settlement was very low (CV=1.8 %). The variations of decomposition *k* values caused by the season of litterbag settlement were all high for the roots at diameter <1, 1–2, and 2–3 mm, for which the values of CV were 19.1, 25.1, and 31.2 %, respectively.

3.3 Root N and P dynamics

The root N dynamics (N concentration and % of initial N) from litterbag were similar among the three litterbag settlements but different across the three diameter classes (Fig. 3). In each settlement, the root N concentrations at the three diameter classes increased over time, with the highest one at diameter <1 mm, followed by those at diameter 1–2 and 2–3 mm (see Fig. 3a–c). N was immobilized into roots over time, particularly in winter settlement and spring settlement, which showed the highest for the roots at diameter 2–3 mm, followed by the roots at diameter 1–2 and <1 mm (see Fig. 3d–f). The root C/N ratios showed a decreasing trend over time (see Fig. 3g–i), mainly due to the N accumulation into roots (see Fig. 3d–f).

The root P dynamics (P concentration and % of initial P) from litterbag were also similar among the three litterbag settlements. Although the root P concentrations across the three diameter classes were different, the patterns of root P mineralization (% of initial P) appeared to be similar (see Fig. 3). In each settlement, after a short decrease period of about 60 days, the root P concentrations at the three diameter classes increased over time. The P concentration of the roots at diameter <1 mm was the highest, followed by the roots at diameter 1–2 and 2–3 mm (see Fig. 3a–c). The root P firstly experienced a period of release (1–120 days) (decreased % of initial P), then a period of immobilization (121–180 days), and underwent a period of release at last, particularly in the winter settlement and the spring settlement (see Fig. 3d–f). The root C/P ratios firstly increased for a short period (less than 60 days) but then showed a decreasing trend with time during the study period (see Fig. 3g–i), mainly due to the root P immobilization or release (see Fig. 3d–f).

4 Discussion

4.1 Fine root production and turnover in southern China

Our study showed that the production or turnover rate of the roots at diameter <1 mm was greater than those at diameter

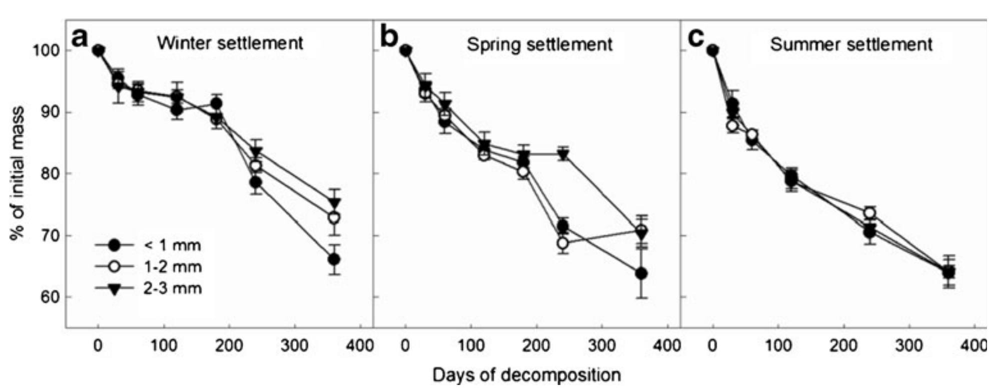

Fig. 2 The mass remaining (%) of *E. urophylla* roots at diameter <1, 1–2, and 2–3 mm in the three litterbag settlements: winter settlement (**a**), spring settlement (**b**), and summer settlement (**c**) during 360 days of decomposition. *Error bars* represent standard errors of means

Table 1 Results from a statistical analysis for the effects of litterbag settlement (initiated at different seasons) and diameter class and their interaction on the root mass remaining (%)

Factors	30 days	60 days	120 days	180 days	240 days	360 days
Settlement	**	**	**	**	**	**
Diameter	ns	ns	ns	ns	**	*
Settlement×diameter	ns	ns	ns	ns	**	ns

Asterisks indicate the effects of primary factors or that their interactions are significant

ns not significant

*$P<0.05$; **$P<0.01$

1–2 mm. These were consistent with the results of the negative correlation between production or turnover rates of roots and their diameter size in other studies (Baddeley and Watson 2005; Wells and Eissenstat 2001). Root longevity was negatively related to root respiration rate and root N concentration (Bouma et al. 2001; Eissenstat et al. 2000). The roots at small-diameter class with relatively short longevity (greater turnover rate) in our study may be partly because of strong physiological activities, such as root respiration rate, and their high N concentration. Plants would allocate large amounts of carbohydrate to roots for their metabolism activities to absorb nutrients. The small-diameter roots play a more important role in nutrient uptake than the relatively large ones, which led to a higher respiration rate in the small-diameter roots (Pregitzer et al. 1997). In addition, high N concentration in roots was strongly linked to high root respiration (Ryan et al. 1996), probably because typically 90 % of the N in plant cells is in protein, which needs energy (carbon) for replacement and repair (Bouma et al. 1994). The cost–benefit model (Eissenstat and Yanai 1997) suggested that the optimal root life span is that which maximizes the ratio of nutrient gained (benefit) per unit carbon expended (cost) on a root mass basis. The expended carbon (cost) for roots may be used in two parts: their biomass construction (production) and maintaining respiration. In this case, the smaller-diameter roots, which play more important role in nutrient uptake than the relatively large ones, would be preferable to grow into soil patches which are rich in nutrients to absorb nutrients as much as possible to maximize the ratio of benefit and cost. The amount of nutrients in the soil patches would decrease over time because of nutrient absorption by roots. When the nutrient status of the previous soil patches became more deficient compared with the new soil patches, the smaller-diameter roots, which are relatively low in carbon cost for biomass construction but high in carbon cost for maintaining respiration (Pregitzer et al. 1997), may firstly be depressed and would easily die (i.e., faster turnover), and then the plant may produce new smaller roots in new soil patches because the ratio of carbon consumption for respiration (cost) and nutrient uptake (benefit) was not maximized.

Using the sequential coring method with "max–min" calculation, Jourdan et al. (2008) reported that production and turnover rate of fine roots (<2 mm) were 73 g m^{-2} year^{-1} and 0.80 year^{-1}, respectively (both higher than our study), in a 6.5-year *Eucalyptus* plantation in Brazil. There were usually three calculation methods for root production based on the sequential coring method: "max–min", "positive increment", and "decision matrix". The "max–min" calculation was suggested to underestimate fine root production (Jourdan et al. 2008; Vogt et al. 1998). However, the lower fine root production and turnover rate, compared with those in Jourdan et al. (2008), may not be caused by the calculation difference in our study. As the biomass of live fine roots showed a single peak pattern (see Fig. 1a), we speculated that the production and turnover rate of fine roots estimated by the "max–min" calculation would be the same as the "positive increment" calculation that considered the possibility of more than one growth phase within a year. Moreover, our results showed that the biomass of dead fine roots was very small relative to live fine roots

Table 2 The root decomposition constant (k value) estimated by the exponential decay model: $X/X_0=\exp(-kt)$, X_0 is the initial root mass, X is the remaining mass at time t, k is the root decomposition constant. P is the significant level

Diameter class (mm)	Winter settlement			Spring settlement			Summer settlement		
	r^2	P	k	r^2	P	k	r^2	P	k
<1	0.90	<0.01	0.353	0.96	<0.01	0.472	0.89	<0.01	0.519
1–2	0.95	<0.01	0.300	0.86	<0.01	0.446	0.81	<0.05	0.503
2–3	0.94	<0.01	0.272	0.91	<0.01	0.353	0.90	<0.05	0.503

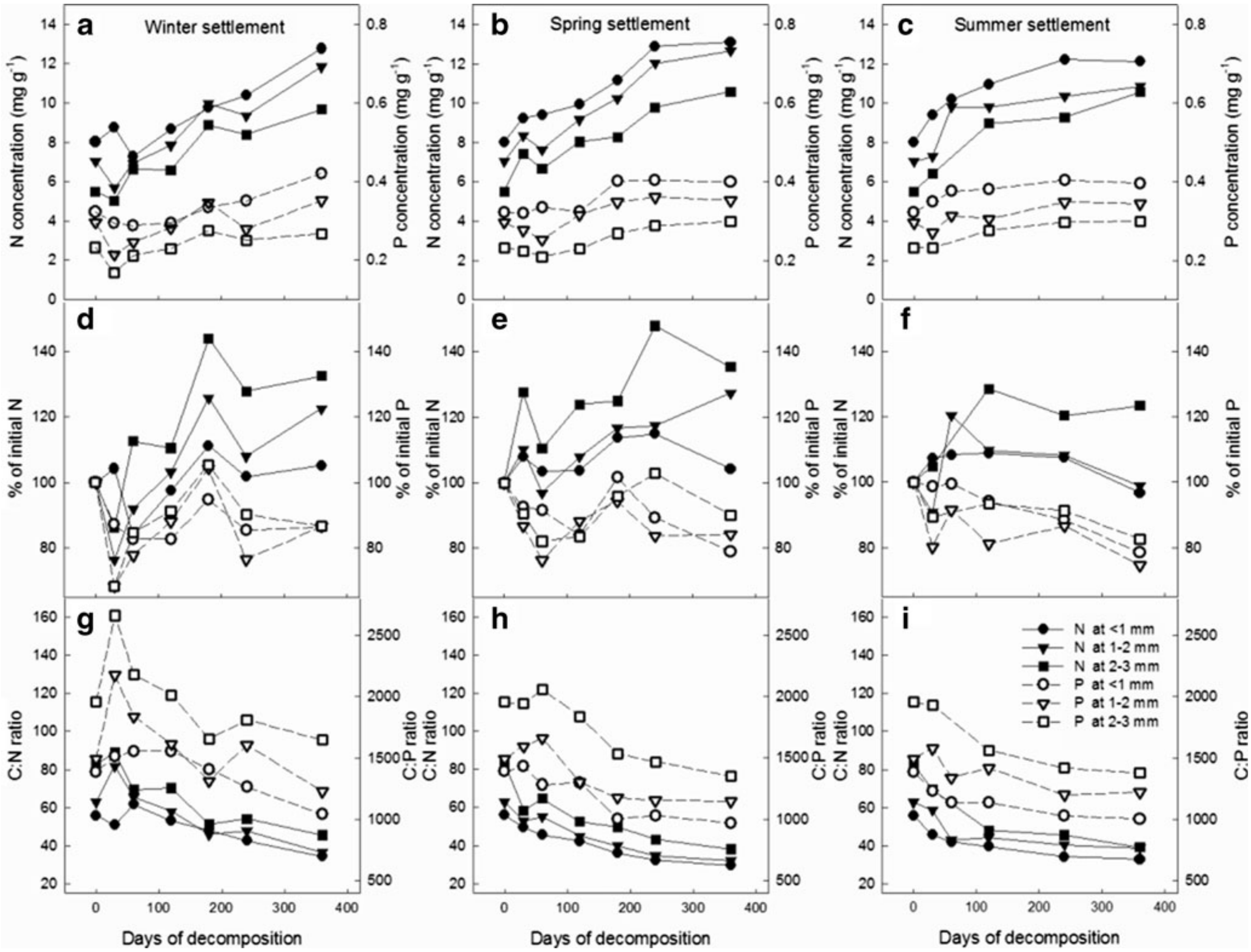

Fig. 3 Root N and P concentrations (**a**, **b**, **c**), % of initial root N and P (**d**, **e**, **f**), and root C/N and C/P ratios (**g**, **h**, **i**) of the three diameter classes (<1, 1–2, and 2–3 mm) in the winter settlement, spring settlement, and summer settlement during 360 days of decomposition. The % of initial N (P) in increase represents root N (P) immobilization, while the % of initial N (P) in decrease represents root N (P) release

(see Fig. 1). This indicated that the production and turnover rate of fine roots would not be different from the "decision matrix" calculation where the mortality of fine roots was considered. However, the lower fine root production and turnover rate may be caused by other reasons. The low estimation relative to that of Jourdan et al. (2008) may be partly due to our *Eucalyptus* trees which were in a younger stage (4.5-year-old). As fine roots could be easily affected by soil environmental factors (Eissenstat et al. 2000; Jackson et al. 1990), the other possible explanation might be related to the interaction between plant and the special subtropical climate in southern China. However, the mechanisms for fine root production and turnover in our study need further investigation.

In addition, when compared with other studies in natural forests or pure plantations in subtropical China, such as those of Wen et al. (1999) and Yang et al. (2004), the production and mass turnover in the *Eucalyptus* plantation were both much lower. In the two studies, they reported that the production of roots (diameter less than 2 mm) in four plantations ranged from 251 to 542 g m^{-2} year^{-1}, and the turnover rates ranged from 1.55 to 1.70 year^{-1}. They also reported that the root production in three natural forests were 242, 265, and 880 g m^{-2} year^{-1}, respectively, and the turnover rates were 0.57, 0.69, and 1.78 year^{-1}, respectively. In summary, compared to the *Eucalyptus* plantations in other regions and other forests in the same region as described earlier, the production and mass turnover of fine roots were relatively low in our fast-growth *Eucalyptus* plantations in young stage. These results reflected that the amount of nutrient returned by fine root turnover may be relatively small. The results may partly explain the soil nutrient deficiency in these *Eucalyptus* plantations and thus supported our hypothesis. We therefore proposed that the

Eucalyptus plantations under the short rotation system, usually 4–6 years in a rotation (data cited from China *Eucalyptus* Research Centre), should require nutrient fertilization to sustain their fast growth in southern China.

4.2 Effects of root N concentration across different diameter classes on root decomposition rate

We estimated the linear relationship of the root mass remaining (%) with the root initial N concentration in different diameter classes (<1, 1–2, and 2–3 mm) during 120 days (early phase) and 360 days of decomposition. The results showed that their correlations were not significant either during the early decomposition (120 days) or after 360 days (all $P>0.14$), except for the correlation in the winter settlement after 360 days of decomposition ($P=0.023$). These indicated that the initial N concentration had weak effects on the root decomposition because the mass loss mostly did not significantly change with N status. The weak relationship between N concentration and mass loss in the early phase of root decomposition in our study was different from some previous studies (e.g., Silver and Miya 2001; Fan and Guo 2010). Generally, the roots at small-diameter class with relatively high N concentrations decompose faster than the larger ones during short-term decomposition (Silver and Miya 2001; Yang et al. 2004). However, some studies had reported that the nutrient-rich finer roots decomposed more slowly than the nutrient-poor coarser roots in tree species (Fan and Guo 2010; Langley and Hungate 2003). The factors of root chemical quality on mass loss may be interactive and complicated. Fan and Guo (2010) indicated that the difference of the decomposition rates of roots across different orders (diameter classes) may be associated with initial C quality (e.g., concentrations of soluble carbohydrates, acid-insolubles) and N concentrations. It indicated that the weak effects of N concentrations on root mass loss in our study may be partly because of the relatively stronger effects of root C quality on mass loss. Another reason may be the limited range of root N concentrations (5.5–8 mg g^{-1}) in the regression of their relationships. The results showed that the root decomposition k values estimated by exponential decay model appeared to decrease with diameter class. This could be explained by the integrated effect of C quality and N concentration (e.g., lignin/N ratio; McClaugherty et al. 1984).

4.3 Seasonal effects of litterbag settlement on root decomposition rate

In our study, the fine roots exhibited two main periods of mortality within a year. The first period of fine root mortality from March to May (the start of aboveground growing season) probably relate to the replacement of aged roots by new roots, which are suggested to be with a relatively strong absorbing capacity for water and nutrients than old roots. The depression of soil moisture on the physiological activities of fine roots may cause the second period of their mortality from September to November (the dry season). Nevertheless, these results suggested the need for different time (seasons) of litterbag settlement for studying the decomposition of *Eucalyptus* roots in our subtropical region with significant seasonal variation.

The correlations between the mean soil temperature (per 30 days) and the root mass loss decreased over time, of which the determination coefficients (r^2) decreased from 0.93 ($P<0.0001$) in 1–120 days to 0.54 ($P=0.038$) in 121–240 days to 0.19 ($P=0.330$) in 241–360 days (Fig. 4). The results showed that the soil temperature had stronger effects on the root mass loss in the early period than the later period. The mass loss of litter was strongly affected by environmental factors in the early period (Aerts 1997) because the fresh litter rich in labile carbohydrates can be easily leached and mineralized by microbes (McClaugherty et al. 1984). In contrast, the effects of environmental factors on mass loss may become less important in the later microbial decomposition as the labile carbohydrates would decrease over time. Our results indicated that the high variation of root decomposition k values estimated by exponential decay model across litterbag settlements may be partly due to the different effects of soil temperature on root mass loss between the early and later periods. In a similar study (eight times of litterbag settlement during a year), Li et al. (2011) also indicated that the various decomposition k values of leaf litter caused by the settled time could be explained by the relatively strong effect of soil temperature in the early decay period. Soil moisture may also be another important factor on litter decomposition, but we

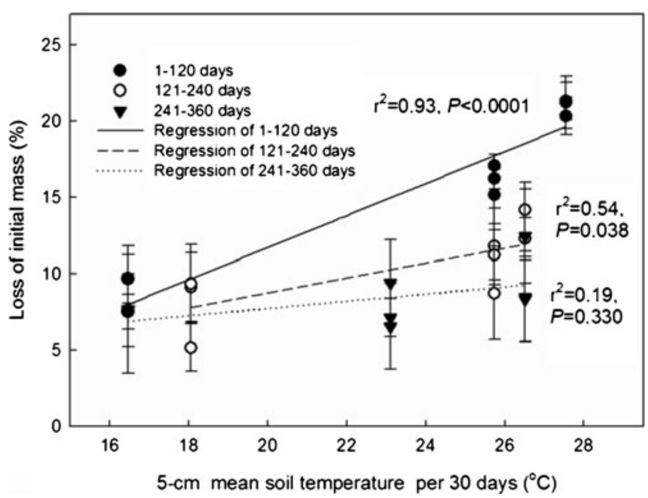

Fig. 4 The correlations between the root mass loss (%) of the three diameter classes (<1, 1–2, and 2–3 mm) and the mean soil temperature per 30 days in the winter settlement, spring settlement, and summer settlement during 1–120 days (*filled circle*), 121–240 days (*unfilled circle*), and 241–360 days (*filled inverted triangle*) of decomposition. Data points which showed very little or negative mass change during 120 days of decomposition were excluded in the regression

did not evaluate its effect on root decomposition. Previous studies found that soil temperature was more important than soil moisture to influence soil heterotrophic respiration (Wang et al. 2011). This suggested that soil temperature may be the dominant factor in explaining the variation of root decomposition rates caused by the season of litterbag settlement in lower subtropical China.

Although the chemical characteristics of roots (e.g., N or lignin concentration) and their decay environment in soil are different from those of leaf litter (Bloomfield et al. 1993; Ostertag and Hobbie 1999; Zhang et al. 2009), our study together with the related study by Li et al. (2011) showed that the time of litterbag settlement would have a strong effect on decomposition rate in subtropical China with significant seasonal variation. As litter decomposition was suggested to be lasting for several years, even more than a decade, we proposed that the seasonal effect of litterbag settlement on long-term litter decomposition needs to be further assessed. Nevertheless, it was suggested that we should consider the seasonal effect of litterbag settlement on decomposition rate during a short-term period in the regions with significant seasonal variation, such as subtropical China.

4.4 Controls on root N and P mineralization during root decomposition

The differences in the fractions of initial N immobilized (% of initial N) across different diameter classes (see Fig. 3) suggested the influence of litter quality, such as N concentrations or C/N ratios, on root N mineralization. Root decomposition is a process in which microbes mineralize root C and N to meet the balance of C and N in their biomass. When the C/N ratios of litter are higher than those of microbes, the microbes may be in an N-limited condition (Cleveland and Liptzin 2007). This N limitation was expected to be more severe in decomposing litter with higher C/N ratios (lower N concentrations), and thus microbes would accumulate more N (Fig. 3; Manzoni et al. 2008; Parton et al. 2007). In contrast, the N limitation would be relatively light in the litter with lower C/N ratios. Hence, the variation of root N immobilized (% of initial N) in our study may be due to the difference in root C/N ratios across different diameter classes. Our results also showed that the fractions of initial N immobilized were similar across different litterbag settlements, indicating the relatively weak effect of the settlement seasons on N mineralization. However, the root N in early decomposition in the winter settlement showed a short period of release in early period, which was different from that in the spring settlement and the summer settlement (see Fig. 3d–f). This difference may be ascribed to the less limited N of microbes (i.e., their relatively low C/N ratios) because of the slower mass loss (i.e., less root C mineralized into microbes) in the winter settlement compared to those in the spring and summer settlements (see Fig. 2).

The similarity in the fractions of initial root P (% of initial P) across different diameter classes (see Fig. 3) suggested that the litter quality, such as P concentration or C/P ratios, may have weak effects on P mineralization (immobilization or release). In a leaf decomposition experiment, Moore et al. (2006) found that when the litter C/P ratio was below 700 (the critical C/P ratio), the litter P would release, but our results did not support the root critical C/P ratios as the root P experienced a process of released–immobilized–released with a decreasing trend of root C/P ratios from 2,000 to 1,000 over time (see Fig. 3g–i). This might indicate that the balance of C/P ratios in microbial biomass may not be as strict as their C/N ratios. The microbes would get available P from litter decomposition and soil. We suggested that the microbes may obtain much more available P from soil than those from root P mineralization to keep their balance of C/P ratios. This could explain why the critical C/P ratios were not found in the root P mineralization in our study but in the leaf P mineralization (Moore et al. 2006). Our results also showed that the patterns of P immobilization and release were similar among different litterbag settlements (see Fig. 3d–f), suggesting that the effects of settlement season on P mineralization were weak. Therefore, the underlying mechanisms for root P mineralization might be complicated and should deserve further study.

5 Conclusions

Our studies on fine root production, turnover, and decomposition provide insight into nutrient cycling between plant and soil in *Eucalyptus* plantations. Our results showed that fine roots had relatively low production and turnover rate, which may partly explain the potential soil degradation under the short rotation systems. The variation of root productions, turnover, decomposition rates, and nutrient dynamics across different diameter classes suggested that we should consider the effects of root diameter size on fine root dynamics to accurately assess their roles in nutrient cycling between plant and soil. The root mass loss from litterbag across different diameter classes mostly did not show a significant correlation with the root N concentration. These reflected that N concentration might have a weak effect on root decomposition rate. The seasons of litterbag settlement caused differences in the mass loss process and the root decomposition constant (k values). The high variation of the root decomposition k value may be due to the stronger effects of soil temperature on mass loss in early period than that in later period. These suggested that the seasonal effect of litterbag settlement should be considered in estimating root decomposition k value, particularly during the short-term decomposition, in subtropical China with significant seasonal variation. The root N showed different patterns across different diameter classes but had similar patterns among different litterbag settlements. These indicated the control of the root C/N ratios on the microbial root N mineralization. The root P patterns of immobilization and release were both similar across different diameter classes and among the litterbag settlements. These reflected that the underlying mechanisms for the root P mineralization might be complicated and should deserve further study.

Acknowledgments This study was supported by 973 Program 2011CB403202. We thank Dr. Wenjuan Huang for her help in English improvement. We thank Dingsheng Mo for his help in litterbag preparation and Shengxing Fu for his help in sampling. We also thank Zhuoyin Lai, Hongying Li, and Juan Miao for their help in root chemical analysis.

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