Methodological Comparisons of Absorptive and Transport Fine Root Production, Mortality and Decomposition in A Loblolly Pine Plantation Forest

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Methodological comparisons of absorptive and transport fine root production, mortality and decomposition in a loblolly pine plantation forest

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Abstract

Background and aims Fine roots can be functionally classified into an absorptive fine root pool (AFR) and a transport fine root pool (TFR) and their production, mortality and decomposition play a critical role in forest soil carbon (C) cycling. Different methods give significant estimates. However, how methodological difference affects AFT and TFR production, mortality, and decomposition estimates remains unclear, impeding us to accurately construct soil C budgets.

Methods We used dynamic-flow model, a model combining measurements of litterbags and soil cores, and balanced-hybrid model, a model combining measurements of minirhizotrons and soil cores, to quantify these fine root estimates in a managed loblolly pine forest.

Results Temporal changes in production, mortality or decomposition estimates using both models were not different for both AFRs and TFRs. Annual production, mortality, and decomposition were comparable between AFRs and TFRs when measured using the dynamic-flow model but significantly higher for AFRs than for TFRs when measured using the balanced-hybrid model. Annual production, mortality and decomposition estimates using the balanced-hybrid model were 75%, 71% and 69% higher than those using the dynamic-flow model ($P < 0.05$ for all), respectively, for AFRs, but 12%, 6% and 5% higher than those using the dynamic-flow model ($P > 0.05$ for all), respectively, for TFRs. Model test showed that the balanced-hybrid model had greater estimation accuracy than the

dynamic-flow model. Lower AFR estimates using the dynamic-flow model appeared to result from the underestimated AFR mass loss rate induced by the litterbag method.

Conclusions Methodological difference had a more significant impact on AFR estimates than on TFR estimates. These results have important implications for better quantifying the most dynamic fraction of fine root system and understanding soil C cycling.

Key words Fine root · production · mortality · decomposition · method · loblolly pine plantation

Introduction

Fine roots are the most physiologically active component of the below-ground plant system (McCormack et al. 2015). Studies conducted at the ecosystem scale showed that fine root growth consumed up to 63% of forests' net primary production (Vogt 1991; Litton et al. 2007). Fine root mortality and decomposition accounted for nearly half of organic carbon (C) input into the soil and around 10% of soil heterotrophic C emission, respectively (Ding et al. 2019; Li et al. 2020a). Thus, accurate measurements of fine root production, mortality and decomposition in forests are critical for quantifying forest C allocation and cycling and parameterizing climate change models (Woodward and Osborne 2000; Ghimire et al. 2016).

The conventional ingrowth core and soil core methods, which are low cost and ready-to-use, had been extensively applied to assess fine root production and mortality (Vogt et al. 1998; Brunner et al. 2013; Addo-Danso et al. 2016). However, these methods are not reliable because the amount of fine roots died and decomposed during sampling intervals cannot be reasonably quantified (Osawa and Aizawa 2012). To overcome this weakness, several improved ingrowth core/soil core models have been developed in which fine root biomass and necromass dynamics and mass loss rate were integrated into mass balance equations (Osawa and Aizawa 2012; Li et al. 2013; Li and Lange 2015). Dynamic-flow model is a new improved soil core model (Li and Lange 2015). In theory, it has greater estimation accuracy than other modified soil coring methods because fine root decomposition rate is assumed to decrease over time rather than remain constant (Santantonio and Grace 1987; Osawa and Aizawa 2012). This assumption has been supported by the facts that the labile and recalcitrant components in fine roots have different mass loss rates, with the former being depleted much faster than the latter (Fan and Guo 2010; Lin et al. 2011). Minirhizotrons allow to monitor the growth and death of individual fine roots continuously while overcoming the

cofounding of spatiotemporal variation (McCormack et al. 2014, 2015). The balanced-hybrid model is an improved minirhizotron-based model to quantify fine root production, mortality and decomposition by combining measurements of soil cores and minirhizotrons with mass balance equations (Li et al. 2020a).

Fine roots have been traditionally defined as distal roots with diameters <2mm. Recent studies have shown that the hierarchical root system is morphologically, chemically and functionally heterogeneous and can be partitioned into two pools: absorptive fine roots (AFRs) and transport fine roots (TFRs) (Pregitzer et al. 2002; McCormack et al. 2015). AFRs represent the most distal roots with relatively higher N concentration and shorter lifespan and involve primarily in the absorption of soil resources. In contrast, TFRs occur higher in the branching hierarchy with relatively lower N concentration and longer lifespan and function mainly as resource transportation and storage. Studying fine roots as two functional pools instead of a single diameter-based pool enables a more accurate characterization of fine root processes (Sun et al. 2012). It has been recommended that multiple methods should be used to yield more reliable fine root estimates (Hendricks et al. 2006; Addo-Danso et al. 2016). However, AFR and TFR production, mortality and decomposition have not been jointly quantified using dynamic-flow and balanced-hybrid models, leading to significant uncertainties in forest fine root C budgets. Loblolly pine (*Pinus taeda* L.) plantation forests cover 11 million hectares, accounting for 50% of the standing pine volume in the southern USA (Wear and Greis 2012). It has been estimated that over 1 billion seedlings are planted annually (Wear and Greis 2012). An improved understanding of AFR and TFR dynamics in loblolly pine plantation forests is critical for developing silvicultural and rotation strategies to increase C sequestration capacity.

In this study, we used the soil core method, litterbags, and minirhizotrons to assess biomass and necromass dynamics, mass loss pattern and growth and death rates of AFRs and TFRs in a managed loblolly pine forest. The objectives were to 1) use both the dynamic-flow model and the balanced-hybrid model to quantify AFR and TFR production, mortality, and decomposition in this forest, 2) assess to what extent methodological difference affects AFR and TFR estimates and 3) determine which method is more reliable.

Materials and methods

Study site

The study was conducted in a commercially managed loblolly pine (*P. taeda* L.) forest (35º48'N 76º40'W) located in the lower coastal plain of Washington County, North Carolina, USA. Mean annual precipitation and temperature for the period 2011-2017 were 1320mm and 12.2 °C, respectively. The topography of the area is flat (<5m above sea level) and on a Belhaven series histosol soil (loamy mixed dysic thermic terric Haplosaprists). The study area was harvested of trees and ditched/drained in the late 19th to the early 20th century before being converted to a commercial pine plantation. The forest was fertilized with nitrogen and phosphorus at the time of planting and mid-rotation. The soil C and nitrogen concentrations at 20cm depth were 26% and 1.0%, respectively. The mean canopy height, diameter at the breast height, and stand age during the study period were approximately 24 m, 33cm, and 23 years, respectively. For a full site description, refer to Noormets et al. (2010). Three plots, about 5m ×9m for each and 100m to 800m apart, were established at random in the plantation in 2013. Only loblolly pine fine roots were studied as they accounted for over 90% of total fine root mass in this forest.

Fine root biomass and necromass measurements

Fine root biomass and necromass were determined using the soil coring method. The number of soil cores required at both plot and stand-level was calculated using the methods in Bartlett et al. (2001) and Dornbush et al. (2002). In each plot, 8 cylindrical soil cores (3.0 cm diameter, 30 cm depth) were randomly collected on 6 sampling occasions from April 2016 to April 2017, forming 5 soil sampling intervals (Li et al. 2020a). Previous study showed that over 90% of fine roots were distributed in 0 – 30 cm soil layer. Collected soil cores were rinsed with clean tap water through a 0.5mm mesh sieve to isolate roots. We only studied loblolly pine fine roots as they accounted for over 95% of total fine root mass. Loblolly pine fine roots with light color and intact stele and periderm were regarded as live roots, while those with dark color and damaged stele and periderm were dead ones. In this study, AFRs represented the first and second-order roots, while TFRs were third-order roots and higher with diameter <2mm. Live and dead AFRs and TFRs were separated according to the procedures described in Li et al. (2020b). All fine roots were dried at 50 °C to a constant weight and weighed. The measurements of biomass and necromass in the soil cores were scaled to g m^{-2} over a 0-0.30 m soil layer.

104 Litterbag measurements

105 AFR and TFR mass loss rates were assessed using litterbags. To provide input parameters for dynamic-flow model,
106 we used four types of fine roots including live and dead AFRs and TFRs as the decomposing substrate in *in situ*
107 decomposition experiments. Each litterbag (20cm ×3.5 cm, 0.05 mm mesh) was evenly filled with about 0.15 g fine
108 root materials and inserted vertically into a 0-20cm of soil. This experimental design intended to have fine root
109 materials distributed evenly in different soil layers. The decomposition experiment began on 8 August 2016. The
110 litterbags were collected after 65, 105 and 310 days of incubation. On each sampling occasion, three litterbags of
111 each of the four root types were retrieved from each plot. Roots from the litterbags were rinsed with clear tap water,
112 carefully sorted, dried at 50 °C to a constant weight and then weighed.

113

114 Dynamic-flow model

115 AFR and TFR production, mortality and decomposition were determined using the dynamic-flow model (Li and
116 Lange 2015; Li et al. 2020b). Interval i was any given soil coring interval ($1 \leq i$) (year). $G_{I\text{-}i}$ and $G_{II\text{-}i}$ were the fine
117 roots that died before the start of interval i and in interval i, respectively. The mass loss patterns of $G_{I\text{-}i}$ and $G_{II\text{-}i}$ were
118 simulated by the litterbag method with dead and live roots used as decomposing substrates, respectively.

119 Fine root mass loss pattern was simulated using an exponential equation with only two parameters:

120 $$y(t) = y_0 e^{(-\lambda/k)(1-e^{-kt})} \quad (1)$$

121 where $y_{(t)}$ and y_0 are root mass at time t (year) and the start, respectively. The two parameters λ (year^{-1}) and k
122 (year^{-1}) were calculated based on the fine root mass remaining in litterbags collected on all sampling occasions using
123 nonlinear regression. e^{-kt} is fine root decomposition rate which is time-dependent. It is the highest at the beginning
124 and decreases over time.

125 The fine root mortality rate in interval i (μ_i) was assumed to be constant. The total production (g_i) mortality (m_i)
126 and decomposition (d_i) in interval i were calculated by the following equations,

127 $$g_i = B_i(0) - B_i + m_i \quad (2)$$

128 $$d_i = m_i - (N_i - N_i(0)) \quad (3)$$

$$N_{\text{I-i}} = N_{\text{i}}(0)\, e^{(-\lambda_{\text{I-i}}/k_{\text{I-i}})(1-e^{-k_{\text{I-i}}T})} \quad (4)$$

$$N_{\text{II-i}} = N_{\text{i}} - N_{\text{I-i}} \quad (5)$$

$$m_{\text{i}} = \mu_{\text{i}}\, \text{T} \quad (6)$$

where $B_{\text{i}}(0)$ and B_{i} represented the fine root biomass in soil cores sampled at the start and the end of interval *i*, respectively, $N_{\text{i}}(0)$ and N_{i} represented the fine root necromass at the start and the end of interval *I*, and $N_{\text{II-i}}$ and $N_{\text{I-i}}$ were the mass remaining of $G_{\text{II-i}}$ and $G_{\text{I-i}}$ at end of interval *i*, respectively. T was time length of interval *i*.

$$\mu_{\text{i}} = k_{\text{II-i}} N_{\text{II-i}} \frac{e^{-(\lambda_{\text{II-i}}/k_{\text{II-i}})e^{-k_{\text{II-i}}T}}}{E_1((\lambda_{\text{II-i}}/k_{\text{II-i}})e^{-k_{\text{II-i}}T}) - E_1(\lambda_{\text{II-i}}/k_{\text{II-i}})} \quad (7)$$

where $\text{E}_1(\text{z}) = \int_{\text{z}}^{\infty} \frac{\text{e}^{-\text{x}}}{\text{x}} \text{dx}$

was an exponential integral function (Abramowitz and Stegun, 1964, ch. 6).

$B_{\text{i}}(0)$, B_{i}, N_{i}, $N_{\text{i}}(0)$, $N_{\text{II-i}}$, and $N_{\text{I-i}}$ had the unit $\text{g}\cdot\text{m}^{-2}$. $\lambda_{\text{I-i}}$, $k_{\text{I-i}}$, $\lambda_{\text{II-i}}$, and $k_{\text{II-i}}$ were decomposition parameters for $G_{\text{I-i}}$ and $G_{\text{II-i}}$, respectively, calculated using Eq.1. $B_{\text{i}}(0)$, B_{i}, N_{i} and $N_{\text{i}}(0)$ were measured in the soil cores, $N_{\text{II-i}}$ was calculated by Eq. (4) and $m_{\text{i}} = \mu_{\text{i}} T$. Thus, g_{i} and d_{i} were calculated by Eqs. 2 and 3, respectively. g_{i}, m_{i} and d_{i} have the unit $\text{g}\cdot\text{m}^{-2}\text{year}^{-1}$.

Minirhizotron measurements

A total of 18 acrylic tubes (80 cm long, 6cm outer diameter) were installed in 2013 at a 45º angle to a vertical soil depth of 50cm in the three plots (5 to 8 tubes per plot). We took root images on 17 sampling dates from late April 2016 through late April 2017, which co-occurred with soil coring (Li et al. 2020a). Images were collected using a Bartz digital camera with the image capture software BTC I-CAP (Bartz Technology Corp., Carpinteria, CA, USA). Fine root length and diameter were quantified by analyzing the images with WinRHIZO software (Regents Instruments Inc., Quebec, Canada). AFR and TFR length production, mortality and standing length density (mean root length per unit root image area) were calculated based on the image analysis. An AFR or TFR was counted as dead if its diameter shriveled to half the original diameter, it showed signs of deterioration including fragmenting

and ectomycorrhizal fungal mantle detachment, or it was consumed by soil animals; otherwise, roots were considered as living (McCormack et al. 2014; Kou et al. 2018).

Balanced-hybrid model

Fine root length production (LP_i, m m^{-2} image) and mortality (LM_i, m m^{-2} image) in a given soil coring interval *i* were estimated from minirhizotron image analysis. LP_i and LM_i were calculated as the length of fine roots that were produced and died in interval *i*, respectively (Kou et al. 2018).

Fine root turnover (TR_i) and death rates (DR_i) in the interval were calculated as

$$TR_i = LP_i / SL_i \quad (8)$$

$$DR_i = LM_i / SL_i \quad (9)$$

where SL_i is the mean standing live fine root length of minirhizotron images captured at the start of interval *i* (m m^{-2} image).

g_i and m_i are assessed by combining measurements of minirhizotrons and soil cores (Hendricks et al. 2006; Li et al. 2020a).

$$g_i = B_i(0) \times TR_i \quad (10)$$

$$m_i = B_i(0) \times DR_i \quad (11)$$

$B_i(0)$ is fine root biomass at the start of interval *i*.

Resorting to Eq. 2, d_i can be calculated (Li et al. 2020a).

Model test

The efficacy of the models for estimating the production, mortality, and decomposition was tested by comparing the predicted with the measured AFR and TFR biomass in July using a subset of data not used for model parameterization. Smaller differences between predicted and measured biomass values mean greater estimation

175 accuracy. The predicted AFR and TFR biomass in July were calculated according to the procedures described in
176 Hendrick and Pregitzer (1993) and Hendricks et al. (2006).

177

178 Statistical analysis

179 The plots were considered as replicates (n = 3), and data collected (sub-replicates) within the same plot were
180 averaged before performing statistical analysis. One-way ANOVA or paired *t*-test was used to assess the differences
181 in means of measured fine root variables. The data were log-transformed to normalize variances among the
182 estimates of the two models before analysis when necessary. All data were analyzed using the SPSS statistical
183 software (version 17.0; IBM Corporation, Somers, NY 10589, USA).

184 **3. Results**

185 Biomass and necromass

186 AFR and TFR biomass showed the same temporal pattern, with the highest values in July and the lowest values in
187 January, while AFR and TFR necromass did not show evident peak and trough values during the whole study period
188 (Fig. 1). AFRs had significantly lower mean biomass than TFRs (67.8 ±5.3 vs. 88.7±2.9 g m^{-2}) (P<0.05). The mean
189 necromass of AFRs was lower than that of TFRs (41.2 ±2.8 vs. 50.4 ±5.2 g m^{-2}), but the difference was not
190 significant (P>0.05).

191

192 Mass loss rate

193 Live AFR substrates had significantly higher percent mass remaining than live TFR substrates at the late
194 decomposing stage, but dead AFR and TFR substrates had comparable percent mass remaining during the whole
195 study period (Fig. 2). All live root substrates decomposed significantly faster than dead root substrates (Fig. 2).

196

197 Temporal changes in fine root estimates

198 Temporal changes in fine root production, mortality and decomposition rates were generally the same between the
199 two models, with greater production in warmer months and greater mortality and decomposition occurring in cooler
200 months (Fig. 3). Production, mortality, and decomposition rates using dynamic-flow model were comparable
201 between AFRs and TFRs at all intervals. In contrast, production, mortality, and decomposition rates using the
202 balanced-hybrid model were significantly higher for AFRs than for TFRs in most intervals (Fig. 3). AFR production,
203 mortality and decomposition rates using the dynamic-flow model were significantly lower than those using the
204 balanced-hybrid model in most intervals, while TFR production, mortality and decomposition rates were not
205 significantly different between the two models in all intervals (Fig. 3).

206

207 Annual fine root estimates

208 Annual production, mortality, and decomposition were comparable between AFRs and TFRs in dynamic-flow
209 model estimation but significantly higher for AFRs than for TFRs in balanced-hybrid model estimation (Fig. 4).
210 Annual AFR production, mortality, and decomposition estimates using the balanced-hybrid model were 75%, 71%,
211 and 69% higher than those using the dynamic-flow model ($P < 0.05$ for all), respectively (Fig. 4). By contrast,
212 annual TFR production, mortality, and decomposition estimates using the balanced-hybrid model were 12%, 6%,
213 and 5% higher than those using the dynamic-flow model ($P > 0.1$ for all), respectively (Fig. 4). Annual fine root (i.
214 e. AFR + TFR) production, mortality, and decomposition were 119 ± 9, 133 ± 7, and 124 ± 11g m^{-2}, respectively,
215 when using the dynamic-flow model and 172 ± 11, 185 ± 12, and 171 ± 14 g m^{-2}, respectively, when measured using
216 the balanced-hybrid model.

217

218 Model Test

219 The measured AFR biomass in July was 28% and 15% higher than that estimated by the dynamic-flow model and
220 the balanced-hybrid model, respectively, while the measured TFR biomass in July was 19% and 11% higher than
221 that estimated by the dynamic-flow model and the balanced-hybrid model, respectively, indicating that the balanced-
222 hybrid model is more accurate than the dynamic-flow model.

223 **Discussion**

Fine root dynamics in forests have been increasingly studied by functional groups. However, most of the existing studies were two-dimensional minirhizotron analysis (McCormack et al. 2015; Kou et al. 2018) and did not include measurements of AFR and TFR biomass and necromass dynamics due to great labor and time input (Li et al. 2020b). Failing to assess the biomass and necromass dynamics impedes us to characterize soil C flux dynamics through AFR and TFR growth, death and decay. In this managed loblolly pine forest, AFRs had significantly lower biomass than TFRs but made comparable or even significantly greater contributions to total fine root production, mortality and decomposition than TFRs did, demonstrating that three-dimensional, function-based study is essential to accurately quantify fine root C budget.

Different methods yielded divergent fine root estimates, but all these methodological comparisons were diameter-based rather than function-based estimates (Hendricks et al. 2006; Osawa and Aizawa 2012; Li and Lange 2015). This knowledge gap has hindered us to better identify the strengths and weaknesses of each method and characterize the C allocation pattern within the root system. Our study for the first time used two types of models, a litterbag-based model and a minirhizotron-based model, to assess AFR and TFR production, mortality, and decomposition. AFR estimates were significantly more responsive to methodological difference than TFR estimates. Thus, methodological difference impact must be taken into account when assessing AFR and TFR dynamics.

Model test showed that the balanced-hybrid model had greater estimation accuracy than the dynamic-flow model. This can be explained by the inherent differences between them. In the balanced-hybrid model, the relative production and mortality rates at the tube-soil interface are assumed to be representative of those in bulk soil. This assumption has been proved to be very likely in previous studies (Hendrick and Pregitzer 1993; Hendricks et al. 2006; Li et al. 2020a). By contrast, in the dynamic-flow model, the estimation is based on the assumptions that fine root mortality rate remains constant in a certain interval and fine root mass loss pattern in litterbags is the same as that in bulk soil. Both are unrealistic as the mortality rate has been found to vary greatly among seasons (McCormack et al. 2014; Kou et al. 2018) and the decomposer community compositions in litterbags are different from those in natural soil (Bokhorst and Wardle 2013; Li et al. 2015; Beidler and Pritchard 2017). As a result, there would be greater errors in fine root estimates using the dynamic-flow model than using the balanced-hybrid model.

The significantly smaller AFR estimates of the dynamic-flow model compared to the balanced-hybrid model can be ascribed to the underestimated AFR mass loss rate by litterbags. In existing litterbag-based models including the

dynamics-flow model (Osawa and Aizawa 2012; Li and Lange 2015), mortality is positively related to the production and decomposition and fine root mass loss rate is the dominant determinant in mortality estimation. Higher fine root mass loss rate results in greater mortality estimate and therefore greater production and decomposition estimates. Since both models used the same biomass and necromass data, lower mass loss rate was the only cause for the smaller AFR estimates in the dynamic-flow model estimation. Whether litterbags significantly underestimate TFR mass loss rate is still unclear. But one thing is certain: litterbag studies misrepresent fine root mass loss rate by using unrepresentative root materials (Kunkle et al. 2009; Fan and Guo 2010; Sun et al. 2018) and disrupting the interactions between roots, soil fauna and soil microbes (Koide et al. 2011; Li et al. 2015; Beidler and Pritchard 2017; Moore et al. 2020).

The balanced-hybrid model can continuously track the growth and death of individual AFRs and TFRs while maintaining the rhizosphere associations (McCormack et al. 2015; Beidler and Pritchard 2017), which makes it effective in comparing fine root estimates between functional groups. By contrast, the capacity of the dynamic-flow model in distinguishing AFR and TFR estimates has been severely undermined by its inherent weaknesses. First, hyphal connections with AFRs and TFRs were cut off when processing the root samples in the decomposition experiment, representing a major departure from in situ conditions (Koide et al. 2011; Sun et al. 2018). Second, AFR and TFR litterbags were placed at different locations in forest soils, which results in a cofounding of spatiotemporal variation (i. e. the effect of variances in soil environmental conditions on the mass loss rate could cover the inherent difference in decomposability between AFRs and TFRs). For this reason, the higher estimates for AFRs than for TFRs in the balanced-hybrid estimation generally reflected the real situation, while the comparable estimates between AFRs and TFRs in the dynamic-flow model estimation was most likely an error of the model.

Conclusion

The balanced-hybrid has a greater estimation accuracy than the dynamic-flow model and differences between the two models did not significantly affect TFR estimates but significantly affected AFR estimates. Thus, the methodological difference must be considered to accurately characterize AFR and TFR dynamics and to quantify fine root C fluxes in forests.

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Declaration of Competing Interest

The authors declare that they have no conflict of interest.

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Fig.1 Absorptive (AFR) and transport (TFR) fine root biomass and necromass dynamics (g m^{-2} for the 0-0.30 m soil depth; n= 3; mean ± SE).

Note: AFR biomass and necromass have been reported. We use these values for the purpose of comparison.

Fig. 2 Mass loss patterns of live and dead absorptive (AFR) and transport (TFR) fine root substrates measured using litterbags in a managed loblolly pine forest (n= 3; mean ± SE; different letters stand for significant difference in means, $P<0.05$).

Fig. 3 Temporal changes in production, mortality and decomposition estimates of absorptive (AFR) and transport (TFR) fine roots using balanced-hybrid model (BH) and dynamic-flow model (DF) in a managed loblolly pine plantation forest (n= 3; mean ± SE). Different letters stand for significant difference in means ($P<0.05$).

Note: AFR production, mortality and decomposition estimates using balanced-hybrid model have been reported. We use these values for the purpose of comparison.

Fig. 4 Annual absorptive (AFR) and transport (TFR) fine root production, mortality and decomposition measured using balanced-hybrid model (BH) and dynamic-flow model (DF) in a managed loblolly pine plantation forest (n= 3; mean ± SE). Different letters stand for significant difference in means ($P<0.05$).

Figures

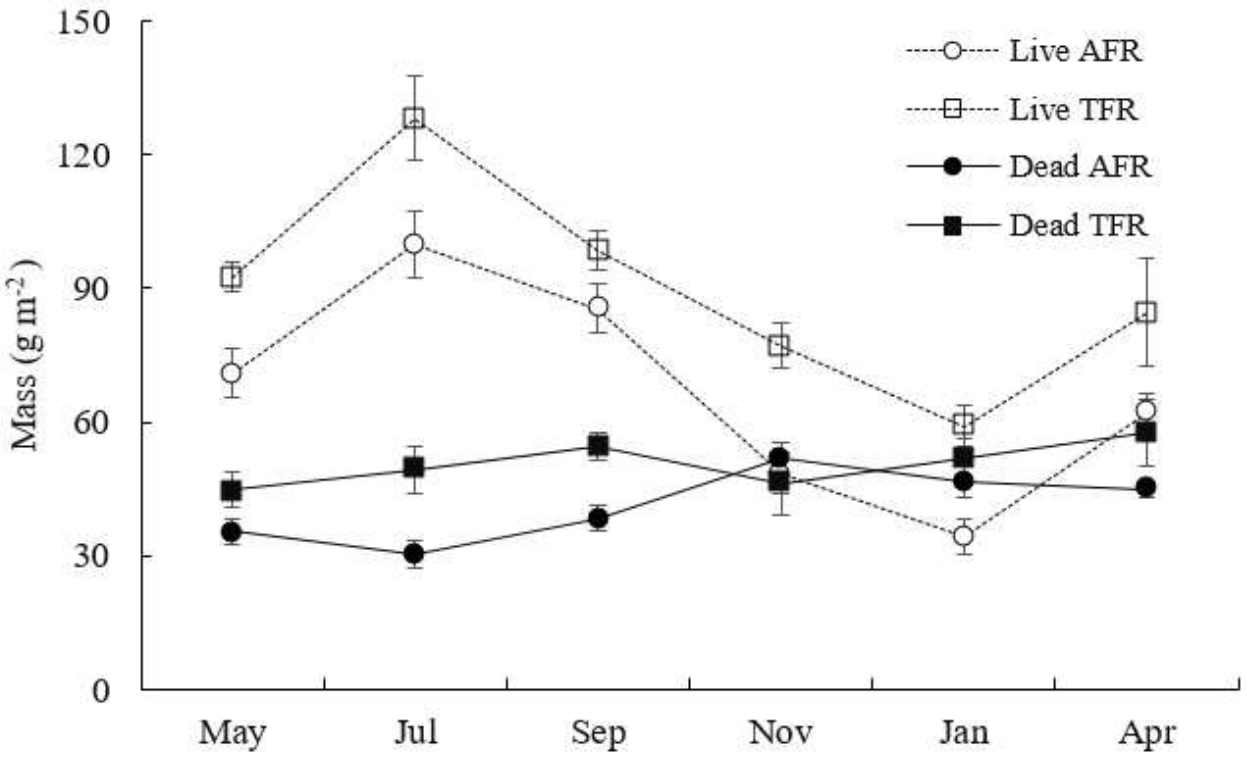

Figure 1

Absorptive (AFR) and transport (TFR) fine root biomass and necromass dynamics (g m-2 for the 0-0.30 m soil depth; n= 3; mean ± SE). Note: AFR biomass and necromass have been reported. We use these values for the purpose of comparison.

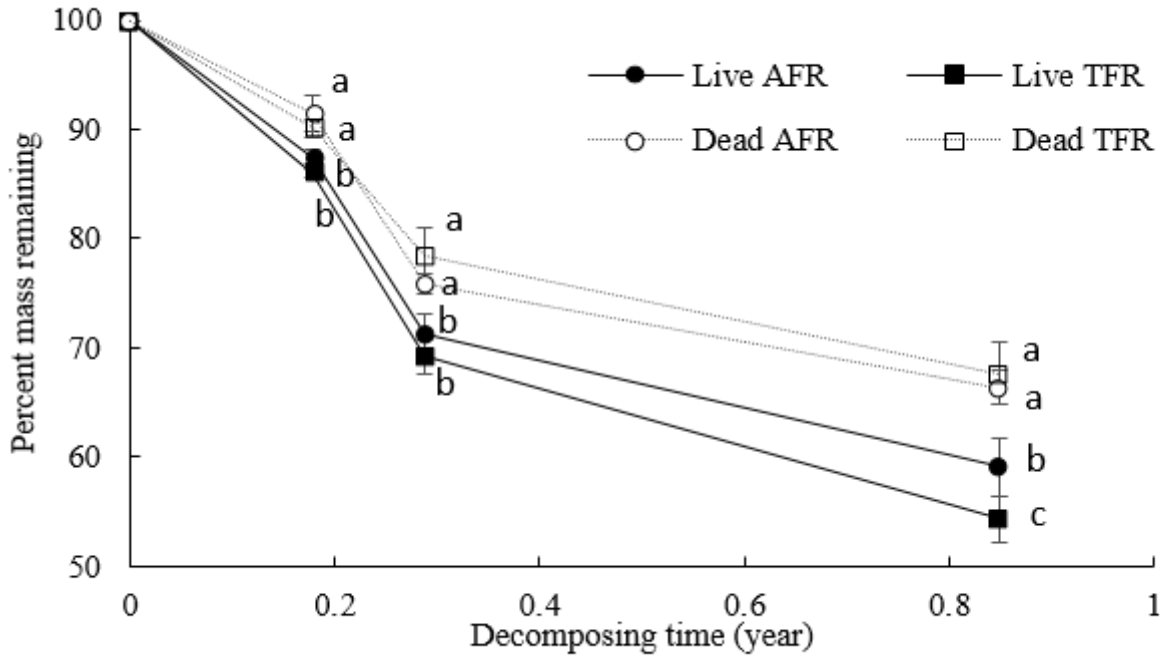

Figure 2

Mass loss patterns of live and dead absorptive (AFR) and transport (TFR) fine root substrates measured using litterbags in a managed loblolly pine forest (n= 3; mean ± SE; different letters stand for significant difference in means, $P<0.05$).

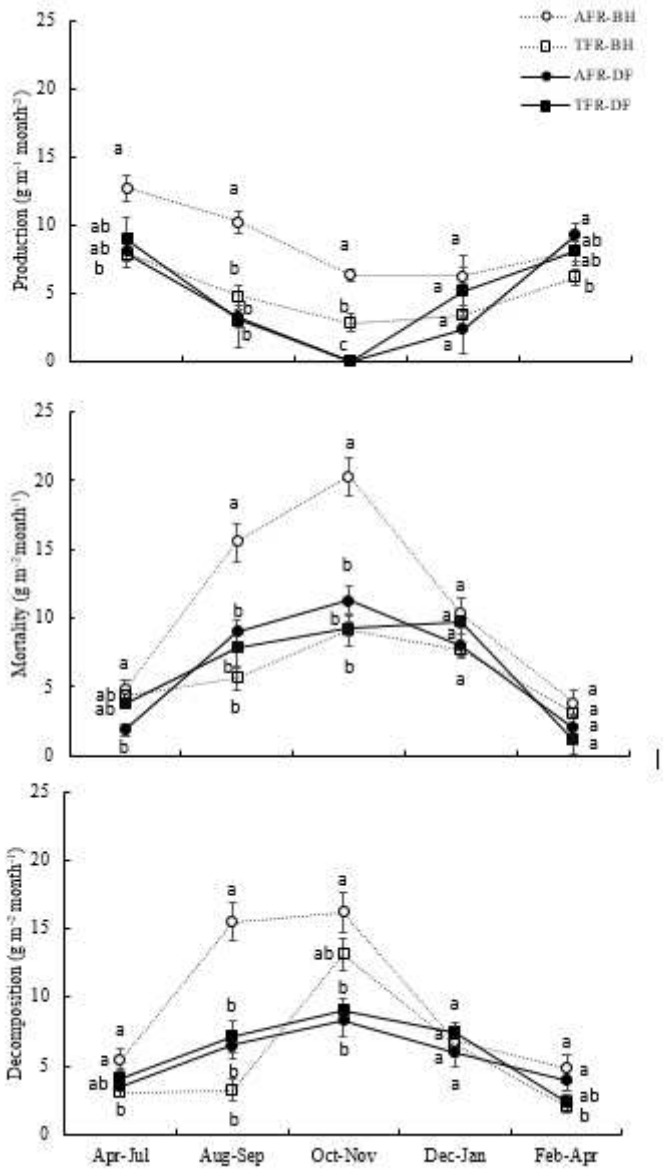

Figure 3

Temporal changes in production, mortality and decomposition estimates of absorptive (AFR) and transport (TFR) fine roots using balanced-hybrid model (BH) and dynamic-flow model (DF) in a managed loblolly pine plantation forest (n= 3; mean ± SE). Different letters stand for significant difference in means ($P<0.05$). Note: AFR production, mortality and decomposition estimates using balanced-hybrid model have been reported. We use these values for the purpose of comparison.

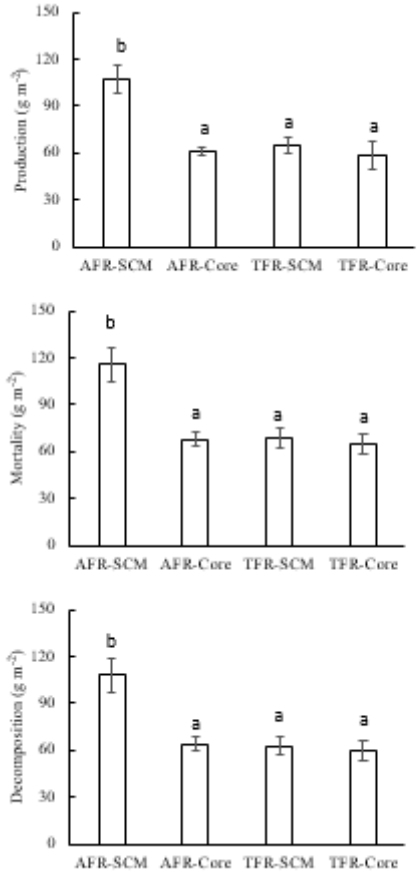

Figure 4

Annual absorptive (AFR) and transport (TFR) fine root production, mortality and decomposition measured using balanced-hybrid model (BH) and dynamic-flow model (DF) in a managed loblolly pine plantation forest (n= 3; mean ± SE). Different letters stand for significant difference in means ($P<0.05$).