Journal of Tropical Forest Science 37(2): 140–153 (2025)
https://doi.org/10.26525/jtfs2025.37.2.140
ISSN: 0128-1283, eISSN: 2521-9847

TEMPORAL VARIATIONS IN FINE ROOTS, LITTERFALL AND SOIL RESPIRATION IN A SECONDARY TROPICAL FOREST OF PAHANG, WEST MALAYSIA

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Submitted October 2023; accepted August 2024

Plant fine roots C dynamics are often overlooked in terrestrial ecosystem carbon cycle. Net fine root production (FrP) is influenced by changes related to root decompositions (Frd), necromass (FrN), root biomass (FrB), and fine root turnover (FrT). Indirect factors such as standing litterfall (Lf), soil respiration (Rs) and seasonal variations (s) may also influence fine root dynamics. The objectives of the study were (i) to determine how fine root dynamics differ with time, (ii) to investigate the causal relationship of litterfall and soil respirations on fine root dynamics and (iii) to assess the effects of climatic factors on fine root dyamics, litterfall and soil respiration. Sequential soil core sampling and the root bag technique were used in a tropical forest at 120 days intervals for two years at Jengka, Pahang, Peninsular Malaysia. The continuous inflow method was used to estimate FrP, FrN, and Frd. Litterfall was estimated using litter traps and Rs using an automated soil CO_2 flux system concurrently with root data collection. The litter and fine root stocks were 3.34 and 0.98 Mg C ha^{-1}, respectively. The annual decomposition decay constant (k) was -0.6168 $year^{-1}$. Fine root dynamics (FrB, Frd, FrN,) differed temporally. Changes in Rs and Lf was observed with seasonal variations. Lf correlated with Rs and Frb. Correlations with mean temperatures were recorded for Frd Frb, FrN, and Frd. Total FrP, FrN, Frd, and FrT ranged between 627.80 –791.05 g m^{-2} yr^{-1}; 854.10 – 704.80 g m^{-2} yr^{-1}; 585.22 – 511.89 g m^{-2} yr^{-1}; 0.71 t $year^{-1}$, respectively. Our results support that FrT and Rs are influenced by FrP whereby changes in FrP are governed by FrB and FrN. These variables studied may increase the understanding of belowground carbon allocations in the tropics.

Keywords: Belowground biomass, climatic drivers, net primary production, root decomposition, soil flux

INTRODUCTION

One of the greatest sources of uncertainty for future climate predictions is the response of the global carbon cycle to climate change. Although approximately one-half of total CO_2 emissions at present is taken up by combined land and ocean carbon reservoirs, models predict a decline in future carbon uptake by these reservoirs, resulting in a positive carbon–climate feedback (Ballantyne et al. 2012). Gross primary production (GPP) refers to the total amount of photosynthesis and carbon taken up by photosynthesis. Generally, the term is used for plant growth (Net Primary Production, NPP) and respiration (Luysaeert et al. 2007). Tropical forests have a high GPP and because of this, they play an important role in the global carbon cycle (Dixon et al, 1994, Luysaeert et al. 2007). Different components of NPP control the balance of tropical forests particularly, in terms of being a net carbon sink or source (after accounting for heterotrophic respiration). Literature on NPP for the tropical forest ecosystems is limited because of the dearth of information on the components of NPP, especially the belowground component (Jackson et al.1997, Silver & Miya 2001). Fine roots with a diameter ≤ 2 mm (Silver & Miya 2001, Osawa & Aizawa 2012) are essential for plant growth and the global carbon cycle (Tran 2020) but they are often neglected in NPP estimations. Approximately 10% to 60% of total NPP in tropical forests are contributed by fine roots production (Gill & Jackson 2000, Malhi 2012) and reports show 0.33 of the annual global NPP fraction is allocated to fine roots (Potter et al. 1993). Significant biases in the annual NPP of the ecosystem may occur if the belowground portion of NPP is excluded (Woodward & Osborne 2000), resulting in erroneous estimations. According to Silver et al. (2005), fine root biomass (Frb), rate of fine root production (FrP), and decomposition of fine roots (Frd) are high in the tropics, and they are controlled by seasonal and annual variations of climate, besides soil type. Soil moisture can influence fine root dynamics besides soil pH and nutrient limitations. Root decompositions are known to be more sensitive to climate as changes in nutrients such as N mineralization and nitrification occur when it is mobile due to microclimatic factors. The common nutrient index which is used is the C:N ratio. Substrate with C:N ratio of less than 20 decompose rapidly and ammonia is released through mineralization (Silver & Miya 2001). The tropical forests FrP is higher than those of the boreal forests (Wang et al. 2018) and there is no clear relationship between FrP and mean annual temperature in the forest ecosystems (Wang et al. 2019). Tran & Sato (2018) cited increased rainfall as a seasonal variation in fine roots dynamics where root biomass increases during wet seasons but die during drier periods (Yavitt & Wright 2000). Also, root decompositions increase with increasing mean air temperatures as when temperature rises, microbial decomposers become more active (Cusack et al. 2009, Wang et al. 2018). Studies have linked fine root dynamics with soil carbon dioxide fluxes (Rs) (Silver et al. 2005), fine root necromass (FrN) (Wang et al. 2019), and litterfall (Lf) (Tran et al. 2015). Soil respiration is the combined effects of root respiration and soil carbon dioxide fluxes emitted during decomposition processes (Silver et al. 2005). Fine root necromass play important roles in nutrient availability (Pan et al. 2022). Understanding the relative importance of these contributors to fine root dynamics is essential because it enables us to understand their intricate relationships, especially as an oversight component of NPP and C balance in secondary tropical forests. Our research questions were as follows: i) how Do fine root dynamics (Frb, FrN, Frd, FrP, and FrT) differ with temporal variations? ii) what are the causal relationships of litterfall and soil carbon dioxide fluxes (respiration) to fine root dynamics? iii) Do mean air temperature and rainfall control the aforementioned variables? Generally, our objectives were to know how fine root dynamics differ with time, to determine the relationships of litterfall and soil respirations on fine root dynamics and finally to assess the effects of climate on fine root dynamics, litterfall and soil respiration.

MATERIALS AND METHODS

Study site

The research was carried out in a secondary lowland forest in Pahang, West Malaysia. This site was chosen because we have existing information on soil type, soil respirations, botanical description, and climatic features (Jeyanny et al. 2014, Jeyanny et al. 2015, Jeyanny et al.2021). It is called Jengka Virgin Jungle Reserve (Jengka VJR), Jengka 18, Pahang (N 3˚ 34.99’ 102˚ 34.29’ E) located at 50 – 90 m asl (above sea level) with a slope ranging from 2° to 8°. The soil texture of the experimental site (0.6 ha) is a silty clay loam; Durian Series (*Typic Paleudult*). The major botanical families are Phyllanthaceae, Euphorbiaceae and Dipterocarpaceae with trees ranging from 4 m to 50 m in height (median 8.00 m) and dbh (diameter at breast height) ranging from 5 cm to 70 cm (median 8.35 cm). The common genera are *Shorea*, *Aporosa*, and *Croton*. There are 1,383 trees ha^{-1}. Portions of the Jengka VJR were logged between 1968 and 1969. It is a secondary forest with minimal disturbances as selective loggings were done (Laidlaw 2011). The wet season of the experimental site usually occurs from November to March whereas the dry season occurs from May to September. The distinctive wet periods were recorded from October 2017 to January 2018; September 2018 to December 2018 and October 2019 to December 2019 (Figure 1). The mean monthly rainfall and temperature for Jengka VJR recorded from 2011 to 2012 ranged from 200 mm to 350 mm and 25 °C to 30 °C, respectively (Jeyanny et al. 2015). During October 2017 to June 2020, rainfall, and temperature at Jengka VJR ranged from 20 mm to 455 mm and 26.0 °C to 28.5 °C (Figure 1).

Soil information and tissue analysis

The complete description of soil analysis and results have been published by us (Jeyanny et al. 2013). The soil pH, C, N, P, K, Ca, and Mg

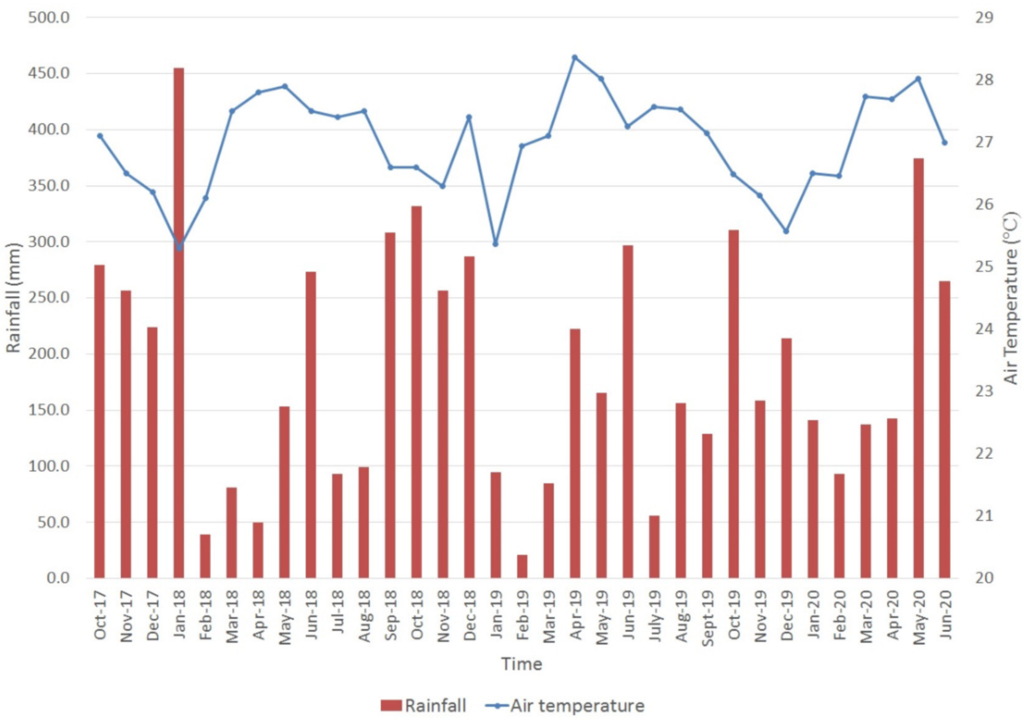

Figure 1 Monthly rainfall and air temperature at Jengka VJR forest, Malaysia from October 2017 to June 2020

Table 1 Selected properties of plant tissue analysis and C stocks

Plant Tissue		Nutrient Properties		C stocks
n=3	C%	N%	C: N	Mg C ha^{-1}
Leaf Litter	42.64±0.03	0.79±0.04	51.10±1.01	3.34
Fine Roots	46.33±0.07	0.84±0.02	53.18±0.98	0.98

at 0 - 11 cm (according to soil horizon) are 3.9, 2.2%, 0.3%, 35.4 µg g^{-1}, 382.0 µg g^{-1}, 47.9 µg g^{-1}, and 98.0 µg g^{-1}, respectively sampled from the soil pit. Representative samples (n=3) of leaf litter and fine roots were taken from the 0.6 ha experimental site to determine C and N before the beginning of the presented study. Organic C was determined using the total combustion method (C analyser) whereas total N was extracted using the Kjeldahl method followed by distillation and the results presented in Table 1. Both litter and root C stocks were calculated by multiplying oven dry mass per area with the C concentration in percentage.

Plot preparation and measurements of fine root dynamics

A transect running from Northeast towards South West was established in the study plot, whereby 60 quadrants measuring 10 m × 10 m were established systematically to obtain a 0.6 ha (Jeyanny et al. 2021). However, 10 quadrants within the study plot were selected randomly for soil sampling for fine roots, which was done every four months, starting from October 2017 to October 2019. For the soil, three replicates of soil cores were collected using stainless steel tubes with 80 mm in diameter totaling 30 soil cores at every sampling interval adjacent to the rootbags experiment. The soil samples were taken to a depth of 20 cm. In this study, we did not separate the roots based on tree species because each quadrant (10 x 10 m) had an average of eight species, and the difficulty in identifying fine roots according to tree species. Besides, we had to adhere to permit approvals on causing only minimal disturbances according to the State Forestry Department. To avoid errors, the soil corings were positioned in a manner that they did not overlap root bag experiments, litterfall collections, and the soil respiration sub

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

$$FrM = (N_j - N_i) + Frd \quad (2)$$

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

plots (Jeyanny et al. 2021). The soil samples were washed and sieved to pass a 0.05 cm mesh size to obtain fine roots ≤ 2 mm diameter in size after which the fine roots were separated into living roots (root biomass, FrB) and dead roots (necromass, FrN). The living and dead roots were separated based on color, texture, and resilience [living] (Hishi & Takeda 2005). For example, dark/black colored roots which could break were deemed dead and bright/yellow roots which were resilient were categorized as live roots. Afterwards, the roots were air-dried (Hishi & Takeda 2005) followed by oven-drying at 80°C until a constant weight was obtained. Fine-root production (FrP) (equation 1), fine root mortality (FrM) (equation 2), and fine root decomposition (Frd) (equation 3) were estimated using the continuous inflow method (Osawa & Aizawa 2012).

In Equations 1, 2, and 3, B_i and B_j are the masses of live fine-roots (biomass) corresponding to times t_i and t_j, respectively ($t_j \geq t_i$); N_i and N_j are the masses of dead fine-roots (necromass), and γ_{ij} is the decomposition ratio of dead fine-roots at a corresponding time interval. The B_i, B_j, N_i, and N_j were obtained by soil core sampling and γ_{ij} by using the root bag technique.

A total fresh weight of 5 kg of fine roots were obtained at a soil depth of 20 cm outside the designated plots using a 150 mm length with 80 mm diameter soil coring probe in May 2017. The roots were washed and air-dried. Roots which were ≤ 2 mm diameter were selected after which they were oven-dried at 80°C. Rootbags were filled with 1.5 g of the weighed roots. There were 120 root bags. The root bags had a mesh opening size of 211 μm (Sefar PET 1500) with a dimension of 10 cm x 10 cm. This configuration prevents the ingrowth of fine roots but enables fine soil particles, water, and microorganisms to penetrate the mesh. The root bags were buried to a 10 cm to 15 cm soil depth in October 2017 in six designated plots (Figure 2) after which 18 of them were taken at 120, 240, 360, 480, 600, and 720 days. Afterwards, the collected root bags were washed and oven-dried at 80°C until a constant weight was obtained. The (decomposition ratio) was estimated as given in equation (3). Additionally, the decomposition rate constant *k* was calculated from the decay curve using equation 4 (Berg & McClaugherty 2008).

$$ln\ (M_0/M_t) = kt \quad (4)$$

where M_0 = mass of roots (g) at time 0, M_t = mass of roots (g) at time t, t = time of incubation (days) and k = decomposition rate constant.

The decomposition rate constant for each sampling interval was calculated as the slope of the exponential decay model in days (*k*, day^{-1}) and then converted to annual (*k*, year^{-1}) based on the percent of remaining roots for each time interval (days), Figure 2.

Fine root production (FrP), fine root mortality (FrM), and fine root decomposition (Frd) were calculated for each sampling interval and summed up for the year 2018 and reported in g m^{-2} year^{-1}. Fine root turnover (FrT) was calculated according to Kubisch et al. (2006).

$$FrT = \frac{\text{annual belowground fine root production (FrP)}}{\text{standing belowground fine root biomass (sFrB)}} \quad (5)$$

The fine root carbon stocks were calculated by converting the mean values for fine roots biomass into tonnes ha^{-1}. Thereafter, the root mass was multiplied with the carbon fraction which is 0.46 (Table 1). We also calculated the C allocation to fine roots as 46% of root production. The common assumption is 50% if root tissue C values are not evident. The average C input to the soil via root turnover was estimated by multiplying root productivity for a given year by the turnover rate for that year (Silver et al. 2005), based on the C percentage obtained from our study for root biomass.

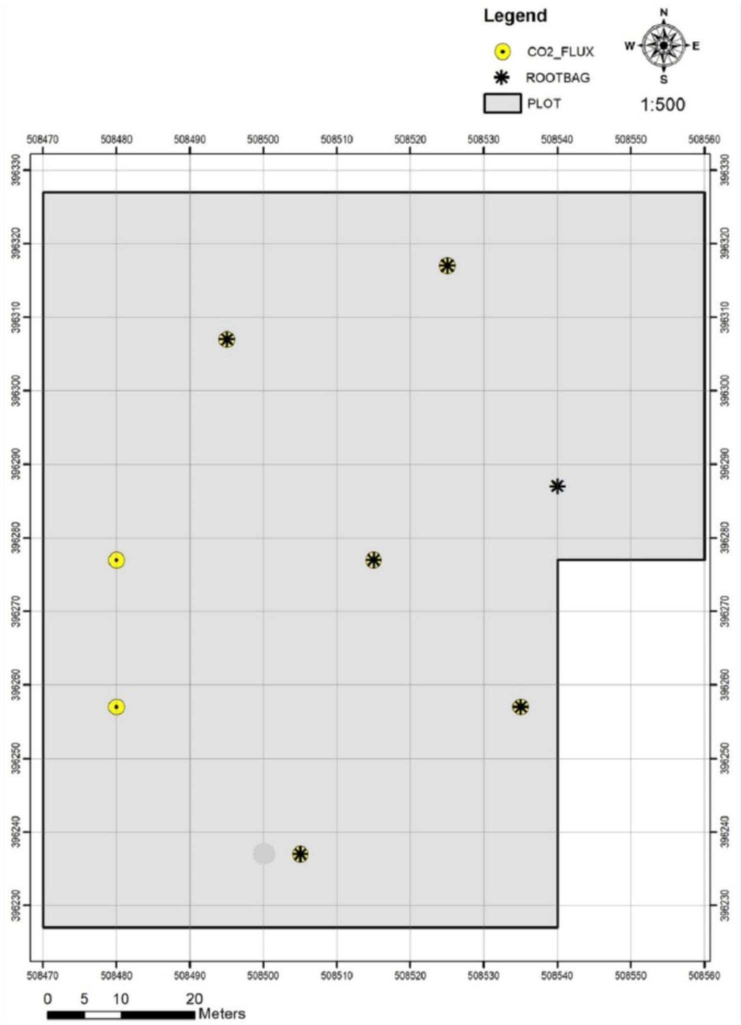

Figure 2 Plot and sampling design for soil respiration and root bag measurements in Jengka Forest Reserve, Pahang, Malaysia

Measurements of litterfall

Lf including all falling materials such as leaves, branches, and reproductive organs (flowers & fruits) were estimated using the traps in the plots. Five plots out of the 10 plots which were used for root samplings were selected whereby four replications of litter traps measuring 1 m x 1 m in dimension and 1 meter from the ground were established systematically in each plot for quarterly litterfall collection as previously described for core sampling. The litterfall samples were oven-dried at 80°C until a constant weight was obtained. Litter stocks were calculated by calculating the mean value of litterfall during the experimental duration converted into tonnes ha^{-1} and multiplied with the carbon fraction (42.6% = approx. 0.43) in Table 1.

Measurements of soil respiration (Rs) and water-filled pore space (WFPS)

An automated soil carbon dioxide (CO_2) flux system (LI-8100, Li-COR Biosciences, Lincoln, United States) was used to measure soil respiration (Rs). The instrument was calibrated with standard CO_2 gas twice within the duration of measurement and also using the zero and span procedure before measurements were recorded. Measurements were taken between 10:00 and 12:00 hours. The experimental design and sampling methods are detailed in Jeyanny et al. (2021). Within this period, the daily Rs were assumed to be at the highest rate (Luo & Zhou 2006). Eight quadrants were chosen for sampling (Figure 2) whereby measurements were taken in duplicates. There were 16 measurements.

Sampling replications were constrained by time because of access from one point to another within the forest reserve. The Rs was determined using the systems software by calculating the initial slope of a fitted exponential curve at the ambient CO_2 concentration and given in units of μg mol CO_2 m^{-1} s^{-1}. These values were converted to mg CO_2 m^{-2} h^{-1} by changing the units from seconds to hours and the μg to mg, and then multiplied by the molecular weight of CO_2. Ancillary variable such as water filled pore space (WFPS) was calculated from the soil water content and bulk density (Jeyanny et al. 2021).

Analysis of variance (ANOVA) for soil respiration, daily air temperatures, rainfall, FrB, Frd, FrN, Lf biomass and WFPS between sampling periods were done using Statistical Analysis System version 9.4 (SAS Institute, North Carolina, United States of America) and the sampling interval means were compared using Student Newmann Keull Test. The trends of root mass loss over time were determined using a single exponential model using the same software. Pearson linear correlation between rainfall, air temperature, Rs, Rb, Frd, Lf and WFPS from 0 to 720 days were also computed to identify if there were any significant correlations between variables.

RESULTS

Substrate analysis, C stocks and fine root decomposition trends

Carbon and nitrogen of the leaf litter and roots were similar (Table 1). The mean C stocks for leaf litter and fine roots were 3.34 and 0.98 Mg C ha^{-1}, respectively. The source of variation and p values are given in Table 2.

There was an exponential relationship between the percentage of the remaining roots and time for the rootbag experiment (Figure 3). The highest decomposition constant was recorded at 720 days (*k:* - 0.0143 day^{-1}) and this value is parallel with the root decomposition ratio recorded at the same period (Table 3). On day 720, the weight loss was 79.61%. The weight loss decreased significantly during the initial stage of the study but plateaued after 480 days when the amount of remaining roots ranged between 20% and 25%. The mean decomposition decay constant, *k* was -0.0017 day^{-1} and when converted was -0.6205 $year^{-1}$ (365 days) for the site. The prediction percentage of the root litter remaining can be done based on the given equation ($Y=103.64e^{-0.002x}$) if an *x* value (t, days) is introduced, and the *y* value falls within the single exponential curve.

Fine root dynamics, litterfall, soil respiration & water filled pore space

Results revealed that FrB, Frd, Lf, FrN, Rs and WFPS significantly differed with regards to sampling intervals (Table 3). The highest FrB was attained in October (222.87-242.67 g m^{-2}) and these values were significantly higher (37%) compared with the rest of the months. The lowest level for FrB in June 2018 was 2 folds lower compared to the October values. The FrN was significantly highest in February 2018 (337.68 g m^{-2}) and this value was comparable with the values in October 2017 and June 2019. The value in February 2019 was eight folds lower compared

Table 2 Source of variation and p-value of Frb:fine root biomass; FrN: fine root necromass; Frd: fine root decomposition ratio; Rs: soil respiration; Lf: Litterfall; WFPS: water filled pore space

Source	Model df	F	p value
Frb	6	2.09	0.05
FrN	6	3.84	0.0013
Frd	5	92.2	<0.001
Rs	6	6.07	< 0.002
Lf	5	12.59	< 0.0001
WFPS	6	2.54	0.05

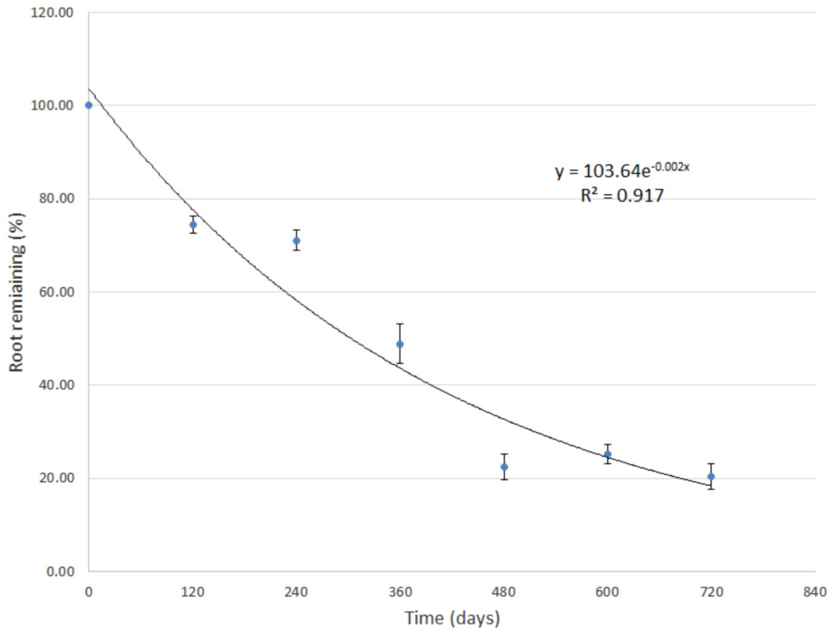

Figure 3 Exponential curve of fine root mass remaining (%) during the decomposition process for 720 days. Error bars represents standard errors (n: 18)

Table 3 Temporal variations of fine root dynamics, litterfall (Lf), soil respiration (Rs) in Jengka FR

Time		Oct-17	Feb-18	Jun-18	Oct-18	Feb-19	Jun-19	Oct-19
Days	n	0	120	240	360	480	600	720
Fine root biomass	30	237.90a	147.98ab	98.68b	222.87a	170.49ab	225.31a	242.67a
($g\ m^{-2}$)		(32.0)	(32.0)	(43.60)	(10.61)	(5.57)	(8.98)	(7.28)
Fineroot necromass	30	306.50ab	337.68a	138.68bc	162.51bc	55.61c	166.64ab	303.29bc
($g\ m^{-2}$)		(11.68)	(5.44)	(4.34)	(8.23)	(1.74)	(11.16)	(4.81)
Fine root	20	nd	0.2641c	0.2823c	0.4908b	0.7743a	0.7743a	0.7899a
decomposition ratio			(0.01)	(0.01)	(0.03)	(0.02)	(0.03)	(0.03)
Litterfall	20	nd	232.99bc	250.67b	304.64a	135.40d	182.55c	230.54bc
($g\ m^{-2}$)			(15.23)	(24.5)	(12.28)	(13.06)	(11.94)	(12.15)
Soil respiration	16	518.60ab	566.76ab	271.77b	260.91b	674.78a	452.76ab	406.86ab
$mg\ CO_2\ m^{-2}\ h^{-1}$		(45.05)	(37.06)	(56.10)	(52.43)	(43.03)	(72.38)	(44.38)
Water filled pore space	8	53.68ab	53.22ab	56.27a	53.75a	57.97a	59.49a	53.54b
(%)		(2.01)	(2.28)	(1.51)	(1.99)	(1.41)	(1.19)	(2.58)

Mean values followed by different letters within each row are significantly different for sampling interval by Tukey Test ($p \leq 0.05$). Values in parentheses represents standard errors with that in February 2018. The Frd was also significantly different. The highest values were recorded between February 2019 and October 2019 (≥ 0.77). Lower decomposition occurred in the months of February and June 2018.

The Lf value was significantly highest in October 2018 (304.64 g m^{-2}). Values for February 2018, June 2018, and October 2019 were similar for Lf. Lf decreased significantly by 55% in February 2019 compared with the previous sampling period. The Rs values were significantly different across sampling time and they ranged from 260.91 to 674.78 mg CO_2 $m^{-2}h^{-1}$. Hence, higher values were recorded in February 2018 and February 2019. The WFPS values were highest from June 2018 to June 2019 (57% to 60%) but lowest in October 2019 (Table 3).

FrB, Frd, and FrN correlated with daily mean air temperatures (Table 4). Also, Rs, FrB, and Frd correlated with Lf. There was a negative correlation between Rs and rainfall. Frd and FrN correlated with FrB whereas FrN negatively correlated with Frd. No significant correlations were obtained for water filled pore space.

The fine root production (FrP) for 2018 and 2019 were 627.80 g m^{-2} yr^{-1} and 791.05 g m^{-2} yr^{-1}, respectively (Figure 4). Generally, the FrM were 854.10 and 704.80 g m^{-2} yr^{-1} for 2018 and 2019, respectively. Frd were 585.22 and 511.89 g m^{-2} yr^{-1} for the same period. The FrT which was calculated for 2018 and 2019 was 0.71 t yr^{-1}, respectively. The mean C allocation for fine roots in 2018 and 2019 was 0.97 Mg C ha^{-1} yr^{-1} during which the mean fine roots C turnover rate was 0.36 Mg C yr^{-1}.

DISCUSSION

Substrate analysis, carbon stocks and fine roots decomposition trends

Plant tissue chemistry such as C and N besides other nutrients constitute an important branch of knowledge in decomposition because it explains the rates of mass loss and nutrient immobilization and mineralization (Scott & Binkley 1997) in the soils. The variables that affect decomposition location (litter on surface and fine roots below surface) may influence microbial diversity besides reciprocal effects of microclimate on these organic substrates (Djukic et al., 2018). Values of C, N, and C: N ratio is usually reported for decomposition studies because they are related to mineralization

Table 4 Pearson correlation coefficient of variables at the study site

Variable	Air Temperature	Litterfall	Rainfall	Soil respiration	Fine root biomass	Fine root decomposition ratio	Water filled pore space
Litterfall	-0.210						
Rainfall	0.071	-0.036					
Soil respiration	-0.080	-0.406**	-0.379**				
Fine root biomass	-0.403**	-0.521**	0.007	0.263			
Fine root decomposition ratio	-0.433**	-0.500**	0.031	0.240	0.992**		
Necromass	-0.329**	0.079	-0.049	0.111	-0.455**	-0.517**	
Water filled pore space	-0.080	-0.088	-0.079	-0.080	0.036	0.0027	

Notes: * significant at $p < 0.05$; ** significant at $p < 0.01$

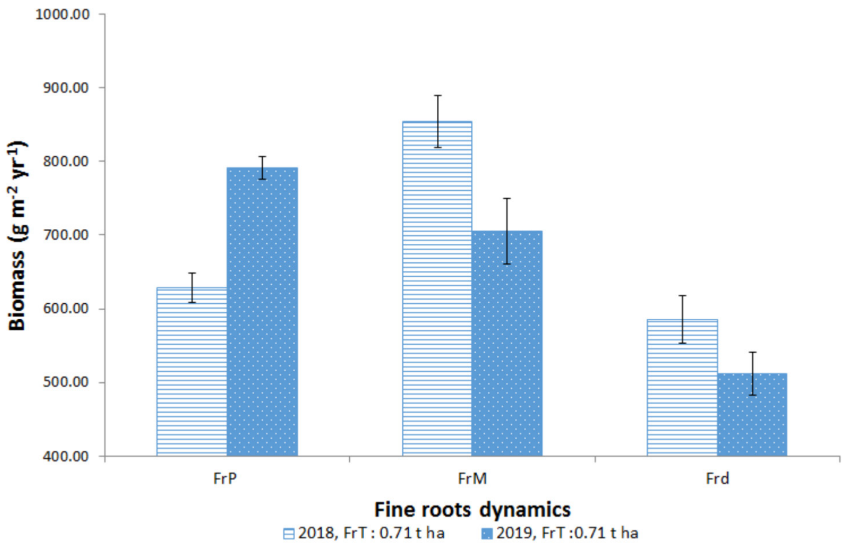

Figure 4 Fine roots production (FrP), mortality (FrM), decomposition (Frd) and turnover (FrT) in 2018 and 2019. Error bars indicate standard errors, n=3

processes. Other nutrients were not tested in this study due to budget restrictions. Values for C, N, and C: N ratio for leaf litter in this present study are consistent with those reported by Jeyanny et al. (2015) [56.22] and higher than that reported by Burghouts et al. (1992) [30.40] for a secondary lowland forest in Sabah, Malaysia, meaning C:N ratios can differ site-specifically despite within a tropical rainforest ecosystem. The C:N for roots in this present study is comparable to those reported by Cusack et al. (2009) [58.70,60.71] in the tropical forests of South America such as Panama, Puerto Rico & Costa Rica. Values were also comparable to Silver & Miya (2001) [62.00] for C:N for a metadata analysis on global patterns on root decompositions. C:N below 20 enables roots to decompose rapidly whereas an intermediate C: N range of 25-75 reduces the N mineralization rate (Silver & Miya 2001) [62.00]. Our results demonstrated lower initial N in roots (< 1%) and high C:N, suggesting N availability influenced roots' decomposition.

The detritus litter (0.7 Mg C ha^{-1}) and root C (0.9 Mg C ha^{-1}) stocks corroborate those of Saner et al. (2012). According to Jeyanny et al. (2018), the fine roots C stocks in the upper surface of soils in Pasoh, Negeri Sembilan, Malaysia range between 1.5 Mg C ha^{-1} and 1.7 Mg C ha^{-1}. The differences were attributed to microclimatic conditions and soil types in different localities.

The annual *k* values in this present study were slightly lower (k =0.62 yr^{-1}) than those reported by Silver & Miya (2001) (k=0.83 yr^{-1}) for broad leaves tropical species and a metadata analysis for broad leaves species (k = 0.71 yr^{-1}) by Zhang & Wang (2015). However, the values were in the range of 0.42 to 1.06 yr^{-1} as reported by Cusack et al. (2009) in tropical forests of South America. The lower values seen in this study can be attributed to the inherent root chemistry properties from a mixed broad leaves forest, the root decay sensitivity to climate, soil chemical and physical properties, precipitation, initial root chemistry, substrate quality, microbial community, and tree species specifics (Silver & Miya 2001, Berg & McClaugherty 2008, Cusack et al. 2009, Zhang & Wang 2015, Tran & Sato 2018). A previous study on leaf litter decomposition in the same site (Jeyanny et al. 2015) cited soil moisture as one of the confounding factors in accelerating decay processes but a similar situation may not support root decomposition studies. The highest *k* values obtained at 720 days could be related to the increased substrate (FrB) and soil respiration values (Table 2) besides climatic factors due to the wet season (Figure 1).

Fine root dynamics, litterfall, soil respiration and water filled pore space

Live and dead roots contribute to labile C to fuel microbial production of CO_2 and other trace gasses (Silver et al. 2005). The increased FrB and FrP (Table 3) provided sufficient substrate for root respiration to take place together with microbial respiration (Frd) at the roots' rhizosphere (Hogberg et al. 2002). This was seen especially in February and June 2019 coinciding with higher Rs and WFPS values reported earlier (Jeyanny et al. 2021). Jeyanny et al. (2021) concluded that fine root biomass (222.93–237.96 g m^{-2}), fine root decomposition ratio (0.49) and litterfall (304.64 g m^{-2}) contributed to Rs in the previous study. The differences were attributed to microclimatic conditions and soil types in different localities.

This led to adequate FrN yield with respect to time, further displaying corresponding relationships with FrB, FrN and Frd with significant negative correlations (Table 3). In contrast, the drier climate in February 2018 (Figure 1) hindered Frd and this resulted in higher standing (available) FrN (Wang et al. 2019) (Table 3). During this period, soil water availability (WFPS) was limited especially in February 2018, but it did not hinder soil Rs. WFPS was comparatively ambient during the wet seasons (± 53.00%) during Octobers and significantly higher (56.00-59.00%) in the dry seasons (June 2018, February 2019, June 2019). Commonly, higher WFPS (55-61%) coincides with increased Rs (Linn & Doran 1984, Torbet & Wood 1992) during drier periods (Teramoto et al. 2017) because both air and water are needed for aerobic respiration. Other microsite factors influenced the elevated Rs levels such as soil temperatures and relative humidity (Jeyanny et al. 2021).

The reported Frd range in this present study (0.2-0.8) was similar to those reported for Sarawak [0.3] (Katayama et al. 2019) and evergreen broadleaf forest in Japan [0.5-0.8] (Van Do et al., 2015). The increased Rs in February 2019 is related to the higher inputs of organic debris because of wind throws during wet season and had a profound effect in accelerating decomposition processes of fresh labile organic carbon (Luo & Zhou 2006, Li et al. 2013). We acknowledged that land clearing activities outside of our research plot within private jurisdiction might have influenced our results during this sampling interval.

Several studies have demonstrated that temporal variations (i.e. rainfall and mean air temperatures) control fine roots dynamics in tropical forests (Green et al. 2005, Jimenez et al. 2009, Katayama et al. 2019). For three consecutive years, FrB, FrN, and Lf increased during the wet seasons (especially in October). The increased rainfall and ambient air temperatures (Figure 1) might have played important roles in the processes related to FrB, FrN, and Lf. Wet seasons are characterized as growing seasons when higher net primary productivity (NPP) occurs because of an increase in FrB for nutrient uptake and cycling by plants. When fine roots grow, die, and decompose, higher FrB and FrN during the wet season were possible due to ecosystem and site-specific species characteristics (Tran & Sato 2018). Evidence of this is the correlation between air temperature with FrB, Frd, and FrN and not rainfall or WFPS. During the drier periods, reduction in FrB was similar to that reported by Jimenez et al. (2009) in the Colombian Amazon.

The higher values of Lf are related to higher precipitation because they enhance leaf abscission. This is a common phenomenon in evergreen rainforests, an example being the Brazilian evergreen forest (van Schaik et al. 1993, Scheer et al. 2009). The significant relationships between Lf and Rs, FrB, and Frd strengthen the fact that these variables are strongly correlated in terms of high biomass inputs into the ecosystem to enable carbon disintegration *via* respiration processes (Silver et al. 2005).

Results obtained for FrB, Lf, Frd, FrN, and Rs were like the findings for the Malaysian moist tropical forests such as Pasoh (Adachi et al. 2006), Sarawak (Katayama et al. 2019), and Sabah (Saner et al. 2012). The literature is replete with similar findings on root dynamics in Indonesia (Violita et al. 2016, Hergoulc'h et al. 2017), and the Amazon (Jimenez et al. 2019), Lf in China (Jiang et al. 2017) and Brazil (White et al. 2013). The Rs in this present study which is a key driver for net ecosystem production is consistent with those of Jeyanny et al. (2015) in Pahang, Malaysia, Kosugi et al. (2007) for Negeri Sembilan, Malaysia; Melling et al. (2009) for Mukah, Sarawak, Saragi-Sasmito et al. (2019) for Central Kalimantan, Indonesia and Rubio & Detto (2017) for Barro Colorado Island, Panama.

Values reported for annual FrP, FrM, Frd (Figure 4), and FrT are important factors for calculating NPP and carbon dynamics in tropical forests. Previous reports pointed out the highest rates of FrP and Frd occurred in tropical forest ecosystems albeit it is the natural source of soil respirations (Vogt et al. 1995, Silver & Miya 2001). Lower values of FrP was reported in 2018 (627.80 g m^{-2} yr^{-1}) compared with 2019 (791.05 g m^{-2} yr^{-1}). In 2019, when FrP was higher, both FrM and Frd were lower. Rapid decompositions (Frd) increased root mortality in 2018; although it adversely affected FrP rates and the situation was reversed in the following year, it did not affect FrT. FrP and FrT are known to increase when there is higher precipitation and temperatures because of elevated maintenance for respiration, nutrient mineralization, pathogen and herbivore load with the changing gradient (Finer et al. 2011). In this present study, there was approximately 70% annual roots turned and this is consistent with those reported by Jiminez et al. (2009) and Silver et al. (2005) for tropical forests. High FrT depicts its essential role in increased nutrient transformation rates for plant uptake, its control in fine root senescence dynamics, and steady state conditions of the study site (Gill & Jackson 2000). The C allocation to fine roots was approximately 1 Mg C ha^{-1} yr^{-1} and this is similar to that reported for two years.

In Brazil, Silver et al. (2005) reported average ranges of 157.0 - 204.0 g m^{-2} yr^{-1} for FrP, 0.69- 0.70 t ha^{-1} for FrT in clayey soils. Jiminez et al. (2009) recorded FrP of 272.0 and FrT of 0.84 t ha^{-1} in similar soils of Colombia. In Sarawak, Malaysia, FrP of 447.4 g m^{-2} yr^{-1}, FrN of 288.8 g m^{-2} yr^{-1} and Frd of ± 250 g m^{-2} yr^{-1} were recorded (Katayama et al., 2019). Our results for FrP were relatively higher than some that had been reported in the literature. The margins of Frd and FrN in our study were also higher, differing between years. The different values in 2018 and 2019 implied inter-annual variability of C fluxes (Rice et al. 2004, Silver et al. 2005) and the possibility of variable lifespans of fine roots (Gaudinski et al. 2001, Silver et al. 2005) in this study site.

CONCLUSIONS

In conclusion, the study, although skewed to one particular site, initiates the need to explore the role of fine root dynamics and soil respiration in local net primary production ecosystem modelling for secondary tropical forests. Therefore, the annual decomposition root decay constant, *k* was -0.6205 day^{-1}. Further understanding of the C, N, and C: N ratio (51-53) is essential to determine its significant role in C cycle in secondary tropical forests. Root decomposition studies should be conducted more than a year to reach steady-state trends because the curve plateaus after 480 days. Inter-annual variations were prominent in our site whereby higher fine root biomass and litterfall were recorded during higher precipitation but drier periods restricted root decomposition in February 2018 and June 2018, resulting in higher fine root necromass (February 2018 only). Soil water filled pore spaces were ambient during wet seasons but were elevated during drier periods (June 2018, February 2019, and June 2019), resulting in higher fine root decomposition ratios and soil respiration values for February 2019 and June 2019. A strong correlation of fine root biomass, fine root decomposition ratio, and fine root neromass with air temperature were revealed. Rainfall data correlated with soil respiration. Litterfall correlated with soil respiration, fine root biomass, and fine root decomposition ratios. FrT and Rs are influenced by FrP whereby changes in FrP is governed by FrB and FrN. The inter-annual variations affect the annual NPP of the forest. Site-specific and fine root lifespan variations influence differing values of fine root production and fine root turnover against annual fine root decomposition ratio and fine root mortality in both years. Future research should study the role of fine root turnovers in controlling steady-state nutrient conditions for the survival of aboveground tropical forest ecosystems and their deviations due to land-use change.

ACKNOWLEDGMENTS

This study was financially supported by the *International Foundation of Science-South East Asian Regional Center for Graduate Study and Research in Agriculture (IFS-SEARCA) Collaborative Research Fund (J-1-D-6024-1).* We deeply acknowledge the funding for the Li-8100A automated soil flux system under the 11th Malaysia Plan funding to facilitate the data collection at the study site. Thanks are due to the staff of Forest Research Institute Malaysia for field and technical assistance. We record our gratitude to the Forestry Department of Malaysia for the approval of the study site.

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