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Season-dependent fine root production at a deciduous *Quercus serrata* plantation in Japan

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Abstract:

The production of fine roots (diameter ≤2 mm) contributes considerably to carbon cycling in forest ecosystems. Fine roots constitute a significant organic matter pool with high net primary productivity and turnover. In this study, fine root decomposition, mortality, and production were estimated at a *Quercus serrata* Murr. plantation in Japan by using rates of diameter-dependent root mortality, decomposition, and the thickening method employed. Sequential soil core and litter bag techniques were used to collect field data. The experiments were set up in a 20×20 m plot. The data were collected five times (May, August, November, and December 2013, as well as April 2014) during a one-year period, and fine roots were classified into ones with a diameter of ≤1 mm and others of 1-2 mm. The results indicate that fine root decomposition, mortality, and production in a *Q. serrata* plantation are season-dependent and are higher in the summer compared to the winter. In the summer, production reached 1.365 g m^{-2} day^{-1}, while it was lower than 0.132 g m^{-2} day^{-1} in the winter. The total fine root production of the *Q. serrata* plantation was 1.364 tonnes ha^{-1} $year^{-1}$. The mortality was 0.440 tonne ha^{-1} $year^{-1}$, and the amount decomposed to return nutrients to the soil was 0.108 tonne ha^{-1} $year^{-1}$.

Keywords: **climate, continuous inflow method, decomposition, fine root differentiation, time interval.**

Classification number: **3.1**

Introduction

Roots with a diameter of ≤2 mm are called fine roots. Their production plays an important role in forest carbon cycling [1]. Fine roots have high net primary production (NPP) and turnover because of their short longevity - up to several months [1-2]. It has been estimated that fine root production may contribute 75% of the total NPP in a forest [2]. Several factors, including vegetation type, soil fertility, temperature, and precipitation, affect the production of fine roots [1, 3]. Using a global database, Finer, et al. [1] indicated that fine root production and turnover increase from boreal to tropical forests. Fine root production and turnover are estimated by different methods, which may cause different estimations even in the same site [4].

A number of methods exist for estimating fine root production [5-7], and there is no standard method available. Comparative studies indicate significant differences in fine root estimation between methods [8]. The true answer regarding the best method is unknown because each method has potential biases, leading to over- or underestimation [3, 8]. Recently, Tran, et al. [9] developed a new method for estimating fine root production based on the continuous inflow method [7], which assumes that fine roots grow, die, and decompose simultaneously. This method [9] provides more accurate fine root production estimation, as it considers the difference in the amount and decomposition ratios of thinner and coarser fine roots (those of ≤1 mm in diameter and those 1-2 mm in diameter).

The objective of this study is to estimate fine root production at a deciduous *Quercus serrata* Murr. (*Q. serrata*) plantation by using rates of diameter-dependent root mortality, decomposition, and the thickening method employed.

Materials and methods

Study site

This study was conducted in a pure plantation of the deciduous *Q. serrata* at $36^0 00'30''$N, $104^0 07'54''$E in

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Tsukuba, Japan. Trees were planted with a spacing of approximately 5×4 m. At the time of the experiment, the plantation had a stem height of 12-30 m and a diameter at breast height of 15-35 cm. A one-year field observation revealed that *Q. serrata* trees produce leaves in early April and shed in mid-October. During the December-April period, no leaves are available on trees. The site has an average annual precipitation of 1,283 mm and an average monthly temperature of 13.2^{0}C. The maximum temperature was recorded in August (35^{0}C), while minimum temperature was recorded in January (0.4^{0}C).

Experiment

Data were collected at a 20×20 m plot. Sequential soil cores and litter bag techniques were used to collect data. A tube of 32 mm in diameter and 45 cm in length was used to take soil samples vertically to a depth of 21 cm in May, August, November, and December 2013, as well as April 2014. During each sampling period, 24 soil cores were collected randomly from a 20×20 m plot. The soil collected was washed and sieved through water to separate fine roots. A steel sieve with a mesh size of 0.2 mm was used. Water was poured directly on the soil in the sieve with high pressure to break and wash away soil particles, and then fine roots were recovered manually. The dead and living fine roots were classified by their colour, resilience, and structural integrity. Generally, dead fine roots have a dark/black colour, while living fine roots are bright and yellow-brown in colour. Fine roots were then further classified into two classes as those with a diameter of ≤ 1 mm and those with a diameter of 1-2 mm. Those categorised as fine roots were dried at 80^{0}C until a constant mass and then weighed (accuracy of 0.0001 g) for a mass of live roots (biomass/*B*), as well as that of dead roots (necromass/*N*) for both size classes, separately.

Litter bags (size of 10×15 cm) were made of special cloth, which was produced by Toyobo Co., Osaka, Japan. The cloth had a pore size of 6 µm, which can block the ingrowth of fine roots. Dead fine roots used in the litter bag technique were collected from the field and then oven-dried for a constant mass as mentioned above. Each bag contained a fine root mass of 0.7-1.3 g, which was inserted inside the bag with some fine soil collected from the same site. Before burying them in the field, litter bags were soaked in ordinary water for 24 hours to ensure that the moisture content of the fine roots in the litter bags was similar to that in nature. In total, 60 bags were made and systematically buried in May 2013 at a 20×20 m plot with a distance of 2 m x 2 m between each other. At the same time as the soil core collection (August, November, and December 2013, as well as April 2014), 15 litter bags were collected. The collected bags were washed and sieved with water for the remaining fine roots, which were then oven-dried for a constant mass. The remaining mass was weighed (accuracy of 0.0001 g) and used to estimate the decomposition ratio (γ) by the following equation: {γ = (initial mass - remained mass)/ initial mass}.

Data analysis

The continuous inflow method [7] was applied to estimate fine root production (*P)* (Eq. 1), mortality (*M)* (Eq. 2), and decomposition (*D)* (Eq. 3).

$$P = (B_j - B_i) + (N_j - N_i) + \left[-(N_j - N_i) - \left((N_j - N_i)/\gamma_{ij} + N_i\right) * ln(1 - \gamma_{ij})\right] \quad (1)$$

$$M = (N_j - N_i) + D \quad (2)$$

$$D = -(N_j - N_i) - ((N_j - N_i)/\gamma_{ij} + N_i) * ln(1 - \gamma_{ij}) \quad (3)$$

where B_i and B_j represent the masses of living fine roots (biomass) at times t_i and t_j, respectively ($t_j > t_i$), N_i and N_j denote the masses of dead fine roots (necromass), and γ_{ij} is the decomposition ratio.

The estimation was conducted for two size classes separately (those with a diameter of ≤1 mm and those with a diameter of 1-2 mm). Then, the total decomposition, mortality, and production of all fine roots (those with a diameter of ≤2 mm) were calculated from two classes.

Differences in fine root biomass (the mass of living fine roots) and necromass (the mass of dead fine roots) amongst the five collection periods (May, August, November, and December 2013, as well as April 2014) - as well as in fine root decomposition ratio, production, mortality, and decomposition amongst four collection intervals (May-August, August-November, November-December, and December-April) - were assessed by univariate analysis of variance (ANOVA) and post-hoc tests. All analyses were conducted using SAS 9.2 (SAS Institute Inc., Cary, NC, USA).

Results

The fine root biomass, necromass, and decomposition ratio differed significantly in the five collection periods and collection intervals (Table 1). In 1-2 mm fine roots, the highest biomass was found in December 2013 (94.2 g m^{-2}), while the lowest biomass was observed in May 2013 (33.9 g m^{-2}). The highest necromass in 1-2 mm fine roots was appeared in November 2013 (32.3 g m^{-2}), and the lowest was found in May 2013 (14.8 g m^{-2}). In terms of the decomposition ratio, the highest figure was found during the May-August period (0.00085 day^{-1}), and the lowest was recorded during the December-April period (0.00010 day^{-1}). A similar pattern was found in ≤ 1 mm fine roots. The highest biomass was found in December 2013 (106.3 g m^{-2}),

Table 1. The fine root biomass, necromass, and decomposition ratio (γ_{ij}) (± standard error) of two size classes.

Collection dates	1-2 mm fine roots			≤1 mm fine roots		
	Biomass (g m^{-2})	*Necromass (g m^{-2})*	γ_{ij} *(day^{-1})*	*Biomass (g m^{-2})*	*Necromass (g m^{-2})*	γ_{ij} *(day^{-1})*
May, 2013	33.9 ± 4.5^{a}	14.8 ± 1.6^{a}		63.0 ± 6.1^{a}	27.5 ± 2.2^{a}	
August, 2013	38.0 ± 4.1^{a}	16.1 ± 1.5^{a}	$0.00085\pm.00009^{a}$	64.7 ± 6.2^{a}	27.4 ± 2.5^{a}	$0.00145\pm.00015^{a}$
November, 2013	60.6 ± 5.8^{b}	32.3 ± 2.9^{b}	$0.00038\pm.00004^{b}$	83.6 ± 7.6^{b}	44.7 ± 4.5^{b}	$0.00052\pm.00009^{b}$
December, 2013	94.2 ± 9.2^{c}	30.6 ± 2.6^{b}	$0.00019\pm.00001^{c}$	106.3 ± 10.1^{c}	34.6 ± 3.2^{c}	$0.00021\pm.00001^{c}$
April, 2014	52.4 ± 4.9^{d}	18.2 ± 1.7^{a}	$0.00010\pm.00001^{d}$	54.5 ± 4.9^{e}	19.0 ± 1.8^{d}	$0.00010\pm.00001^{d}$

Different letters ($^{a, b, c, d, e}$) in a column indicate significant differences of means at $p = 0.05$.

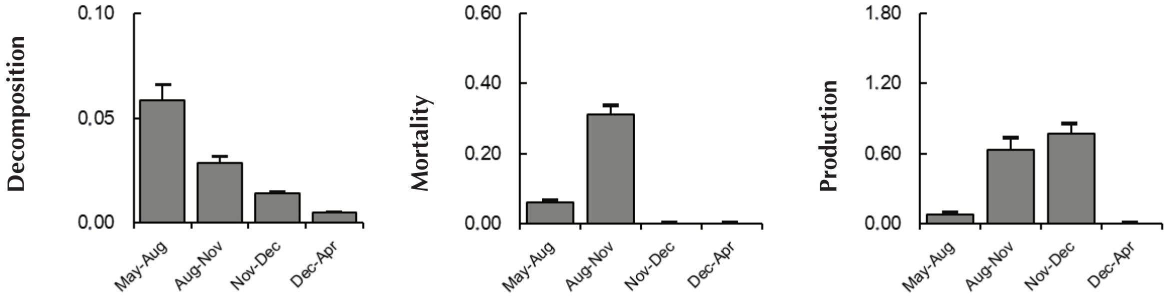

Fig. 1. Decomposition, mortality, and production (g m^{-2} d^{-1}) of ≤1 mm fine roots. Bars indicate + standard error.

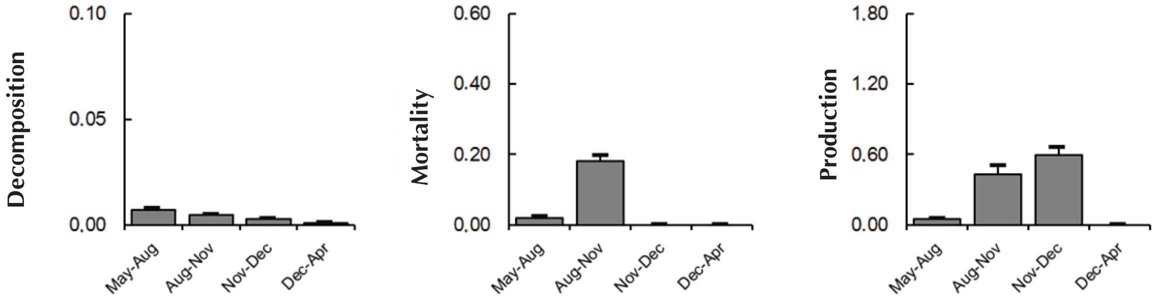

Fig. 2. Decomposition, mortality, and production (g m^{-2} d^{-1}) of 1-2 mm fine roots. Bars indicate + standard error.

while the lowest biomass was discovered in May 2013 (63.0 g m^{-2}). The highest necromass was found in November 2013 (44.7 g m^{-2}), and the lowest was recorded in August 2013 (27.4 g m^{-2}). In terms of the decomposition ratio, the highest figure was found during the May-August period (0.00145 day^{-1}), and the lowest was discovered during the December-April period (0.00010 day^{-1}).

The fine root decomposition, mortality, and production in both size classes of ≤1 mm (Fig. 1) and 1-2 mm (Fig. 2) were season-dependent, and the trends were similar in both classes. The highest decomposition was found during the May-August period (0.058 g m^{-2} day^{-1} for the ≤1 mm class and 0.0072 g m^{-2} day^{-1} for the 1-2 mm class; Figs. 1 and 2), while the lowest decomposition was recorded during the December-April period. The highest mortality was found during the August-November period (0.311 g m^{-2} day^{-1} for the ≤1 mm class and 0.186 g m^{-2} day^{-1} for the 1-2 mm class), and the lowest mortality was observed during the December-April period for both classes. The highest production levels occurred during the November-December period (0.769 g m^{-2} day^{-1} for the ≤1 mm class and 0.595 g m^{-2} day^{-1} for the 1-2 mm class). The lowest production was recorded during the December-April period for both classes.

The total fine root decomposition, mortality, and production of both classes (Fig. 3) had the same trends in each class (Figs. 1 and 2), with the highest decomposition during the May-August period (0.066 g m^{-2} day^{-1}) and the lowest during the December-April period; the highest mortality during the August-November period (0.493 g m^{-2} day^{-1}) and the lowest during the December-April period; the highest production during the November-December period (1.36 g m^{-2} day^{-1}) and the lowest during the December-April period (Fig. 3).

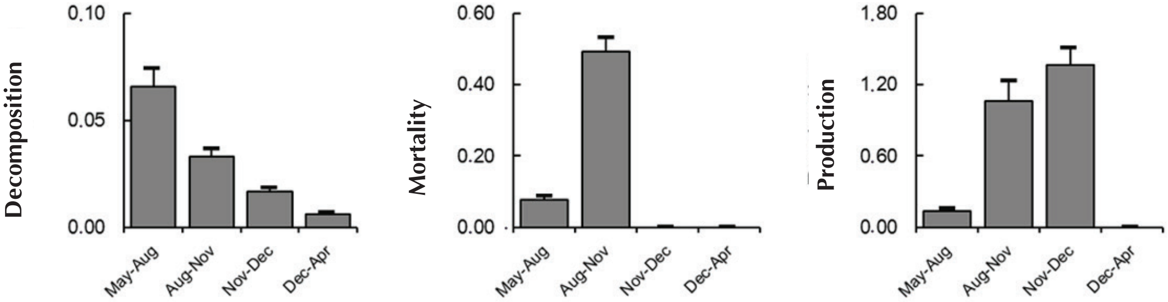

Fig. 3. Decomposition, mortality, and production (g m^{-2} d^{-1}) of all fine roots (≤2 mm). Bars indicate + standard error.

In this study, the *Q. serrata* plantation had a fine root decomposition of 0.108 tonnes ha^{-1} year^{-1}, a mortality of 0.440 tonnes ha^{-1} year^{-1}, and a production of 1.364 tonnes ha^{-1} year^{-1} (Fig. 4).

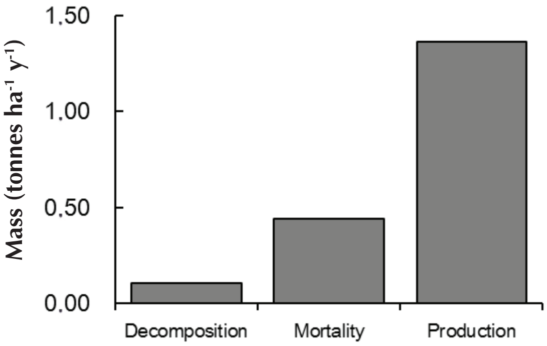

Fig. 4. Total decomposition, mortality, and production of fine roots in a 1-year duration.

Discussion

The fine root production of *Q. serrata* is season-dependent (Figs. 1 and 2). The *Q. serrata* plant produces leaves in the early summer (April) and sheds in the early winter (mid-October). The quick growth of fine roots during the April-May period and the peak during October correspond to leafing and shedding, respectively [10]. Leafing requires energy and nutrients to support the growth of numerous new leaves; therefore, fine roots must grow quickly to meet such requirements, sustaining tree life. During the winter when there are no leaves, trees still require energy while there is no photosynthesis, so they must store energy during photosynthesis. Thus, the high level of fine root production before shedding leaves could be explained by saving energy for the winter.

The decomposition of litter in general and fine roots, in particular, is controlled by several factors, such as environmental conditions (temperature, humidity) and quality of the litter itself (nutrient content) [11-12]. The low decomposition in the present study (Fig. 4) was probably controlled by temperature. Since there is a prolonged winter of 6 months, the temperature dropped to -2^{0}C with snowfall during the field experiment, leading to inhibited microorganism activity for the decomposition of dead fine roots. In addition, *Q. serrata* sheds all leaves in winter, leading to large amounts of organic matter on the forest floor. Therefore, the decomposing fine roots were limited because of the overload of organic matter [13].

The amount of dead fine roots was also low in the present study (Fig. 4; less than 30% production), which indicates less organic matter returning to the soil from fine roots, leading to low soil nutrient content. This phenomenon is probably a physiological reaction of *Q. serrata* to the low temperatures in winter [9-10]. If more fine roots die, then new fine roots must grow in the following year to support the tree's growth. This process requires a great deal of energy, but trees cannot absorb nutrients from the soil or conduct photosynthesis because leaves are not available in the winter. Therefore, the fine root decomposition, mortality, and production of deciduous forests differ from those of evergreen broadleaved forests [14, 15].

Several factors affect fine root production, including forest type and age, climate, and soils. The fine root production in this study was 1.36 tonnes ha^{-1} year^{-1}. It was 5.78 tonnes ha^{-1} year^{-1} in a secondary *Q. serrata* forest in Ohtsu, Japan [9]. According to another study, fine root production was 3.65 tonnes ha^{-1} year^{-1} [15] and 1.13 tonnes ha^{-1} year^{-1} in old-growth and secondary [14] evergreen tropical forests, respectively, in Vietnam. Those figures demonstrate the significant difference of fine root production amongst sites. Therefore, estimating fine root production locally is becoming important for a deep understanding of fine root functioning in the forest carbon cycle and nutrient return.

Conclusions

The fine root decomposition, mortality, and production at a *Q. serrata* plantation were estimated based on the continuous inflow method to separate fine roots into two classes: ≤1 mm in diameter and 1-2 mm in diameter.

Mortality and production were season-dependent, and they were higher in the summer as compared to the winter.

The total production of the study forest was 1.364 tonnes ha^{-1} year^{-1}, of which mortality accounted for 0.440 tonnes ha^{-1} year^{-1}. In a duration of one year, 0.108 tonnes ha^{-1} year^{-1} of dead fine roots decomposed to return nutrients to the soil.

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