Litter production and leaf litter decomposition rate in secondary peat swamp forests in Central Kalimantan, Indonesia

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Abstract. Peat swamp forest is an important ecosystem in global climate change through its high carbon content and role as a carbon sink. In peat swamp forest, there is a near-closed cycle of nutrients including carbon. In order to better understand the rate of plant litter production and decomposition, a study was carried out in three secondary peat swamp forests in Central Kalimantan, Indonesia. Litterfall collection was undertaken using a litter trap with samples collected every month in the first year and every two months thereafter between June 2018 and June 2021. The rate of litter decomposition was assessed by measuring the reduction in dry weight of litter at 3, 6, 12 and 24 months. At each of three study sites, two sets of recently fallen litterfall were placed in 25cm x 25cm mesh bags on the peat soil surface to assess decomposition rates under aerobic conditions, and another two sets of litter were placed at a depth of 40 cm to assess decomposition rates under anaerobic conditions. Dry weight of fresh litterfall and decomposed litter samples was determined at 3, 6, 12 and 24 months, and total carbon content was analyzed using the loss of ignition method. The results showed that litterfall production in secondary peat swamp forests was about 9.52 ± 3.57 t ha⁻¹ and it followed a seasonal pattern, with higher production in the dry season. The rate of litter decomposition was exponential and faster under aerobic conditions.

1. Introduction
Tropical peat swamp forest is an important ecosystem for global interests, including in relation to climate change and as a carbon store that reaches 528 Pg (Pg = 1 x 10¹⁵g), equivalent to one-third of global soil carbon [1, 2]; biodiversity support (especially for endemic species) as well as being a source of livelihood for local communities. To maintain the sustainability of peat swamp forest ecosystem, nutrient cycles are important. Carbon and nutrient cycles are the main ecosystem processes that are crucial in peat swamp forests, with cycling via litter production and decomposition playing an important role [3]. In peat swamp forests, litter production and decomposition are a component of the soil-plant system [4], with litter directly involves in the plant-soil interaction because it is one of the main pathways of carbon and nutrients inputs from plants into the soil [5]. The quantity and quality of litter have been shown to determine the function of forest ecosystems [6], while nutrient cycling has been shown to be...
directly related to productivity in forest ecosystems through its control on plant growth [7]. Studies of ecosystem primary production are usually evaluated through litter production [8] with varying production rates according to altitude, latitude, soil fertility, forest stand structure, climate, and tree species composition [9, 10]. In most tropical forests, the amount of litter supplied to the soil will vary depending on the season [11], with differences between wet and dry seasons.

Litter decomposition in terrestrial ecosystems has a major role in biogeochemical cycles of elements in the environment. It is estimated that decomposition of litter (including belowground root litter) accounts for about 70% of the total annual carbon flux, which is estimated at 68 Pg C yr⁻¹ (Pg = 10¹⁵ g) [12]. Climatic factors, such as temperature, rainfall, humidity, and seasonal variations, affect the rate of litter decomposition. Plant litter decomposition refers to physical and chemical processes involved in reducing litter to its constituent chemical elements. As such, litter is a major determinant of nutrient cycle of most terrestrial ecosystems [13-15], with soil properties and litter quality among the main factors which determine the level of litter decomposition [11].

There are three main levels controlling litter decomposition operating in the following order: climate > litter chemistry > soil organisms [16, 17]. Climate has a direct effect on litter decomposition due to the effects of temperature and humidity which regulate the microbial respiration activity and the volume of oxygen in the soil. However, as a result of climate control of soil formation and nutrient cycling [17, 18], it is expected that climate also has an indirect effect through climate impacts on litter chemistry [14].

Litter decomposition is the consequence of several processes. First, soil litter is broken down by detritivores, such as macroinvertebrates, into small pieces so the organic matter can be further chemically decomposed. Second, through the activities of microorganisms (such as bacteria and fungi), these small pieces of organic matter are further reduced and mineralized into basic inorganic molecules, such as ammonium, phosphate, carbon dioxide, and water. Suitable environmental conditions that support the activity of aerobic soil microorganisms enhance organic matter decomposition. The rate of litter decomposition is controlled by environmental conditions, chemical composition of the litter, and by soil organisms [16, 19-21].

This study aims to investigate the rate of aboveground litter production in secondary peat swamp forest and jelutung plantation in Indonesia and to study the rate of leaf decomposition, which is the main component of tree litterfall, under various environmental conditions. The results provide further understanding of the controls on litter and soil carbon inputs; and hence, nutrient cycling in a low nutrient ecosystem.

2. Methodology
This research was carried out from September 2018 to August 2019; however, observations of litter production were continued until June 2021. This research was conducted in secondary forest and jelutung plantation areas located in Hampangen Village, Katingan Regency, Kalampangan, Palangka Raya and Tumbang Nusa Village, Pulang Pisau Regency. Sites within each land-use class were of similar characteristics. Figure 1 shows the research locations and the coordinates of the locations along with the general condition of the research area presented in Table 1.
Figure 1. Map of research locations in Hampangen and Kalampangan/Tumbang Nusa, Central Kalimantan

Table 1. General condition of the research area

| Location                  | Latitude  | Longitude | Peat Depth (m) | Groundwater Depth (cm)* | Bulk density 0-50 cm (g/cm³) | Management History                                      |
|---------------------------|-----------|-----------|----------------|--------------------------|-------------------------------|--------------------------------------------------------|
| Forest JP                 | -2.35275  | 114.09232 | 3.35           | 5.25 to -27.60 (avg -9.26) | 0.08 (0.05-0.11)              | Secondary forest, drainage since 1980, burned in 1997   |
| Forest KDHTK              | -2.35275  | 114.09232 | 2.84           | 2 to -52.80 (avg -25.35)  | 0.16 (0.12-0.22)              | Secondary forest, drainage since 1980, burned in 1997   |
| Forest UPR                | -1.88456  | 113.47334 | 1.83           | 9.05 to -49.75 (avg -19.48) | 0.18 (0.13-0.23)              | Secondary forest, burned in 1997                        |
| Jelutung Kalampangan      | -2.28936  | 114.01026 | 3.00           | -19.45 to 90.70 (avg -46.40) | 0.22 (0.17-0.30)              | Agroforestry opened with drainage since 1979, no history of fires |
| Jelutung Tumbang Nusa     | -2.35311  | 114.10085 | 2.50           | -42 to -101.25 (avg -65.43) | 0.18 (0.11-0.26)              | Opened with drainage since 1980 and caught fire in 1997 |
| Jelutung Hampangen        | -1.89725  | 113.52635 | 1.50           | -1.25 to -44.75 cm (avg -20.85) | 0.19 (0.15-0.26)              | Opened with drainage since 1980 and caught fire in 2007 |

* A negative scale was used for groundwater depth values below the soil surface and a positive scale was used for flooding conditions.
The study area has an average annual temperature of 26°C, with little seasonal variation, and an average rainfall of 2500 mm yr\(^{-1}\) [22]. Rainfall is highly seasonal with a rainy season from November to April and a dry season from about June to September, although this can last until October (Figure 2).

**Figure 2.** Monthly rainfall for 2018, 2019 and 2020 (Data from Palangka Raya Meteorological Station, Meteorology, Climatology and Geophysics Agency)

2.1. Litter sampling and dry weight measurement
For aboveground litterfall production measurements, litterfall was collected in 1 x 1 m litterfall traps made of nets. At each secondary forest and three jelutung plantation sites, 15 litter traps were placed at 1 m above soil surface. Litter traps were distributed randomly in an area of 50 x 50 m. Litterfall collection commenced in June 2018 and was carried out every month in the initial year of measurement to observe its monthly distribution pattern. In the following year, collections were carried out every two months until June 2021. After each collection, dry weight of the litter was obtained by oven-drying the samples at 70°C for 48 hours.

**Figure 3.** Litter trap (left) and placement of samples for decomposition (right)

2.2. Sampling and measuring litter decomposition rate
Leaves of geronggang (*Cratoxylum arborescens*), tumih (*Combretocarpus rotundatus*) and jelutung (*Dyera costulata*) were specifically obtained from trees that were felled to obtain fresh biomass. These were then oven-dried (Heraterm and Memmert types) at 70°C for 48 hours, to obtain the initial dry weight. After a total of 288 packages of leaf samples were weighed to obtain their dry weight, each
biomass was placed in a litterbag consisting of a mesh of 0.5 mm diameter net with a size of 20 cm x 20 cm. Within each site, two litterbags were placed on the surface of the peat, within the oil litter layer, and two were buried at a depth of 40 cm. Samples were placed over an area of 2 x 1 m, which was previously divided into four parts, corresponding to each one of the sampling events.

Litterbags were taken from the field at 3, 6, 12 and 24 months. To calculate dry biomass, leaves were first gently cleaned with water to remove all peat particles and, if any, to detach roots entering the litterbag, air-dried and then oven-dried for 48 hours at 70 °C. The 70 °C oven-dried biomass was weighed to obtain its dry weight.

The data obtained from observations at each location were processed in tabulated form. The data analyzed were the average dry weight loss after 3, 6, 12 and 24 months from which the decomposition rate equation was derived.

3. Results and discussion

3.1. Litter production
Seasonal aboveground litterfall production from June 2018 to May 2019 at secondary forest and jelutung plantation research locations is presented in Figure 4. Average annual litter production (mean of the three years from June 2018 to June 2021) is presented in Figure 5.

Results of this study showed that, for both forest and jelutung sites, litterfall production followed a seasonal pattern (Figure 4). Highest litter production occurred at the peak of the dry season, namely in August and September (Figure 2). At forest sites, litterfall production was 1.77 ± 3.12 and 2.03 ± 3.64 tons ha⁻¹ month⁻¹, in August and September, respectively. Similarly, at jelutung sites, litterfall production was 2.34 ± 3.07 and 3.03 ± 4.23 tons ha⁻¹ month⁻¹ in August and September, respectively. Average monthly litterfall production was 0.81 ± 0.83 tons ha⁻¹ month⁻¹ for forest and 0.89 ± 0.93 tons ha⁻¹ month⁻¹ for jelutung. Across three forest locations, the range of monthly litter production varied between 0.75 – 0.91 tons ha⁻¹ month⁻¹. Similarly, across three jelutung sites, monthly litter production ranged between 0.76 and 0.98 tons ha⁻¹ month⁻¹. In general, the age of jelutung trees was relatively the same, but if viewed from the quality of tree growth, the litter production was in line.

![Figure 4. Production of litter for one year from June 2018 to May 2019](image-url)
Averaged annual litter production in secondary forest areas is greater than the one in jelutung plantations (Figure 5), with an average of 8.28±1.92 tons ha⁻¹ year⁻¹ (forest) and 7.28 ± 3.41 tons ha⁻¹ year⁻¹ (jelutung). This litter production at both land uses seem to follow the amount of above ground biomass (ABG) and the tree density. The ABG at forest was 226 ± 100.82 ton ha⁻¹ with tree density of 2,042 ± 426 trees ha⁻¹, whilst at jelutung plantation, it was 167.72 ± 65.87 ton ha⁻¹ and tree density of 833 ± 165 trees ha⁻¹. This level of litter production is higher than that obtained by Sundarapandian and Swamy [23] in other tropical forest areas, i.e. 5.63 to 8.65 ton ha⁻¹ year⁻¹ and almost the same as in other tropical peat swamp forest areas, which is between 6.53-8.41 ton ha⁻¹ year⁻¹ [24]. Based on a conversion factor of C of 0.48 [25], total carbon input into the soil varied between 3.05 and 4.90 tons ha⁻¹ year⁻¹ from forest areas and 1.86-5.13 tons ha⁻¹ year⁻¹ from jelutung area. Nitrogen inputs from litter productions ranged between 35 and 56 kg ha⁻¹ year⁻¹ in secondary peat swamp forest areas and between 21 and 59 kg ha⁻¹ year⁻¹ in jelutung plantations. Based on the three years of litter collection, annual carbon and nitrogen inputs were 3.05-4.90 ton C ha⁻¹ and 35.16-56.38 kg N ha⁻¹ at the forest land use and 1.86-5.13 ton C ha⁻¹ and 21.39-59.09 kg N ha⁻¹ at the jelutung plantation. Although not quantified in the present study, other nutritional elements were cycled with the litter inputs, including N, P, K, Ca, Mg, Na, Fe and Mn [24].

### 3.2. Leaf litter decomposition

Dry biomass decreases with time for all species and treatments. The rate of reduction of dry biomass in the leaves of jelutung, tumih, and geronggang, both under aerobic and anaerobic conditions, is presented in Figure 6, while the equation for the decomposition rate and R² value for each equation is presented in Table 2.
Figure 6. The rate of reduction of dry biomass of leaf in aerobic and anaerobic condition

Table 2. Model decomposition rate of leaf litter

| Treatment          | Equations          | R²    |
|--------------------|--------------------|-------|
| Jelutung aerobic   | Y = 44.62 + 53.23 e^{-0.07x} | 0.973 |
| Jelutung anaerobic | Y = 66.17 + 31.47 e^{-0.11x} | 0.922 |
| Tumih aerobic      | Y = 41.52 + 56.06 e^{-0.14x} | 0.948 |
| Tumih anaerobic    | Y = 57.81 + 41.35 e^{-0.23}  | 0.969 |
| Geronggang aerobic | Y = 96.86 e^{-0.04}       | 0.983 |
| Geronggang anaerobic | Y = 93.62 e^{-0.03}   | 0.903 |

The decomposition rate follows an exponential decay function (Table 2), with the R² value above 90%. A rapid rate of decline in the early stages of decomposition is observable, except for the geronggang leaf where the rate of decline is relatively constant during the 24 months. From Figure 6, it can be seen that for the decomposition rate after 24 months, geronggang leaves progressed faster, followed by tumih and jelutung. For tumih leaves, interestingly, the rate of decomposition is fast at the beginning up to 12 months before decreasing, even for anaerobic conditions that tend to be sloping. It is likely that during these first 12 months, most of the labile carbon was oxidized by soil heterotrophs. After that period, more recalcitrant and complex composition of organic matter lowered decomposition rates. As expected, for all leaf types studied, the rate of decomposition was faster at the soil surface layer than at a depth of 40 cm. This higher presence of oxygen over soil surface layer promoted aerobic soil respiration and the oxidation of organic matter. By contrast, lower oxygen concentration at the 40 cm soil depth reduced aerobic biological activities in the soil and shifted into more anaerobic decomposition processes.

Decomposition is a key process in global carbon cycle, which has extensively been studied in well-drained forests and recently in the FSF. We showed here that the rate of decomposition was highly dependent on soil moisture conditions (aerobic and anaerobic) and the type of vegetation (in this case leaves) as the basis for decomposition. With the most efficient model estimating the decomposition rate to be the average of 34.12% month⁻¹ under anaerobic conditions and average of 28.74% month⁻¹ under aerobic conditions, the latter is very close to that estimated by previous publications [24, 26, 27] in PSFs. Our findings agree with the general observation that leaf litter buried or submerged in swamps decomposes more slowly than leaf litter that is not submerged or more exposed [28-30]. Therefore, keeping groundwater level close to the surface is an important strategy to reduce organic matter oxidation and to increase carbon accumulation in tropical peat soil in both peat swamp forests and tree plantations such as jelutung.
4. Conclusion
The highest litter production occurred at the peak of the dry season in August and September. Average monthly litterfall production was 0.81±0.83 tons ha⁻¹month⁻¹ for forest and 0.89±0.93 tons ha⁻¹month⁻¹ for jelutung. The decomposition rate followed an exponential decay function with a rapid declining rate in early stages of decomposition and the rate of decomposition was faster at the soil surface layer (aerobic) than at a depth of 40 cm (anaerobic).

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