Contribution of CO$_2$ emission from litter decomposition in an oil palm plantation on tropical peatland

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Abstract. Soil carbon dioxide (CO$_2$) emission consists of peat decomposition, root respiration, and litter decomposition. Although there are some publications on soil respiration in oil palm plantations, information of CO$_2$ emission from palm litter (frond) decomposition is still limited. Therefore, our objective was to estimate the CO$_2$ emission from frond decomposition in an oil palm plantation on tropical peat. The study was conducted in a smallholder oil palm plantation with two different cultivars (M and S) on peat in Jambi, Indonesia, using meshed litter bags of 40 cm x 80 cm. The temporal pattern of carbon loss was similar to that of dry weight loss, following a negative exponential. Annual carbon inputs through pruned fronds into the plantation were 189 and 281 g C m$^{-2}$ year$^{-1}$, respectively, for M and S cultivars. Annual CO$_2$ emissions through oxidative frond decomposition were estimated to be 98 and 153 g C m$^{-2}$ year$^{-1}$ for M and S cultivars, respectively. The annual CO$_2$ emission from oil palm litter decomposition accounted for about 13% of soil heterotrophic respiration of oil palm plantations on tropical peatland.

1. Introduction

Peatland is an accumulation of organic matter that storing carbon in thick layers and usually associated with logs conditions [1]. Vast accumulation of organic matter in peatlands is primarily caused by slow rates of litter and dead plants decomposition. Indonesia becomes the leader of tropical peatland owner that cover 65% or 68.5 Gt of carbon store [2]. Peatland is important ecosystems in the global carbon balance as they sequester and store a huge atmospheric carbon for thousands of years [3]. Approximately 35% of the Indonesian peatland area (7.2 million ha) is in Sumatra [4], with other areas mainly in Kalimantan and Papua. However, large area of peatlands has been converted for agricultural and plantation purposes [5]. Palm oil, as a promising source of cooking oil and energy of biodiesel, become a major land use change of tropical peatlands during a past few years in Indonesia [6]. Total area of oil palm plantations on peat soil was estimated increase from 0.4 million ha in 1990 to 2.43 million ha by 2010 in Indonesia and Malaysia as Sumatra island in Indonesia has the largest absolute extent (1.4 million ha) [7]. Miettinen et al. [8], also reported that oil palm plantations on peatland have increased 3.1 million ha in 2015.

It has been reported that a major component of the soil C balance on peat forest and plantation is heterotrophic respiration or oxidative peat decomposition [9-11]. Even for that, however, to our knowledge, there are fewer than ten peer-reviewed publications presenting heterotrophic respiration or oxidative peat decomposition data under oil palm plantations in South East Asian peatlands [12-18]. None of these have studied the contribution of litter decomposition of oil palm plantation to...
heterotrophic respiration. Although, Hirano et al. [9] have reported that heterotrophic respiration in surface soil of tropical forest ecosystem mainly consists of litter decomposition. As a major builder of peat soil, litter plays an important role in the carbon balance and nutrient cycle of terrestrial ecosystems. Litter decomposition greatly affect the carbon cycle through carbon dioxide (CO$_2$) emissions to the atmosphere [19]. Furthermore, the increasing of litterfall in tropical forests potentially promote the transfer of soil CO$_2$ to the Atmosphere [20]. In oil palm plantation, frond bases of oil palm trees, same as leaf litter fall in a forest, be expected having an important role on the carbon balance and nutrient cycling of oil palm plantations. Particularly, having significant contribution to the heterotrophic respiration or soil CO$_2$ emission of an oil palm ecosystem.

Litter decomposition in terrestrial ecosystem is commonly studied using litter bag method (LB), of which determines the decomposition rate by evaluating the loss of mass or elements of litter in meshed bags placed in the field during a given times period. The litter bags are widely used [21], even the mesh size probably affects the decomposition rates because the limitation of soil fauna that can access inside the litter the bags [22]. Sun et al. [23] reported that litter bag method provided better results of leaf litter emission in a temperate evergreen forest in central Japan compare to chamber method with litter addition and removal treatments. To our knowledge, presently, there are no data of emission from frond decomposition in an oil palm plantation on tropical peat. Thus, more field data need to be accumulated. This study objectives was to estimate frond decomposition rate and quantify carbon dioxide (CO$_2$) emission resulting from frond decomposition in an oil palm plantation on tropical peat.

2. Materials and methods

2.1. Site description
The study was conducted in an oil palm plantation on tropical peat in Tanjung Jabung Timur, Jambi, Sumatra. Sumatra is the biggest island of oil palm plantations on tropical peatlands are mainly distributed in Indonesia [4]. The peat depth average was 200 cm. The study site was originally a peat swamp forest but was deforested and drained by a timber company in the early 1990s. Oil palm trees were planted started at 1994 by smallholder farmers. Small ditches were installed every 4 lines of oil palma trees as well as a harvesting path. Palm seedlings were planted on a rectangular grid with a tree density of 125 trees ha$^{-1}$. Palm tree cultivar was mix between Marihat (M) and Sofin (S). The ratio of two cultivars was 1:4 or 25 and 100 palms ha$^{-1}$ of M and S cultivar, respectively.The field was opened without artificial compaction that usually perform to prevent palms from leaning and toppling before trees planted. Chemical fertilizer was applied applied twice a year on average of 64.8 kg N, 64.8 kg P$_2$O$_5$, 64.8 kg K$_2$O and 2 kg MgO (ha$^{-1}$ year$^{-1}$), by piling up the fertilizer at tree bases within 3 m of each stem. However, fertilization was not regular, depending on the farmer’s financial condition. Oil palm plantations are commonly replanted every 25 to 30 years [24], so this study site was in the first cycle of cultivation. The lower fronds of oil palm trees were periodically lopped and piled in inter-row spaces. Thus, frond pruned was regularly accumulated on the ground.

2.2. Experimental design
Frond decomposition was measured using a litter bag method. Litter bags of 40 x 80 cm, made of fiberglass mosquito netting, and had a mesh size 2 mm were selected for fronds decomposition measurement. The mesh size was chosen to prevent loss of frond fragments while permitting most soil microbial fauna access to the fronds and contact with the microclimatic conditions which affect decomposition. The old leaflets were collected and prepared following the practical management where only the older fronds are cut during harvesting or periodically pruning. Fronds were cut become 2 parts i.e. base and tip parts, of which frond leaf and rachis were separated. Thus, different rates of each part of frond decomposition could be calculated. Then the fresh weight of each part was weighed and batched of about 300 to 1400 g, tagged, recorded and placed together in bags.

A total of 48 (2 times retrieving x 2 parts, frond tip and frond base x 2 positions, soil surface underground and top of frond pruned x 2 varieties, marihat and sofin x 3 replications) frond litter bags
were left in March 2018 and retrieved in September 2018 and February 2019. Fronds were installed at different distances from the ditches within 5 plots on the straight path in line with the CO₂ measurement plots. Litter bags were left on the frond heap on top of the pile as naturally plantation did and at the bottom under the oil palm residues in contact with the ground. 6 bags subsamples of the initial materials (3 bags of different varieties) were taken for determination of dry weight and water content. The dry weight of all samples were determined after oven drying representative sub-samples of fronds at 70 °C to constant weight (48 hours). One frond was estimated pruned periodically every month from one tree.

Freshly pruned frond on both plantations after the initial setup was put above the sample bags following the practical management where the older fronds that cut during harvesting or periodically pruning are stacked in inter-row spaces. After retrieved, each litterbag was carefully cleaned to remove external materials such as soil, root, and litter particles. The remaining frond litter was weighed, dried, and then weighed again in the dry condition. 6 bags subsamples of each retrieve date were taken to determine the carbon (C). C concentration was determined by the loss of ignition (LoI) method at 550°C in a muffle furnace (Thermolyne type 48000, USA) with a conversion factor of 0.58 from organic matter to organic C. Nitrogen (N) content of pruned fronds was determined with the Kjeldahl technique.

Frond decomposition or litter loss (g g⁻¹) at time t was calculated as

\[
\text{Frond decomposition} = \frac{M_0 - M_t}{M_0}
\]

(1)

where \(M_0\) and \(M_t\) are denoting mean weight of dry matter at the beginning of the experiment (\(t = 0\)) and at time \(t\), respectively.

Litter carbon loss caused by decomposition (gC gC⁻¹) was assessed using data of total carbon content as

\[
\text{Carbon loss} = \frac{(M_0 C_0 - M_t C_t)}{(M_0 C_0)}
\]

(2)

where \(C_0\) and \(C_t\) represent the mean carbon contents of frond (\(n = 3\)) at the beginning and time \(t\).

Then, decomposition rates were calculated using an exponential decay function [25]:

\[
M = M_0 \exp (-kt)
\]

(3)

where \(M\) is the amount of dry matter remaining at time \(t\) (month); \(M_0\) is the initial amount of dry matter; and \(k\) is the decomposition rate constant (y⁻¹), where the larger \(k\) value, the higher rate of decomposition. Using the \(k\) value and initial C amount, C loss through the decomposition of pruned fronds was estimated. Under the assumption that C loss was caused by oxidative decomposition, area-based CO₂ emission was calculated monthly and summed up annually using pruned frond production.

2.3. Statistical analysis

Statistical tests were performed using R ver. 3.3.1 (R Development Core Team, 2018). Differences among the treatment groups were analyzed using analysis of variance (ANOVA) or t test. Also, specific differences among groups were analyzed using Tukey's multiple comparison test.

3. Results and discussion

3.1. Frond and peat characteristic

In general, peat properties in the root circle have the highest nutrient compared to the harvesting path and frond stack (table 1). Carbon amount of pruned frond was in the range of 53 to 57% (table 2). CN ratio of the leaf was significantly lower compared to CN ratio of the rachis. The potential rate of decomposition of material with lower CN ratio usually faster than that of material contain a high CN ratio.
emissions through frond decomposition should be different between the cultivars because of the different size of fronds. Thus, using all data for each cultivar \((n = 12)\), the \(k\) values of C loss were determined to be 125 and 1.35 year\(^{-1}\) for \(M\) and \(S\) cultivars, respectively. Annual carbon inputs through pruned fronds into the plantation were 189 and 281 g C m\(^{-2}\) year\(^{-1}\), for \(M\) and \(S\) cultivars, respectively. Annual CO\(_2\) emissions through frond decomposition were estimated to be 98 and 153 g C m\(^{-2}\) year\(^{-1}\), respectively, for \(M\) and \(S\). Therefore, in total, carbon input and CO\(_2\) emission of an oil palm plantation in Jambi were 207 and 109 g C m\(^{-2}\) year\(^{-1}\).

Seasonal processes that rule the carbon productivity in forest ecosystem was litter production [26-28]. Therefore, the pruned frond was assumed to have an important function for carbon balance in oil palm plantation. Pruned frond can be defined as annual carbon (C) return to the soil as there is a carbon input from that plant materials. Estimation of annual C sequestration from pruned frond was 207 g C m\(^{-2}\) year\(^{-1}\) (C input was calculated from two different cultivars, 80% for \(M\) and 20% for \(S\)). That result was a bit lower compared to the total C input of oil palm plantation developed on mineral soil in Jambi up to 289 g C m\(^{-2}\) year\(^{-1}\) of pruned frond litter input [27]. However, our result of C input through pruned

### Table 1. Peat properties on different area

| Area        | C content (%) | N (%)   | P (ppm P) | K (cmol+/kg) |
|-------------|---------------|---------|-----------|--------------|
| Root        | 53 ± 0.24     | 1.22 ± 0.31 | 17.4 ± 12.8 | 0.27 ± 0.14  |
| Harvesting Path | 51 ± 1.76   | 1.09 ± 0.17  | 13.2 ± 2.01  | 0.13 ± 0.05  |
| Frond stack | 52.7 ± 0.61   | 1.41 ± 0.08  | 14.2 ± 2.99  | 0.34 ± 0.09  |

### Table 2. Frond characteristic

| No | Samples   | C-org (%) | N (%)   | CN Ratio |
|----|-----------|-----------|---------|----------|
| 1  | Leaf (tip)| 54.0 ± 0.33 | 1.90 ± 0.33 | 28.5     |
| 2  | Rachis (tip)| 57.1 ± 0.07 | 0.66±± 0.08 | 86.3     |
| 3  | Leaf (base)| 54.4 ± 0.40 | 2.00 ± 0.19 | 27.3     |
| 4  | Rachis (base)| 56.9 ± 0.25 | 0.60 ± 0.10 | 94.5     |
| 1  | Leaf (tip)| 53.1 ± 0.89 | 2.27 ± 0.16 | 23.4     |
| 2  | Rachis (tip)| 56.8 ± 0.09 | 0.75 ± 0.13 | 75.5     |
| 3  | Leaf (base)| 53.6 ± 1.32 | 2.15 ± 0.51 | 24.9     |
| 4  | Rachis (base)| 56.4 ± 0.11 | 0.79 ± 0.20 | 71.5     |

3.2. CO\(_2\) emission through frond decomposition

The dry weight of pruned fronds from two cultivars were 2254 ± 188 and 3387 ± 567 g frond\(^{-1}\) (±1 standard deviation (SD), \(n=5\)) for \(M\) and \(S\) cultivars, respectively. The frond size of \(S\) was about 1.5 times larger compared to \(M\). Contrast to its size, \(S\) frond in Jambi having the lowest CN ratio compared to \(M\) (table 3). Therefore, in the same site, the frond decomposition rate constant \((k)\) of \(S\) was larger compared to \(M\). \(S\) was decomposed faster than that of. From these \(k\) values, the pruned fronds of \(M\) and \(S\) cultivars were estimated to be decomposed by 90% in 1.50 and 1.25 years, respectively. The dry weight loss pattern following the exponential, which decomposed faster in the first 6 months of periods (figure 1). Through 181 days, 44 and 43% of pruned fronds of \(M\) and \(S\), respectively, were lost in dry weight. \(S\) was slower at the first 6 months compared to \(M\), but faster at the later stage of decomposition.
frond was higher than that of pruned frond input in the range of 133-179 g C m⁻² year⁻¹ from oil palm plantation that also developed on mineral soil [29].

![Figure 1](image1.png)

**Figure 1.** Remaining of dry matter of $M$ and $S$. $Y_m$ and $Y_s$ represent equation for $M$ and $S$ cultivars, respectively.

![Figure 2](image2.png)

**Figure 2.** $C$ loss pattern of $M$ and $S$ cultivars. $Y_m$ and $Y_s$ represent equation for $M$ and $S$ cultivars, respectively.

This carbon sequestrations was lower compared to the estimation of soil carbon emissions from oil palm plantations developed in Southeast Asian tropical peatland [12: 693 g C m⁻² year⁻¹; 14: 1800 g C m⁻² year⁻¹; 13: 930-1042 g C m⁻² year⁻¹; 18: 690 g C m⁻² year⁻¹]. This imbalances made oil palm plantation become one of a source of carbon emission on tropical peatland. However, if carbon returns from the seasonal fruit production are included in the balance calculation, the regular carbon sequestration would be increase and probably comparable with some estimations of emission as described above. However, in the small scale, the empty fruit bunches are usually removed from the plantation on peat soil as it will reduce the soil nutrient content [30], and increase the potential plant disease such as fungus to the oil palm trees if put back on the peat soil surface.

Pruned frond decomposition is the main sources of soil organic matter in the oil palm plantation ecosystem. Frond decomposition of $S$ was faster compared to $M$ (the $k$ values were 1.25 and 1.35 year⁻¹, for $M$ and $S$, respectively). The emission rate of $S$ was about 1.5 times higher compared to $M$ (153 and 98 g C m⁻² year⁻¹, for $S$ and $M$, respectively). Based on those $k$ values, the pruned fronds of $S$ was
estimated to be emitted by 90% of total emission at 1.7 years, about 2 months faster than that of $M$ (1.8 years). The quality of $S$ pruned frond which has a lower value of CN ratio with a larger size of frond resulting in a faster decomposition with a higher CO$_2$ emission compared to $M$. The rate of frond decomposition of $M$ and $S$ was lower to oil palm on mineral soil in Selangor, Malaysia with the $k$ value of 1.8 year$^{-1}$ [31].

The first dominant controlling decomposition rate of fine root and frond would be caused by the different of cultivar and CN ratio. The litter type and quality clearly become the dominant factor on the rates of litter decomposition in temperate and tropical peatland [32,33,30]. The rapid drying of pruned frond in open area made the rate of decomposition become slower [34]. Furthermore, a few understory vegetation of oil palm plantation tends to loss the macrofauna diversity that resulting in a slow rate of plant material decomposition [35]. In contrast, a dense understory vegetation provides more favorable microhabitat and microclimate for microbial fauna, due to the increasing soil cover that enhances the microbial diversity and function [36]. The decay rate possibility also affected by peat properties such as N content that promotes humification rather than decay [30].

Study about CO$_2$ emission through frond decomposition on peat soil is very rare, thus there is no comparative study even on mineral soil. However, our annual CO$_2$ emission through frond decomposition of 109 g C m$^{-2}$ year$^{-1}$ was lower than that of C input through pruned frond decomposition from oil palm plantation on mineral soil in the range of 133 to 179 g C m$^{-2}$ year$^{-1}$ [29]. Eventually, the total CO$_2$ emissions until the last stage of frond decomposition (more than 1 year) could be equal to the total carbon input through the pruned fronds if the oil palm plantation is undisturbed (no carbon change can be assumed). The annual CO$_2$ emissions through frond decomposition (109 g C m$^{-2}$ year$^{-1}$) was accounted for 13% of heterotrophic respiration of oil palm plantations measured under oil palm plantation on tropical peatland [12, 13, 18]. When considering soil respiration, the CO$_2$ emission from frond decomposition accounted for 8% of total soil respiration reported in previous studies conducted in oil palm plantations on peat soil [37, 12, 13, 15, 18]. Within a default CO$_2$ emission factor of oil palm plantations on peat soil (1100 g C m$^{-2}$ year$^{-1}$) from the Intergovernmental Panel on Climate Change [38], our result accounted for 10 % of the default CO$_2$ emission factor from their Tier 1 methodology.

4. Conclusions
This study showed the CO$_2$ emission through pruned frond decomposition. The pattern of carbon loss through litter (frond) decomposition was following a negative exponential. The contribution of CO$_2$ emission from litter decomposition to peat soil respiration was in the range of 8 to 13 %. This contribution was not large but not negligible. Further field measurements are necessary considering the difference in tree age and scale of plantations.

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