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Transformation of lowland rainforest into oil palm plantations results in changes of leaf litter production and decomposition in Sumatra, Indonesia

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Abstract

Leaf litter plays an important role for nutrient availability in ecosystems. Conversion of tropical rainforest into different land-use systems could largely alter nutrient cycling via changes in litter production and decomposition. In Indonesia, particularly on Sumatra and Kalimantan, a large area of natural lowland forest was increasingly replaced by oil palm plantation. However, how the impact of the lowland rainforest transformation to oil palm plantation in Sumatera to soil nutrient status is unknown yet. Here we investigated the leaf litter production, decomposition rate constants, and seasonal litter fall patterns in oil palm plantation (OP) and natural forest (NF) in Bukit 12 National Park Jambi, Sumatra Indonesia using litter traps and litter bag methods. The annual litter production was higher in OP than that of in NF. However oil palm fruits as the dominant component of litter production (79.6% of total litterfall production) are removed from the system caused nutrient lost. Litterfall production was influenced by climatic factor, mainly by rainfall and humidity. Litterfall production increased by increasing of rainfall and decreasing of humidity in NF and on contrary in OP, litterfall production increased with decreasing of rainfall and increasing of humidity. Leaf litter nitrogen and C/N ratio were the main factors that influenced litter decomposition. Our data showed that decomposition rate constants of leaf letter was significantly higher in NF than that of in OP, it means that nutrient turn-over via leaf litter of OP was slower than that of in NF.

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Introduction

Indonesia is one of the countries with highest deforestation rate among tropical countries (Hansen *et al.*, 2013; Margono *et al.*, 2014). Oil palm expansion hereby is one of the major drivers of current land-use change (Abood *et al.*, 2014). In Sumatra, this rapid conversion to oil palm plantation occured in most lowland forest regions (e.g. provinces of Jambi, Riau, South Sumatra) with increasing pressure on forest remnants, on going secondary forest transformation and older agroforestry systems to oil palm monocultures (Villamor *et al.*, 2014). This large scale land-use change from structurally diverse forest to monoculture plantations not only has negative impact to biodiversity (Sodhi *et al.*, 2004; Fitzherbert *et al.*, 2008; Wilcove *et al.*, 2013) but also changes in ecosystem function (Sangha *et al.*, 2006) like leaf litter production and decomposition process as a key biogeochemical processes (Hättenschwiler *et al.*, 2005; Hertel *et al.*, 2009) and as the major contributor to total net primary productivity (NPP) in tropical rainforests (Clark *et al.*, 2001) . These changes most likely will alter the plant-derived nutrient input to the soil and could influence ecosystem functioning (Triadiati *et al.*, 2011). Despite their key role in the global carbon cycle and ecosystem functions (Dixon *et al.*, 1994; Houghton 2005; Del Grosso *et al.*, 2008; Pan *et al.*, 2011),

Several studies showed that tropical natural forests contain higher annual leaf litter production compared to plantations, like monoculture plantations of *Cunninghamia lanceolata* (Wang *et al.*, 2008), fast growing monoculture plantations of teak (*Tectona grandis* Lim.) (Ojo *et al.*, 2010), and cacao agroforestry (Hertel *et al.*, 2009; Triadiati *et al.*, 2011). Differences in leaf litter production occurred due to varying environmental condition (Pausas, 1997) and plant species in the ecosystem (Kaye *et al.*, 2000).

Leaf litter decomposition is the main path of nutrients recycling and nutrients turnover in the forest ecosystem, including N (Sariyildiz, 2003; Odiwe & Moughalu, 2003). It has been shown, that the patterns of leaf litter decomposition is different between plantation and natural forest ecosystems (Taylor *et al.*, 1989). According to Triadiati *et al.*, (2011), natural forest showed the most rapid decomposition rate constants, while cacao agroforestry systems with shade tree system have lowest decomposition rate constants. Besides ecosystem, the quantity and quality of litter also impacts the decomposition process (Hättenschwiler *et al.*, 2011). Quality of leaf litter, such as N concentration and the C/N ratio are strongly correlated with decomposition rate constants (Taylor *et al.*, 1989), and the introduction of shade trees in plantations can support the crop nutrient availability through decomposition process (Triadiati *et al.*, 2011). Kang *et al.*, (1999) stated that litter can help supply of the agricultural N, reduce the use of N fertilizer, and prevent the loss of N. To understand the dynamics of N in the plantation or in the forest ecosystem, it is important to analyze the quantity and quality of leaf litter, including leaf litter decomposition rate constants. However, studies on leaf litter production and decomposition particularly in oil palm plantations as compared to natural forests have not done so far. Knowledge of production and decomposition rate constants of leaf litter as a fundamental role in the biogeochemical cycle of organic matter needs to be extended, especially to estimates nutrient turnover, C and N fluxes and changes of energy flow in transformation systems. The overall objective of our study was to investigate the impact of transformation systems to production and decomposition of leaf litter in oil palm plantation and natural forest in the Sarolangun district in Jambi (Sumatra). We tested the hypotheses (i) that leaf litter production is lower in the oil palm plantation than in the natural forest, and (ii) that leaf litter decomposition and related nutrient return to the soil is lower in the oil palm plantation than in the natural forests.

Materials and methods

Study site

The study was conducted from September 2012 to September 2013 in Sarolangun district, Jambi province. The Bukit 12 National Park (TNBD) is a relatively small national park that covers 605 km² in Jambi (Indonesia), which represent the lowland tropical rain forests in Jambi province. Only the northern part of this park consists of primary rainforest, while the rest is old-growth forest with selective logging activities. In the past, the forest area was functioned as a permanent production forest, limited production forest, and other forest land uses which were later merged to a National Park.

The study was conducted in 2 location: natural forest (NF in three sites at TNBD, Sarolangun district) and oil palm plantation (OP (8-12 old) in three sites in Sarolangun district), the coordinate are: S 01°59'42.5" E 102°45'08.1" (NF1), S 01°56'33.9" E 102°34'52.7"(NF2), S 01°56'31.9' E 102°34'50.3"(NF3), S 02°04'32.0" E 102°47'30.7" (OP1), S 02°04'15.2" E 102°47'30.6" (OP2), S 02°04'15.2" E 102°47'30.6" (OP3). Plot size was 50 m x 50 m. The monthly rainfall was 217.47 mm with the highest and lowest precipitation were in December 2012 (529 mm) and June (33 mm) 2013, respectively. The average daily temperature was ranged from 26.6°C to 28°C. The daily air humidity and solar radiation ranged between 77-90% and 45%-62%, respectively. Climate data were acquired from Climatology Station of Jambi.

Litterfall production

Leaf litter production in NF was measured by collecting the litterfall using litter traps, which was placed on the plot. Litter traps were made of nylon gauze with a mesh size of 3 mm with PVC-tubed frames with the trap surface size of 0.75 m x 0.75 m. The traps were set up at about 50 cm above soil surface, with 16 traps for each plot. In OP, data were acquired from pruned oil palm fronds at every harvesting time, as well as the harvested fruits every month. The collected litter was separated into components of leaf, twig (≤ 2 cm diameter), and reproductive parts. The litter was then dried in the oven at 80°C until constant weight. Leaf litter production was assumed to equal annual leaf litter.

Leaf litter decomposition

The quantification of leaf litter decomposition was determined using the litter bag methods. The fresh leaf litter was placed in nylon bags (30 cm x 30 cm and mesh size of 0.5 mm). For every plot, we placed 24 litter bags during 12 month period of observation time. The litter bags were placed randomly on the forest floor surface and tied on a nail plugged to the ground to prevent displacement or site exchange. Two bags were retrieved once a month. The leaf litters were oven dried at 80°C until constant weight. The dried leaf litter was placed in plastic bags until N and C analysis were conducted. Nitrogen and organic carbon content in leaf litter were determined using the Kjeldahl and the Walkley and Black method, respectively.

The litter decomposition rate constants was measured based on Olson (1963):

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

Where Xt is the weight of litter after t time, t is time (months), Xo is the fresh litter weight, and k is the decomposition rate constant.

Periodic curve fitting

Periodic curve fitting can be used for periodic data as the observations are equally spaced a complete cycle (daily, weekly, monthly, or yearly cycles). Periodic curve appoint to as a harmonics (Little and Hills, 1977). In this study, periodic curve was applied for monthly data of litterfall production and climates (rainfall, temperature, air humidity, and solar radiation).

Data Analysis

Data on leaf litter production and decomposition, N and C release were analyzed using Independence sample t-test. In order to investigate relationship among parameters linear regressions and Pearson's correlation analysis were performed. The standard level of significant was $p < 0.05$. All analyses were done using SPSS 17 software.

Results and discussions

Litterfall production

We found different patterns of litter production between NF and OP (Fig. 1 and 2). The annual forest litterfall production reach to 1.4 kg $m^{-2}y^{-1}$ (Tab. 1). The same with Triadiati *et al.* (2011) annual litterfall production of tropical rain forest in Central Sulawesi, Indonesia approximately 1.4 kg $m^{-2}y^{-1}$. On the other hand according to Lowman (1988) annual litterfall production of tropical rain forest in Australia reach to 0.7 kg $m^{-2}y^{-1}$. The different of annual litterfall production between influenced by plant diversity and climate factor (Lowman, 1988), whereas the annual oil palm litterfall production was 2.4 kg $m^{-2}y^{-1}$. Height of the annual oil palm litterfall production because harvesting doing by the farmer.

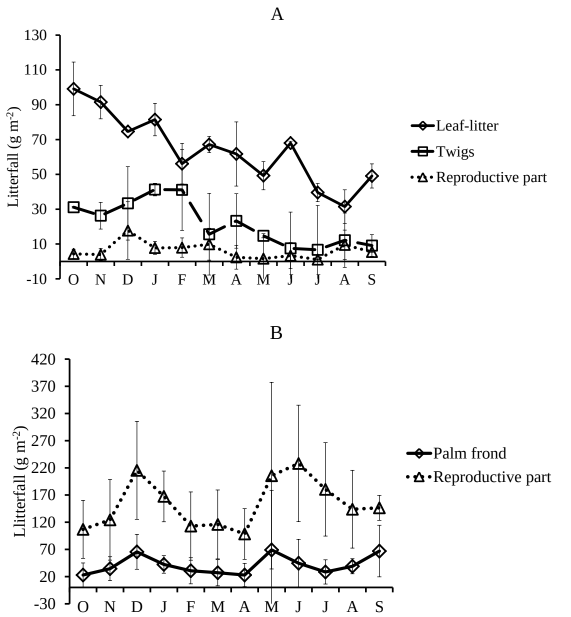

Fig. 1. Component of litterfall production in natural forest (NF) (A) and oil palm plantation (OP) (B) from October 2012 to September 2013. Error bars indicate ± SD.

Leaf litter was the most dominant litter components that contributed to litter production of NF, followed by twigs and reproductive parts (Fig. 1.A). Smith *et al.*, (1998) state that the highest litterfall resulted in both natural forests and three plantation types of *Pinus caribae*, *Carapa guianensis,*and *Euxylophora paraensis* is the leaf litter, and generally followed by stem, branches, and reproductive parts,. Meanwhile, reproductive parts were the largest litter components of OP litterfall that contributed 79.6 % to the litterfall production (Fig. 1.B). However, these parts were not returned to the ecosystem, but it was lost as nutrients loss, resulting in high nutrients loss to the system and disturbance of nutrient recycling. Conversely, all litterfall in NF was returned to the soil, and become a source of nutrients for plants and completing the nutrient cycles.

The highest litter fall production in NF occurred in April 2013, while in OP most leaf litter was produced in December 2012, May and June 2013 (Fig. 2). We found significant differences in December 2012 and September 2012 and divergent patterns of litterfall production between both ecosystems.

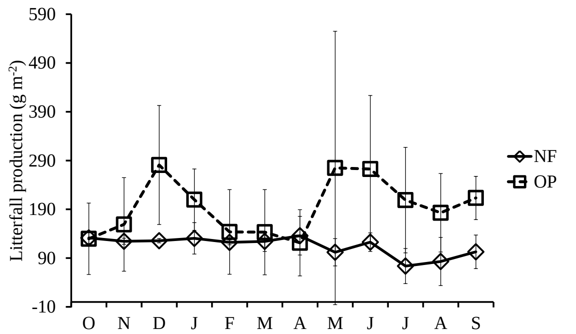

Fig. 2. Litterfall production in natural forest (NF) and oil palm plantation (OP) from October 2012 to September 2013. Error bars indicate ±SD.

Leaf litters from forest were rich of nutrient elements and had great effect in improving the soil humus productivity. Level of litterfall effect in improving the soil humus depends on the plant species, environmental factors, and the type of soil, climate, accumulation of organic matter, and microbial activity (Sharma and Sharma, 2004). Nutrient concentrations (include N and C) in forest tree contributed to soil nutrient by means of decomposition process and become soil humus in ecosystem (Vitousek and Sandford, 1987). Our result showed that there were different in N and C production of fine litterfall between two type ecosystems. Leaf litter in NF contained the highest N and C production, followed by twigs and reproductive parts (Fig .4). According to Oladoye *et al.*, (2010), leaf litter contributed more nutrients, especially N, than other fine litterfall. On the other hand in OP, the highest N and C production showed in reproductive parts (68.1% and 77.8%, respectively) and significant different among other fine litterfall (Fig. 4). This reproductive part in OP was not return to the systems and become nutrient loss.

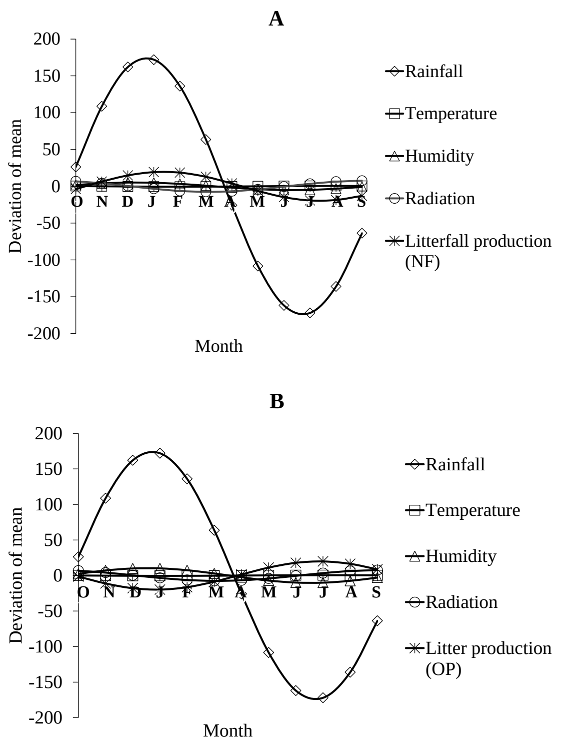

Fig. 3. Periodic curve of litterfall production in October 2012 to September 2013 in natural forest (A) and oil palm (B), and several climatic factors (rainfall, air temperature, air humidity, and solar radiation). NF = positive correlation to rainfall and temperature, and negative correlation to humidity and solar radiation; OP = negative correlation to rainfall and temperature, and positive correlation to humidity and solar radiation.

High litterfall production in monokultur OP is driven by intensive fertilization to counterbalance nutrient loss due to harvesting and soil erosion (Witt *et al.*, 2005). According to Witt *et al.*, (2005) fertilization became a major factor of high productivity in oil palm systems (Witt *et al.*, 2005; Danyo, 2013).

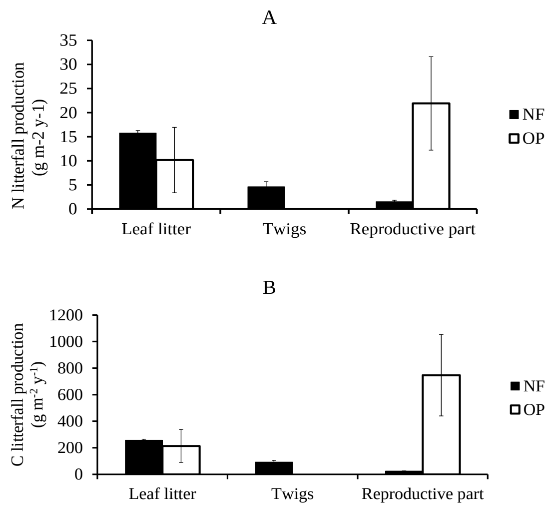

Fig. 4. Nitrogen and carbon content of fine litter-fall of natural forest (NF) compared to oil palm plantation (OP). A = nitrogen litterfall production and B = carbon litterfall production. Error bars indicated ± SD.

Periodic curve of monthly litterfall and climatic factors (rainfall, temperature, humidity, and solar radiation) were shown in Fig. 3. Based on the periodic curve (Fig. 3) we concluded that high litterfall production in NF occurred during the period of high rainfall, high temperature, low humidity and low radiation (Fig. 3A). According to Zheng *et al.*, (2005) and Triadiati *et al.*, (2011), leaf litter production is influenced by climatic factors especially; rainfall, temperature, and humidity. In contrast to NF, high litterfall production in OP occurred during the period of low rainfall, low temperature, high humidity and high radiation. Zhu *et al.*, (2008) stated that oil palm tree grows commonly and produced optimal production in hot (high radiation), wet tropical lowland climates with temperature ranging from 24-27°C and the annual rainfall distribution of 2000-3000 mm annual rainfall. . However, different ecosystem was influenced by different climatic variable (Yuan and Chen, 2010). The litterfall in OP was artificially influenced by the harvesting done by farmers, as well as by environmental factors. Cutting of oil palm fronds during the harvesting process, cleaning of the yellow senescent fronds, and exposure to pesticide spraying, caused the higher production of litter in the oil palm plantation. In OP, there were cuttings of fronds every harvesting. This was understandable that the production of palm fronds was associated with pruning by the farmers, including the harvesting of oil palm fruits. In certain conditions, the farmers did not cut the fronds trees of the harvested palm trees, thus decreased the litter production (its make wide ± SD in the statistics analysis) (Fig. 1 and 2). Regarding to the life cycle of palm frond, the oil palm plantation takes over 4 years to the leaves senescent, whereas NF plants usually require a much shorter time. Therefore, the fronds obtained as litters in OP in this study were not senescent leaves, but the leaves that pruning by farmer. In other conditions, the farmers did pruning on a large scale if there were too many fronds yellowing, and during the study, it happened in September 2013 (Fig. 1), in which the palm fruit production was low while the fronds production increased. So we can conclude that not only climatic factor but many other factors such as human treatment and fertilization that influenced the different pattern of litterfall production in NF and OP.

Leaf litter decomposition

Initial chemical content (N, C, C/N ratio) of leaf litter before decomposition is shown in Table 2. The N content was higher in NF than that of sin OP, whereas the C content and C/N ratio was higher in OP than that of in NF (Tab. 2).

Table 1. Annual litterfall production in Natural forest (NF) and oil palm plantation (OP).

Site	Annual litterfall production ($kg\ m^{-2}\ year^{-1}$)
NF	1.4±1.6
OP	2.3±1.1

Value are mean ± SD.

Table 2. Initial N and C content of leaf-litter in forest (NF) and oil palm (OP).

Site	Plant parts	Initial N, C content and rasio C/N		
		C (%)	N (%)	C:N
NF	Leaf litter	40.2±1.0	1.66±0.3	24.22±4.6
OP	Palm frond	41.1±0.7	1.47±0.1	27.81±5.9

Value are mean ± SD.

Table 3. Correlation between nitrogen content and C/N ratio to decomposition rate constants (*k*) (Pearson's).

Parameter	Source	Correlation	
		r (Pearson's)	*p*
Decomposition rate constants (*k* value)	N content (%)	0.77**	0.00
	C content (%)	-0.32	0.31
	C/N ratio	-0.79**	0.00

** indicated significantly different at $p < 0.01$.

Dry weight decreased with increasing incubation time in NF and OP (Fig. 5). The reduction of remaining mass was more rapid in NF than that of in OP. In the first month of observation, dry weight in NF decreased drastically reached to 28.8%, while in OP it was only 6.7%. The faster decreased could cause by water-soluble material at the beginning of incubation and slowed down over time as the recalcitrant substances become more abundant in the leaf litter (Berg & McClaugherty, 2008). Physical and chemical processes occurred during this period. Physical process generally dominated the early state of decay in decomposition process. The microorganism will decay leaf litter in order to gain carbon, nutrients and energy for growth and reproduction (McClaugherty, 2001). This process is through physical fragmentation by wet–dry, shrink-swell, hot-cold, and other cycles. Leaching and transport water is another important physical mechanism (Berg and McClaugherty, 2008). Chemical transformation included oxidation and condensation of leaf litter (Berg and McClaugherty, 2008).

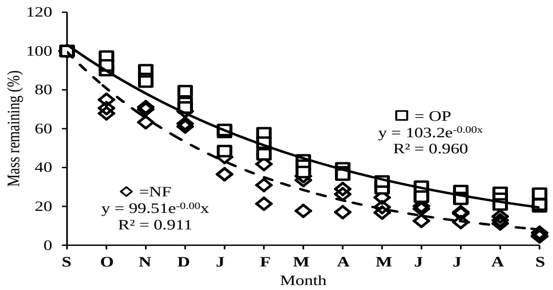

Fig. 5. Exponential curve of mass remaining (%) in the decomposition process during 12 months of incubation from September 2012 to September 2013 in natural forest (NF) and oil palm (OP). y = leaf-litter mass remaining and x= time (month).

Generally, the most rapid weight loss occurred in the water-soluble component (Andren and Paustian, 1987), such as soluble sugars, phenolics, hydrocarbons, and glycerides (Berg and McClaugherty, 2008). At the end of the incubation, the percentage of mass remaining of leaf litter in NF was lower (5.27%) than that of in OP (22.48%) (Fig.5). According to Haron and Anderson (2000), the percentage mass remaining in decomposition of oil palm leaves ranged between 5-20% during the 12 months of incubation. The decomposition rate constants increased with the increasing time incubation. Decomposition rate constant of leaf litter during 12 month incubation in NF was higher than that of in OP. It was reached to 2.95 and 1.5, respectively (Fig. 6). According to Berg and McClaugherty (2008) decomposition rate constants becomes one of indicator of nutrient return in ecosystem. We concluded that the nutrient turnover derived from leaf-litter in OP was much slower than that of NF.

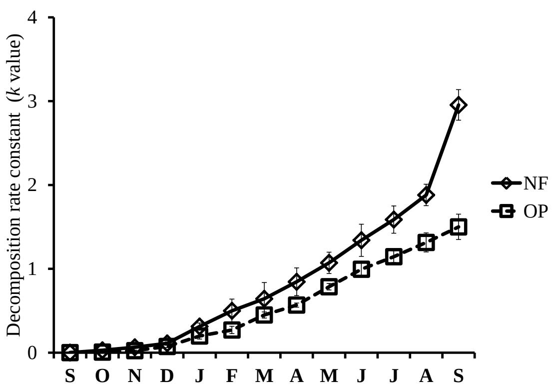

Fig. 6. Decomposition rate constants constants (*k* value) in natural forest (NF) and oil palm plantation (OP). Error bars indicates ± SD.

The leaf litter decomposition rate constants was positively correlated with initial N content and negatively correlated with initial C/N ratio of leaf litter (Tab. 3). Leaf litter quality was the major factor for leaf litter decomposition in forest ecosystems (Vitousek, 1982). Our results showed that he dry weight loss was faster in NF than that of in OP. This might be caused by different nutrient content of the leaf litter from both ecosystems (Vitousek, 1982) as we found higher N content in NF leaf litter, and lower C content and C/N ratios than that of in OP litter (Tab. 3). These results were supported by correlation between N and C/N ratio to decomposition rate constants. Decomposition rate constants increased with the increased of N content, and decreased with the increased C/N ratio. Similar result showed by other researchers who reported that that decomposition rate constants increased with the increased of N and decreased with the increased of C/N ratio (Semwal *et al.*, 2003; Sing *et al.*, 2003; Scherer-Lorenzen *et al.*, 2007; Zhang *et al.*, 2008). Wenyau *et al.*, (2000) and Xu and Hirata (2005), states that N and lignin content or ratio of lignin/N in plants had a greater influence on the decomposition process compared to the other quality parameters. In addition, Taylor *et al.*, (1989) said that as lignin/N ratio, C/N ratio was the prominent parameter of leaf litter quality in determined decomposition rate constants (Bosire *et al.*, 2005).

Oil palm plantations produce a number of agricultural by-products such as fronds and empty fruit bunches. These by-products usually support nutrients turnover in oil palm plantations through the decomposition process. Salétes *et al.*, (2004) studied the nutrient loss in empty fruit bunches of oil palm during the storage period, and found that the empty fruit bunches yield mineral nutrients quickly, especially the elements of potassium, magnesium, and boron. According to Haron *et al.*, (2000), the efficient management of oil palm residues can improve palm nutrients and hence their uptake, growth and production. However in this study plots, the farmers did not apply the empty fruit bunches of oil palm to the plantation area, so that many nutrients were lost.

Conclusions

Transformation of natural forest to oil palm plantations influences the litterfall production and decomposition process in tropical lowlands. There was different seasonal pattern of litter production between NF and OP. Total litter production was found to be higher in OP than that of in NF. Leaf litter was the largest component of litterfall product in NF, while reproductive part was major component of litterfall product in OP that contributed reach 79.6% to litterfall production. The reproductive parts, however, were removed from the ecosystem and were not returned to the soil, therefore many nutrients were lost in OP. Climate factors influenced litterfall production mainly by rainfall and humidity. We found that the decomposition rate constant of litter was significantly higher in NF than that of in OP. This indicated that nutrient turnover in NF was faster than that of in OP. The initial N content and C/N ratio of leaf litter affected decomposition rate constants, which implicated on the slower of nutrient turn over.

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