HAYATI Journal of Biosciences 23 (2016) 7–12

HOSTED BY
ELSEVIER

Contents lists available at ScienceDirect

HAYATI Journal of Biosciences

journal homepage: http://www.journals.elsevier.com/hayati-journal-of-biosciences

Original research article

Fine Root Production and Decomposition in Lowland Rainforest and Oil Palm Plantations in Sumatra, Indonesia

Violita Violita,[1,2] Triadiati Triadiati,[3*] Iswandi Anas,[4] Miftahudin Miftahudin[3]

[1] Graduate Program in Plant Biology, Department of Biology, Faculty of Mathematics and Natural Sciences, Bogor Agricultural University, Dramaga Campus, Bogor, Indonesia.
[2] Department of Biology, Faculty of Mathematics and Natural Sciences, Padang State University, Padang, Indonesia.
[3] Department of Biology, Faculty of Mathematics and Natural Sciences, Bogor Agricultural University, Dramaga Campus, Bogor, Indonesia.
[4] Department Soil Science and Land Resources, Faculty of Agriculture, Bogor Agriculture University, Dramaga Campus, Bogor, Indonesia.

ARTICLE INFO

Article history:
Received 15 June 2015
Accepted 13 October 2015
Available online 10 July 2016

KEYWORDS:
C/N ratio,
decomposition,
fine root,
land use change,
N and C content

ABSTRACT

Transformation of tropical rainforest into oil palm plantation not only has impacts on biodiversity but also affects ecosystem functions such as production and decomposition of fine roots as a nutrient source for plant. The objective of the research was to evaluate the production and decomposition rate of fine roots in natural forest (NF) at Bukit 12 National Park and oil palm plantation (OP) in Jambi, Sumatra. The soil core and litter bag methods were used to obtain fine root production and decomposition data. The results showed that generally, there was the same pattern in fine root production between NF and OP. The annual fine root productivity was found to be higher in NF than that of OP. Rainfall in NF and air temperature in NF and OP were the most significant climate factors affecting fine root production. The remaining fine root biomass decreased as the incubation time increased. The decomposition rate constant (*k* value) was significantly higher in NF than in OP. Our data showed that the nutrient turn-over of NF fine roots was faster than of OP fine roots. Nitrogen, carbon content, and C/N ratio were the main factors that influenced fine root decomposition.

1. Introduction

Transformation of tropical rainforest into agricultural systems not only leads to massive losses in the biodiversity (Koh and Wilcove 2008) but also has major impacts on ecosystem function such as the availability of nitrogen. Fine roots play an important role in fulfilling the nutrient cycles of forest ecosystems (Santantonio and Hermann 1985) and are known as a prominent sink of canopy photosynthetic carbon (Nadelhoffer and Raich 1992). Roots provide pathways for carbon and energy movements from canopy to the soil, so the root production and root turnover directly affect the biogeochemical cycle of carbon (Koh and Wilcove 2008) and nitrogen (Nadelhoffer and Raich 1992). Although fine roots are individually very small (≤2 mm in diameter), in total, they can make up 30%–50% of the annual primary production (Ruess *et al.* 1996; Gill and Jackson 2000). The small diameter, short lifespan, and low C/N ratio of fine roots affect their turnover and decomposition rate (Hendrick and Pregitzer 1993). Fast growth and rapid turnover of fine roots become important factors in nutrient cycles including N cycle. Therefore transformation of forests to oil palm plantations (OPs) may affect the fine root system, turnover of nutrients, and nutrient cycling in the ecosystem (Silver *et al.* 2005).

Large areas of natural forest (NF) in Jambi have been converted into plantations and thus likely changed the nutrient cycles, including the fine root system and its contribution to the ecosystem. This conversion likely has impacts on the biomass and the distribution of fine roots, and their decomposition. The conversion of NFs into plantations could reduce fine root biomass, particularly in the uppermost soil layer (0–10 cm depth). A decrease in production and decomposition of fine roots, including a reduction in litter production above ground, will lead to the decline of soil organic matter and the presence of soil nutrients (Yang *et al.* 2004). Furthermore, biomass and fine root production are altered by disturbances, such as disturbance during selective logging and clear-felling of trees (Barbhuiya *et al.* 2012; Gautam and Mandal, 2012) and forest disturbance (Barbhuiya *et al.* 2012; Leuschner *et al.* 2006).

* Corresponding author.
E-mail address: adiatiipb@gmail.com (T. Triadiati).
Peer review under responsibility of Institut Pertanian Bogor.

http://dx.doi.org/10.1016/j.hjb.2015.10.008

One area of Jambi's tropical rainforest that has experienced large scale conversion is Bukit 12 National Park (TNBD). Formerly, TNBD was an area that consisted of permanent production forest, limited production forest, and forest for other uses. Currently, TNBD is dominated by secondary forest because of the conversion into plantations including OPs.

The importance of fine roots as a principal sink in TNBD needs to be considered, especially in the context of land use changes that interfere in the process of nutrient recycling and availability of plant nutrients. To predict the influence of land use change on the belowground ecosystem, especially on fine roots, a better understanding of production and decomposition processes of fine roots as well as the effects of environment factors and litter quality to those processes is required. Therefore the studies comparing the production and decomposition of fine roots between OP areas and NF are needed. This research objective was to determine and compare the production and decomposition of fine roots in OP and NF in TNBD, Jambi, Indonesia.

2. Materials and Methods

2.1. Time and place of the study

The study was conducted from September 2012 to September 2013 in Sarolangun, Jambi province. The TNBD is a relatively small national park that covers 605 km^2 in Jambi (Indonesia), which represents the lowland tropical rain forests in Jambi province. Only the northern part of this park consists of primary rainforest, whereas the rest is secondary forest, as a result of the previous logging activity. In the past, the forest area was designated as permanent production forest, limited production forest, and other forest land uses which were later merged to become a National Park.

The study site of this research was Bukit 12 National Park (TNBD) NF and OP with 7–10 in age, with the following specific plot location coordinates:

1. S 01°59′42.5″ E 102°45′08.1″ (NF1).
2. S 01°56′33.9″ E 102°34′52.7″ (NF2).
3. S 01°56′31.9′ E 102°34′50.3″ (NF3).
4. S 02°04′32.0″ E 102°47′30.7″ (OP1).
5. S 02°04′15.2″ E 102°47′30.6″ (OP2).
6. S 02°04′15.2″ E 102°47′30.6″ (OP3).

in Sarolangun district, Jambi (Figure 1). The soil at this experimental site is podsolic soil with the soil pH between 3 and 5. The average monthly rainfall was 291.08 mm while the highest and lowest precipitation occurred in December 2012 (529 mm) and June (33 mm) 2013, respectively. The average daily temperature varied from 26°C to 28°C. The daily precipitation and solar radiation ranged between 77% and 91% and 41.5% and 64.25%, respectively. Climate data were acquired from the *Badan Meteorologi Klimatologi dan Geofisika* Climatology Station of Jambi, at Jl. Raya Jambi-Muara Bulian Km 18, Simpang Sungai Duren, Jambi.

2.2. Fine root production

Fine root was sampled in NF and OP by collecting 20 soil cores (5 cm in diameter) at a depth of 20 cm at random from each observation plot every 3 months. Soil cores were cut into 20 cm

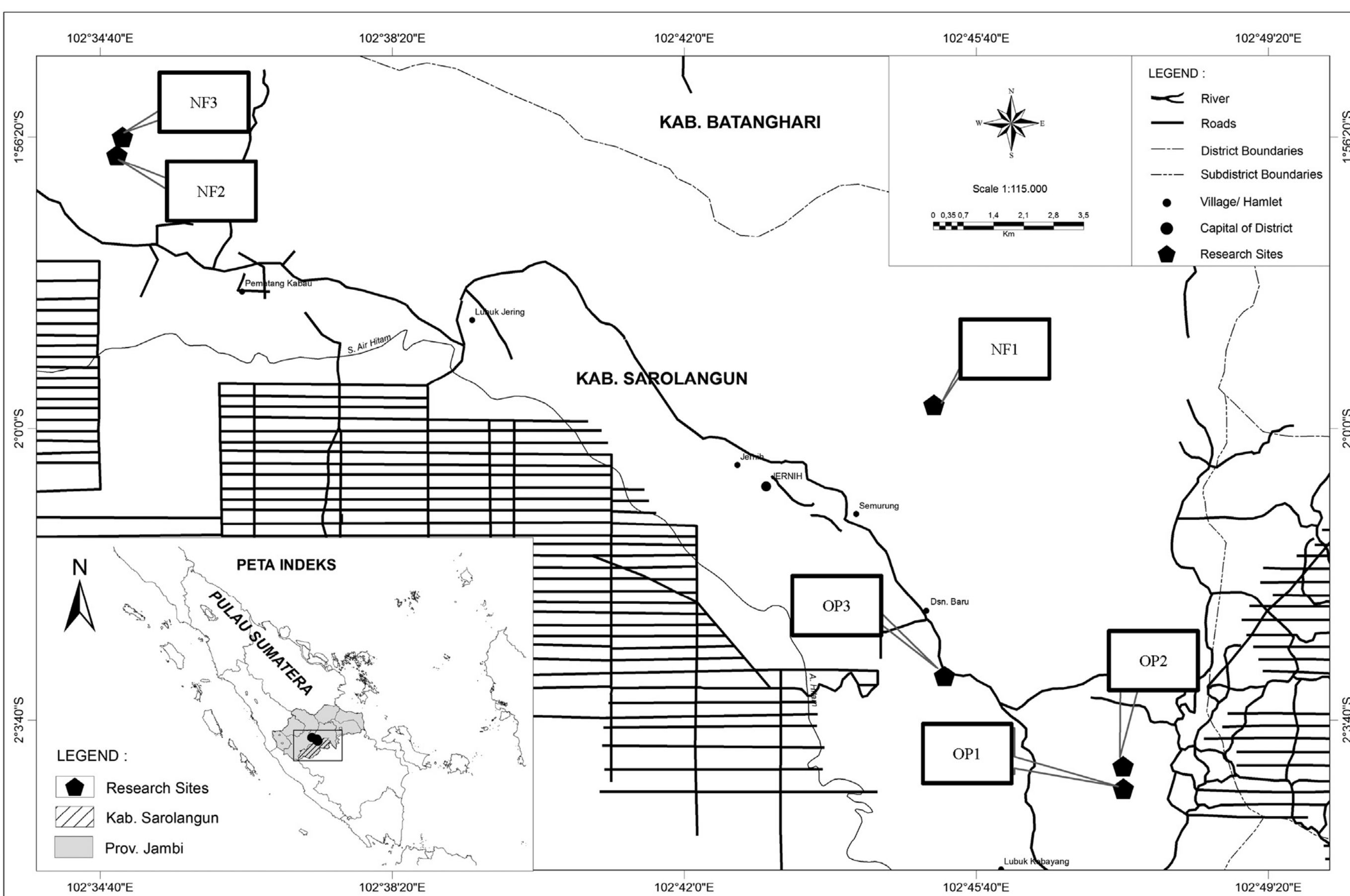

Figure 1. Map of study site of natural forest (NF; Bukit 12 National Park) and oil palm plantation (OP) at Jambi, Indonesia.

depths. The soil samples were soaked in water and cleaned from soil residues using a sieve with a mesh size of 2 mm. Only fine roots of trees, which are ≤2 mm in diameter, were collected. Their physiological status (live or dead) was assessed based on the color, texture and shape of the root (McClaugherty *et al.* 1982). Only live roots were collected for use to determine fine root production. All fine root samples were dried in the oven at 80°C until constant weight. Nitrogen and organic carbon contents in live fine root were determined by the Kjeldhal and the Walkley and Black methods, respectively.

2.3. Fine root decomposition

The quantification of fine root decomposition was determined using the litter bag method. Fine roots were collected from each tree stand from the soil surface down to 20 cm soil depth. The roots were carefully washed with water to remove attached soil particles and were dried at room temperature for 24 hours (McClaugherty *et al.* 1984). The roots with the diameter ≤2 mm were selected. Only live roots were collected for use in the litter bags (Yang *et al.* 2004). Approximately 10 g of air-dried fine root samples were weighed and placed in 18 × 18 cm nylon cloth litter bags with mesh size of 0.5 mm. We placed 24 litter bags in each observation plot at 10 cm depth for a total 12-month period. Two litter bags were retrieved once a month. The roots were taken from the bag, cleaned from attached plant, sand, and soil, dried in oven at 80°C until constant weight. Initial nitrogen and organic carbon contents in live fine root were determined by the Kjeldhal and the Walkley and Black methods, respectively.

The mass loss over time was fitted with a simple exponential curve. The decay-rate coefficient (k value) for the decomposition rate was calculated as outlined in Olson (1963).

$$\ln\ (Xt/Xo) = -kt$$

where Xt is the weight of fine roots after t time, t is the time (months), Xo is weight of fresh fine roots, and k is the decay-rate coefficient (Olson 1963).

Decomposition rate was calculated using the following formula:

$$\text{Decomposition rate} = \frac{\text{Mass loss}(\%)}{\text{Time incubation}(\text{day})}$$

2.4. Data analysis

Data on fine root production, decomposition, and N and C release were analyzed using an independent sample t test. The standard level of significance was $p < 0.05$. All analyses were done using SPSS 17.0 software. To investigate relationships among parameters, regression and correlation analysis was performed.

3. Results

3.1. Fine root production

Generally, fine root biomass production followed the same pattern in NF and OP, except for March and June 2013. The highest production of fine roots in NF occurred in March 2013 (12.2 g/m^2) whereas the highest production in OP occurred in June 2013 (11.6 g/m^2; Figure 2). Fine root N production in NF was higher than that in OP reaching 0.7 g N/m^2/year and 0.3 g N/m^2/year, respectively. On the other hand, fine root C production was not significantly different between NF and OP, reaching 13.9 and 14.1 g N/m^2/year, respectively (Figure 3).

Fine root production was influenced by environmental factors such as rainfall, air temperature, and precipitation. However, only air temperature positively correlated with fine root production in both NF and OP. In addition, rainfall was only positively correlated with fine root production in NF but not in OP (Table 1).

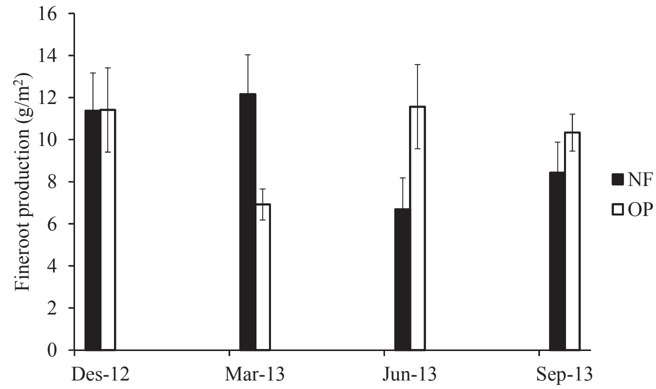

Figure 2. Fine root production in natural forest (NF) and oil palm plantation (OP) in December 2012, March 2013, June 2013, and September 2013. Error bars indicate ± standard deviation.

3.2. Initial C and N content

Table 2 provides the initial C and N content of fine root before incubation. Carbon content and C/N ratio of fine root in OP was higher than in NF, whereas N content of fine root was higher in NF than in OP and there was a significant difference between both NF and OP.

3.3. Fine root decomposition

A sharp decline of fine root decomposition occurred in the first month after incubation treatment. The remaining fine root dry weight reached 78% in NF. Meanwhile in OP, the decrease was not as sharp, and the mass remaining after the first month of treatment only reached 92.5% (Figure 4). The decrease of dry weight continued with increasing incubation time. At the end of the observation, the remaining mass in NF and OP was only 6.02% and 26.43%, respectively. In this study, the remaining mass of fine root during decomposition decreased with increasing incubation time in both NF and OP. But the decrease in remaining mass was slower in OP than in NF (Figure 4).

The decay-rate coefficient (k value) of the decomposition in NF and OP is provided in Table 3. The decay-rate coefficient of decomposition of fine roots in NF reached 2.9, whereas in OP it reached 1.3 after a 1 year period of incubation (Table 3).

There was a positive correlation between decay-rate coefficient of decomposition and N content of fine root. The decay-rate coefficient of decomposition increased with increasing initial N content and decreased with increasing initial C and C/N ratio (Table 4).

4. Discussion

Overall fine root production in NF and OP during four time observations in a 1 year research period reached 39.0 g/m^2 and 40.1 g/m^2, respectively. There is approximately the same rate of root production in OP despite much higher number of trees per area in the NF. Fine root production in OP approximately 50% of the total roots in OPs are dominated by fine roots (diameter ≤2 mm; Haron *et al.* 1999). Palms are monocot plants with fibrous root systems, thus a greater proportion of total root growth are fine roots spread near the soil surface, especially to a depth of 30–60 cm (Haron *et al.* 1999).

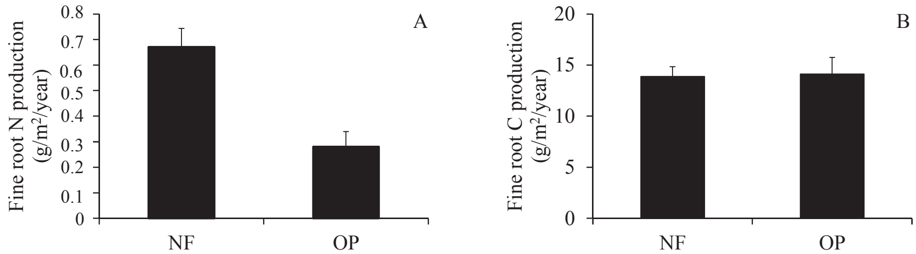

Figure 3. Fine root N and C production (g/m^2/year) in natural forest (NF) and oil palm plantation (OP). Error bars indicate ± standard deviation.

Table 1. Regression and correlation between fine root production and the climate factors (rainfall, air temperature, precipitation, and solar radiation) in natural forest (NF) and oil palm plantation (OP)

Site	Parameter	Source	Regression		Correlation	
			Equation	r^2	*r* (Pearson)	*p*
NF	Fine root production (g/m^2)	Rainfall	y = 0.012X + 9.442	0.48	0.691**	0.01
		Air temperature	y = 4.828X − 118.2	0.39	0.623*	0.03
		Precipitation	y = −0.364X + 42.92	0.24	−0.49	0.11
		Solar radiation	y = −0.090X + 17.36	0.04	−0.193	0.55
OP	Fine root production (g/m^2)	Rainfall	y = 0.004X + 10.65	0.04	0.211	0.51
		Air temperature	y = 6.771X − 171.4	0.46	0.679**	0.01
		Precipitation	y = 0.018X + 10.30	0	0.019	0.952
		Solar radiation	y = 0.283X − 3.437	0.22	0.47	0.123

**Significantly different in $p < 0.01$.
*Significantly different in $p < 0.05$.

Fine root production of NF decreased sharply in the 3-month period harvested in June 2013 compared to the other 3-month periods. June 2013 also coincided with a peak in NF litter production (Violita *et al.* 2015). In this condition the energy available in the canopy is not sufficient to meet the growth of fine roots, so that the production of fine roots in NF decreased. On the other hand the lowest fine root production in OP occurred in the 3-month period harvested in March 2013. In this month, litter production of palm fronds and fruit on the location of OP was decreased (Violita *et al.* 2015). The low production of litter palm fronds and fruit followed by low production of fine roots in OP indicated declining metabolism in oil palm, so that root growth is not optimal as well as litter production of palm fronds and fruit. This is understandable, because the litter production of palm fronds and fruit on OP is influenced by harvesting by farmers (does not occur naturally). Differences in the pattern of production of fine roots between NF and OP are due to differences in ecosystem types (Leuchner *et al.* 2006; Hertel *et al.* 2009) and different types of plants found in these ecosystems (Barbhuiya *et al.* 2012).

Table 2. Initial fine root C and N content in the natural forest (NF) and oil palm plantation (OP)

Site	Plant parts	Nutrient properties		
		C (%)	N (%)	C/N
NF	Fine root	35.91 ± 3.10	1.53 ± 0.16	23.98 ± 1.24
OP	Fine root	38.06 ± 2.35	0.78 ± 0.02	49.26 ± 1.18

Values are mean ± standard deviation.

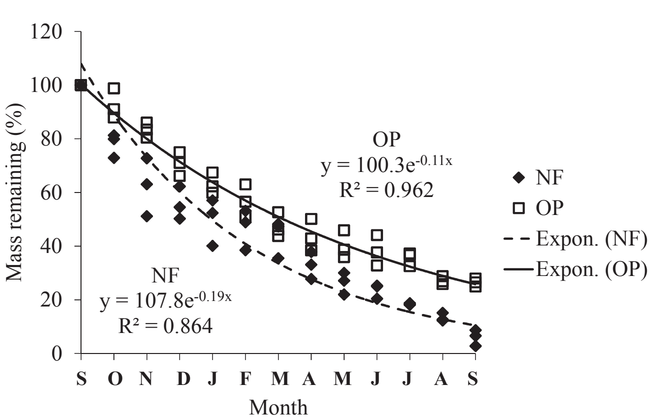

Figure 4. Exponential curve of fine root mass remaining (%) in the decomposition process during 12 months of incubation from September 2012 to September 2013 in the natural forest (NF) and oil palm plantation (OP).

Fine root production N and C showed different pattern between NF and OP. Fine root N production was much higher in NF than in OP, whereas fine root C productions in NF and OP were not significant different ($p > 0.05$). In this study, annual fine root N production in NF reached 0.7 g N/m^2. This result is much lower than the 2.7 g N/m^2 measured in tropical montane forest in Sulawesi by Leuschner *et al.* (2009). Forest in TNBD is dominated by secondary forests that have undergone changes compared with primary forest vegetation. On the other hand annual fine root N production of OPs reached only 0.3 g N/m^2. This in contrast with results of Haron *et al.* (1999), where annual fine root N production reached 1.3 g N/m^2. This difference may be the result of differences in environmental conditions between the two study sites. According to Gill and Jackson (2000), different environmental conditions affect the production of fine roots. Fine root production was correlated with air temperature in NF and OP, and rainfall in NF. Fine root production increased with increased air temperature in NF and OP and fine root production increased with increased rainfall in NF. Production of fine roots is influenced by environmental factors such as climate factors mainly by air temperature and precipitation (Yuan and Chen 2010).

According to Jimenéz *et al.* (2009), climate change will affect rainfall which may especially impact fine root production in forest ecosystems. The rate of fine root growth was low during the dry season, and increased during the rainy season. According to Gill and Jackson (2000), the influence of increasing rainfall on fine root production is unclear, because the impact of rainfall is not the same across different ecosystems. According to Majdi and Ohrvik (2004), soil warming leads to increased production and mortality of fine roots in ecosystem. Yuan and Chen (2010) added that the environment greatly affects the biomass, production, and turnover of fine root in the forest. In our study, the climatic factors were not correlated with fine root production except rainfall in NF and air temperature in NF and OP. However, fine root production in different ecosystems appears to be influenced by different climatic variables (Yuan and Chen 2010).

The initial chemical composition of litter is important in predicting the decomposition process and nutrient turnover in ecosystems (Berg and McClaugherty 2008). Chen *et al.* (2002) and

Table 3. Fine root mass remaining (%), decay-rate coefficient of decomposition, and decomposition rate after 1 year incubation period in natural forest (NF) and oil palm plantation (OP)

Site	Fine root mass remaining (%) after 1 year incubation period	Decay-rate coefficient of decomposition (*k* value) during 1 year incubation period	Decomposition rate (%/day) during 1 year incubation period
Natural forest (NF)	6.0 ± 3.0	2.9 ± 0.6	0.3 ± 0.01
Oil palm plantation (OP)	26.4 ± 1.5	1.3 ± 0.04	0.2 ± 0.06

Values are mean ± standard deviation.

Table 4. Pearson correlation between decomposition rate and fine root N, C, and C/N ratio

Parameter	Source	Correlation	
		r (Pearson)	*p*
Decomposition rate (*k* value)	N content (%)	0.952**	0.000
	C content (%)	−0.695*	0.012
	C/N ratio	−0.913**	0.000

**Significantly different at $p < 0.01$.
*Significantly different at $p < 0.05$.

Taylor *et al.* (1989) stated that initial C/N ratio was a better predictor of the decomposition process. These predictions are supported by the results of this study with the NF showing both greater N and lower C/N coupled with greater decomposition rate of fine roots compared to the OP. The slow rate of OP fine root decomposition in this study is similar to that found by Haron *et al.* (2000) who conducted a study on the decomposition of the oil palm residues including roots. They analyzed the primary and secondary roots and found that the decrease in dry weight during the decomposition process in the roots was slow. Mass remaining after the 6 and 12 months of incubation was only about 70% and 30%, respectively. This indicates that nutrient turnover in OP is rather lengthy. The same result was shown for the decay-rate coefficient of decomposition. It seems that nutrient turnover in OP from fine roots occurs slowly with likely impacts on soil nutrient content.

The decomposition process is a fundamental ecosystem process which is intimately linked to soil fertility through breakdown of plant organic matter to release plant nutrients and soil organic matter sequestration (Lambers *et al.* 2008). The decomposition rate of fine root was positively correlated with initial nutrient content of fine roots and soil (Hendricks *et al.* 2006). The fine root decomposition rate in this study increased with high initial N content and decreased with high initial C content and C/N ratio. All these correlations were statistically significant at the $p < 0.01$ level except for the correlation between decomposition rate and C content which was significant at $p < 0.05$. According to Nahwari *et al.* (2011) the nutrient concentration in plant tissue correlates with loss of leaf and root residues. High C/N ratios in plant tissue result in the slow decomposition of sago leaves and pineapple fine roots. Decomposition rate of fine root is highest on sago followed by the decomposition rate on oil palm and pineapple (Nahwari *et al.* 2011). The chemical composition in fine roots is an important factor that affects the decomposition rate. This was supported by our research, with the C/N ratio negatively correlated with the decomposition rate. However, Chen *et al.* (2002) found that initial N content was not correlated to the decomposition rate, in contrast with our results where N content had a positive and significant correlation with the decomposition rates of fine roots. According to Lin *et al.* (2011) N is the limiting factor in the decomposition of fine roots. Zhang *et al.* (2008) stated that litter decomposition rates increase with the increase of N, P, K, Ca, and Mg content, but decrease with the increasing C/N, lignin, and lignin/N (Taylor *et al.* 1989). Nitrogen and lignin have opposite effects on decomposition rates, N is a rate simulating and lignin is rate retarding factor. The lignin-degrading microorganisms usually grow very slowly and lignin as a chemical compound is largely resistant to decomposition, but this can change with the high level of N (Berg and McClaugherty 2008), therefore initial chemical content of N, lignin, and lignin/N determines the litter decomposition rates in many ecosystems (Taylor *et al.* 1989). In addition, Taylor *et al.* (1989) found that the C/N ratio was a better predictor of decomposition rate than the lignin/N ratio. It can be concluded that N and C content and C/N ratio are important factors in fine root decomposition in addition to the environmental factors.

References

Barbhuiya AR, Arunachalam A, Pandey HN, Khan ML, Arunachalam K. 2012. Fine root dynamics in undisturbed and disturbed stands of tropical wet evergreen forest in northeast India. *Trop Ecol* 53:69–79.
Berg B, McClaugherty C. 2008. Plant Litter: Decomposition Humus Formation, Carbon Sequestration, 2nd ed. Germany: Springer.
Chen H, Harmon ME, Sexton J, Fasth B. 2002. Fine-root decomposition and N dynamics in coniferous forests of the Pacific Northwest, U.S.A. *Can J For Res* 32: 320–31.
Gautam TP, Mandal TN. 2012. Effect of disturbance on fine root biomass in the tropical moist forest of eastern Nepal. *Nepalese J Biosci* 2:10–6.
Gill RA, Jackson RB. 2000. Global patterns of root turnover for terrestrial ecosystems. *New Phytol* 147:13–31.
Haron K, Zin ZZ, Anderson JM. 1999. Quantification of oil palm biomass and nutrient value in a mature plantation. II. Below-ground biomass. *J Oil Palm Res* 11:63–71.
Haron K, Zin ZZ, Anderson JM. 2000. Decomposition processes and nutrient release patterns of oil palm residues. *J Oil Palm Res* 12:46–63.
Hendrick RL, Pregitzer KS. 1993. Patterns of fine root mortality in two sugar maple forests. *Nature* 361:59–61.
Hendricks JJ, Hendrick RL, Mitchell RJ, Pecot SD, Guo D. 2006. Assessing the patterns and controls of fine root dynamics: an empirical test and methodological review. *J Ecol* 94:40–57.
Hertel D, Marieke AH, Leuschner C. 2009. Conversion of a tropical forest into agroforest alters the fine root-related carbon flux to the soil. *Soil Biol Biochem* 41:481–90.
Jiménez EM, Moreno FH, Penuela MC, Patino S, Lloyd J. 2009. Fine root dynamics for forests on contrasting soils in the Colombian Amazon. *Biogeosciences* 6: 2809–27.
Koh LP, Wilcove DS. 2008. Is oil palm agriculture really destroying tropical biodiversity? *Conserv Lett* 1:60–4.
Lambers H, Chapin III FS, Pons TL. 2008. Plant Physiological Ecology, 2nd ed. New York: Springer.
Leuschner C, Harteveld M, Hertel D. 2009. Consequences of increasing forest use intensity for biomass, morphology and growth of fine roots in a tropical moist forest on Sulawesi, Indonesia. *Agric Ecosyst Environ* 129:474–81.
Leuschner C, Wiens M, Harteveld M, Hertel D, Tjitrosemito S. 2006. Patterns of fine root mass and distribution along a disturbance gradient in a tropical montane forest, Central Sulawesi (Indonesia). *Plant Soil* 283:163–74.
Lin C, Yang Y, Guo J, Chen G, Xie J. 2011. Fine root decomposition of evergreen broadleaved and coniferous tree species in mid-subtropical China: dynamics of dry mass, nutrient and organic fractions. *Plant Soil* 338:311–27.
Majdi H, Ohrvik J. 2004. Interactive effects of soil warming and fertilization on root production, mortality, and longevity in a Norway spruce stand in Northern Sweden. *Global Change Biol* 10:182–8.
McClaugherty CA, Aber JD, Melillo JM. 1982. The role of fine roots in the organic matter and nitrogen budgets of two forested ecosystems. *Ecology* 63:1481–90.
McClaugherty CA, Aber JD, Mellilo JM. 1984. Decomposition dynamics of fine roots in forested ecosystems. *Oikos* 42:378–86.
Nadelhoffer KJ, Raich JM. 1992. Fine root production estimates and belowground carbon allocation in forest ecosystems. *Ecology* 73:1139–47.
Nahwari H, Husni MHA, Othman R, Bah A. 2011. Decomposition of leaf and fine root residues of three different crop species in tropical peat under controlled condition. *Malaysian J Soil Sci* 15:63–74.
Olson JS. 1963. Energy storage and the balance of producers and decomposers in ecological systems. *Ecology* 44:322–31.
Ruess RW, VanCleve K, Yarie J, Viereck LA. 1996. Contribution of fine root production and turnover the carbon and nitrogen cycling in taiga forest of the Alaska interior. *Can J For Res* 26:1326–36.

Santantonio D, Hermann RK. 1985. Standing crop, production, and turnover of fine roots on dry, moderate, and wet sites of mature Douglas-fir in western Oregon. *Ann For Sci* 42:113–42.

Silver WL, Thompson AW, McGroddy ME, Varner RK, Dias JD, Silva H, Crill PM, Kellers M. 2005. Fine root dynamics and trace gas fluxes in two lowland tropical forest soils. *Global Change Biol* 11:290–360.

Taylor BR, Parkinson D, Parsons W. 1989. Nitrogen and lignin content as predictors of litter decay rates: a microsom test. *Ecology* 70:97–104.

Violita, Kotowska MM, Hertel D, Triadiati, Miftahudin, Anas I. 2015. Transformation of lowland rainforest into oil palm plantations results in changes of leaf litter production and decomposition in Sumatra, Indonesia. *J Bio Env Sci* 6:544–54.

Yang YS, Chen GS, Lin P, Xie JS, Guo JF. 2004. Fine root distribution, seasonal pattern and production in four plantations compared with a natural forest in subtropical China. *Ann For Sci* 61:617–27.

Yuan ZY, Chen HYH. 2010. Fine root biomass, production, turnover rates, and nutrient contents in boreal forest ecosystems in relation to species, climate, fertility, and stand age: literature review and meta-analyses. *Crit Rev Plant Sci* 29:204–21.

Zhang D, Hui D, Luo Y, Zhou G. 2008. Rates of litter decomposition in terrestrial ecosystems; global patterns and controlling factors. *J Plant Ecol* 1:85–93.