INTRODUCTION

Tropical peatland has become one of the most efficient carbon sinks on the earth and plays an important role in the global carbon (C) cycle. This ecosystem mostly concentrated in Southeast Asia (SEA), the upper Amazon and in Congo Basin, covers only 16% of global peatland areas but is stored up to 105 Pg of C (Dargie et al., 2017; Page et al., 2011). However, this huge C deposit is now becoming vulnerable to being changed as a massive C source due to the land conversion that promotes peat decomposition and peat fires (Hooijer et al., 2011; Page et al., 2011). Driven by population growth and economic development, during the last two decades, many areas of tropical peat swamp forest in SEA have been converted to agricultural plantations, mostly for oil palm and acacia trees (Miettinen et al., 2012). The total area of peat swamp forest in Peninsular Malaysia, Sumatra and Borneo has been estimated to decrease from 64 x 105 ha in 2007 to 46 x 105 ha, while oil palm plantations on peatland had extended up to 31 x 105 ha in 2015 (Miettinen et al., 2016). The global demand for palm oil in the world is expected to double by 2030 compared to 2000 (Yan, 2017). Thus, the impact of this plantation on the global C balance could be large.

To date, there are several publications on oxidative peat decomposition or heterotrophic respiration in oil palm plantations on peat (e.g. Dariah et al., 2014; Hergoualc’h et al., 2017; Ishikura et al., 2018; Manning et al., 2019; Melling et al., 2013 and Wakhid and Hirano, 2021a). Unfortunately, none of these have studied carbon dioxide (CO₂)
emissions through palm litter (pruned fronds) decomposition, except Wakhid and Hirano (2021a), which conducted the study on a young oil palm plantation (7 years old). More field experiments are necessary, particularly in mature oil palm plantations to understand the contribution of CO	extsubscript{2} emissions through frond decomposition to the C balance of oil palm plantations on peat. The objective of this study was to quantify how much CO	extsubscript{2} is emitted from the decomposition of pruned fronds left on the ground in mature oil palm plantations on peat soil.

**MATERIALS AND METHODS**

The study was conducted over one year from February 2018 to March 2019, in mature oil palm (Elaeis guineensis Jacq.) plantations in Sumatra, Indonesia. One site was an industrial plantation in Riau (0° 42’ 16” N, 101° 42’ 52.8” E), and another site was a smallholder plantation in Jambi (1° 14’ 20” S, 103° 35’ 23” E). The oil palm cultivar in Riau was Marihat and in Jambi was mixed between the Marihat and Socfin with a ratio of 4:1. Thus, information about the study sites was described in Wakhid et al. (2022).

To estimate the decomposition, fresh fronds were cut down, separated into two parts (tip and base), and put into litter bags. The litter bags were 40 cm x 80 cm, with a mesh size of 2 mm. Before being inserted into the litter bags, the fresh weight of each frond was recorded. Each bag contained about 800 g of frond. Also, the initial values of dry weight and C content of fronds were measured (n = 3). In Riau, the litter bags were set on the top of frond heaps in February 2018 with a total of 100 bags for each tip and base. The bags were retrieved in September 2018, January 2019 and June 2019, but only 99 bags were in total because most of them were missing. In Jambi, 36 bags of tips and bases for each of Marihat and Socfin were set equally on the top of and under frond heaps, in February 2018. In total, six bags of each tip and base from the two positions were retrieved in September 2018, February 2019 and July 2019. Each litter bag was cleaned after being retrieved, and the dry weight and C content were measured.

The dry weight was measured by oven drying for 48 hours at 70°C. The C content was estimated by the loss of ignition method, using a conversion factor from organic matter to organic C of 0.58 (Agus et al., 2011). The decomposition rate constant (k) was estimated using a negative exponential equation from the plot of the residual ratio of C amount (Y) against elapsed time (t) following Moradi et al. (2014) as shown in Equation (1).

\[
Y = Y_0 \exp (-kt)
\]

where C loss through frond decomposition was estimated using the k and initial C amount (Y). Then, the annual CO	extsubscript{2} emission was calculated using pruned frond production \times monthly amount of CO	extsubscript{2} emissions. The annual C input was estimated from annual pruned fronds \times tree density \times dry weight \times C content. Statistical analysis (ANOVA, Tukey HSD test, and exponential graph) were conducted using Excel and R software (R Development Core Team 2019, version 3.5.3). Further detail about CO	extsubscript{2} emissions calculation was described in Wakhid and Hirano (2021a; 2021b).

**RESULTS AND DISCUSSION**

The C content of pruned fronds in Riau and Jambi was in the range of 53%-57% (Table 1). C and Nitrogen (N) contents of leaf were significantly different with rachis (Table 1). However, the C and N contents of the tip and base parts were not significantly different. CN ratio was significantly higher in rachis than in leaf. Socfin in Jambi has the lowest CN ratio than that of Marihat in Riau and Jambi, respectively (Table 1).

In Riau, the amount of litter bags in the second and third retrieving was smaller than that of the first retrieving (n = 45, 27 and 27 litter bags, respectively, for the first, second and third retrieving) because several bags were lost during the study. Thus, the k value was calculated using all retrieved samples without tip and base parts separation to be 1.86 yr\textsuperscript{-1} (Figure 1). The annual C input was 2.54 Mg C ha\textsuperscript{-1} yr\textsuperscript{-1}, and CO	extsubscript{2} emissions from frond decomposition were estimated at 1.48 Mg C ha\textsuperscript{-1} yr\textsuperscript{-1} (Table 2).

In Jambi, although the k values among tip and base parts and between two cultivars were not significantly different, CO emissions through frond decomposition should be different among the cultivars because the size of Socfin was 1.4 times larger than that of Marihat (Table 1). Thus, the k values were calculated using all data for each cultivar (n = 12), to be 1.57 and 1.81 yr\textsuperscript{-1}, respectively, for Marihat and Socfin (Figure 1). The annual C input and CO	extsubscript{2} emissions from pruned fronds were estimated at 2.07 and 1.12 Mg C ha\textsuperscript{-1} yr\textsuperscript{-1}, respectively (Table 2).

CO	extsubscript{2} emissions from frond decomposition in this study were higher than in a young oil palm plantation in Banjarbaru (Wakhid and Hirano (2021a): 0.38 Mg C ha\textsuperscript{-1} yr\textsuperscript{-1}). This discrepancy was most likely caused by the production of frond that was larger in mature than in young plantations. The CO	extsubscript{2} emissions (1.48 and 1.12 Mg C ha\textsuperscript{-1} yr\textsuperscript{-1}, in Riau and Jambi, respectively) accounted for 14% and 11% of heterotrophic respiration from mature oil palm...
TABLE 1. INITIAL AMOUNT OF CARBON (C), NITROGEN (N), CN RATIO, AND WATER CONTENT (WC) OF FROND (MEAN ± 1 SD, n = 3).

| Samples                  | C (%)          | N (%)          | CN ratio       | WC (%)         |
|--------------------------|----------------|----------------|----------------|----------------|
| **Marihat (M) in Riau**  |                |                |                |                |
| (dry weight = 2578 ± 509 g frond⁻¹, n = 5) |                |                |                |                |
| Leaf (tip)               | 54.60 ± 0.54a  | 1.23 ± 0.58a   | 50.30 ± 19.10a | 59.30 ± 0.30a  |
| Rachis (tip)             | 56.70 ± 0.28b  | 0.38 ± 0.13b   | 160.90 ± 58.90b| 60.20 ± 8.30b  |
| Leaf (base)              | 55.00 ± 0.29a  | 1.62 ± 0.44a   | 35.40 ± 8.40a  | 59.10 ± 1.60a  |
| Rachis (base)            | 55.60 ± 0.35b  | 0.39 ± 0.06b   | 143.70 ± 20.00b| 37.80 ± 6.60b  |
| **Marihat (M) in Jambi** |                |                |                |                |
| (dry weight = 2254 ± 188 g frond⁻¹, n = 5) |                |                |                |                |
| Leaf (tip)               | 54.00 ± 0.33a  | 1.90 ± 0.33a   | 29.20 ± 5.70a  | 54.90 ± 2.70a  |
| Rachis (tip)             | 57.10 ± 0.07b  | 0.66 ± 0.08b   | 87.20 ± 11.40b | 65.90 ± 4.20b  |
| Leaf (base)              | 54.40 ± 0.40a  | 2.00 ± 0.19a   | 27.40 ± 2.30a  | 58.50 ± 2.30a  |
| Rachis (base)            | 56.90 ± 0.25b  | 0.60 ± 0.10b   | 96.20 ± 15.40b | 71.10 ± 7.50b  |
| **Socfin (S) in Jambi**  |                |                |                |                |
| (dry weight = 3387 ± 567 g frond⁻¹, n = 5) |                |                |                |                |
| Leaf (tip)               | 53.10 ± 0.89a  | 2.27 ± 0.16a   | 23.50 ± 1.50a  | 50.10 ± 11.40a |
| Rachis (tip)             | 56.80 ± 0.09b  | 0.75 ± 0.13b   | 77.00 ± 13.30b | 69.80 ± 3.70b  |
| Leaf (base)              | 53.60 ± 1.32a  | 2.15 ± 0.51a   | 25.90 ± 6.00a  | 56.50 ± 2.60a  |
| Rachis (base)            | 56.40 ± 0.11b  | 0.79 ± 0.20b   | 74.90 ± 20.60b | 71.10 ± 4.80b  |

ANOVA (p-value)

- Component (leaf vs. rachis): <0.001
- Position (tip vs. base): 0.76
- Site (M in Riau vs. M in Jambi): 0.74
- Cultivar (M vs. S in Jambi): 0.42
- Interaction (component-position): <0.05

Note: Data of C (%) of Marihat and Socfin in Jambi was adapted from Wakhid and Hirano (2021b). Different letters denote significant differences between leaf and rachis.

TABLE 2. CARBON (C) INPUT AND CARBON DIOXIDE (CO₂) EMISSIONS FROM FROND DECOMPOSITION IN RIAU AND JAMBI

| Site and cultivar       | Tree density (trees ha⁻¹) | Frond production (dry weight, Mg ha⁻¹ yr⁻¹) | C input (Mg C ha⁻¹ yr⁻¹) | CO₂ emissions (Mg C ha⁻¹ yr⁻¹) |
|-------------------------|----------------------------|---------------------------------------------|--------------------------|---------------------------------|
| Industrial in Riau (Marihat) | 148                        | 4.58                                        | 2.54                     | 1.48                            |
| Smallholder in Jambi    | 125                        | 3.72                                        | 2.07                     | 1.12                            |
| (Marihat)               | 100                        | 2.71                                        | 1.51                     | 0.80                            |
| (Socfin)                | 25                         | 1.02                                        | 0.56                     | 0.32                            |

Figure 1. C loss pattern of a) Marihat in Riau and b) Marihat (squares, dash line) and Socfin (circles, solid line) in Jambi. An exponential curve is fitted for each retreive time. Riau: Y = e⁻¹.86x (r² = 0.83), and Jambi: Ym = e⁻¹.57x (r² = 0.90), Ys = e⁻¹.81x (r² = 0.84). Ym and Ys represent the equations for Marihat and Socfin cultivars, respectively.
plantations on tropical peat (Dariah et al. (2014): 15 years old, 10.4 Mg C ha⁻¹ yr⁻¹). Also, accounted for 13% and 10 %, in Riau and Jambi, respectively, to a default CO₂ emission factor Tier 1 methodology of oil palm plantation on peat soil (11 Mg C ha⁻¹ yr⁻¹) from the Intergovernmental Panel on Climate Change (IPCC, 2014). Following the amount of CO₂ emissions, the contribution in mature was larger than in young oil palm plantations (Wakhid and Hirano (2021a): Accounting for 2.4% of heterotrophic respiration).

Some data in Jambi from February 2018 to February 2019 was presented at International Conference on Sustainable Tropical Land Management (Wakhid and Hirano, 2021b). Unexpectedly, CO₂ emission in Jambi from February 2018 to February 2019 (Wakhid and Hirano (2021b): 1.09 Mg C ha⁻¹ yr⁻¹) was similar to February 2018 to September 2019 (this study: 1.12 Mg C ha⁻¹ yr⁻¹). Frond decomposition could likely be estimated in a short study as long as the disturbance and environmental changes are minimal. To our knowledge, previous studies on CO₂ emissions from frond decomposition were limited, thus more studies for comparison were not found.

The annual C input from pruned fronds and k values from this study were compared with some previous studies. Annual C input in this study (2.54 and 2.07 Mg C ha⁻¹ yr⁻¹, respectively, in Riau and Jambi) was lower than the C input of pruned fronds from oil palm on mineral soil in Jambi (Kotowska et al. (2016): 2.89 Mg C ha⁻¹ yr⁻¹). However, our result was higher than that of 1.33-1.79 Mg C ha⁻¹ yr⁻¹ of C input from pruned fronds in an oil palm plantation on mineral soil in North Sumatra (Lamade and Bouillet, 2005). k values of Marihat in Riau and Socfin in Jambi (Figure 1) were similar to the k value of pruned fronds from oil palms on mineral soil in Malaysia (1.80 yr⁻¹; Moradi et al., 2014), but higher than that of another study also in Malaysia (0.73 yr⁻¹; Khalid et al., 2000).

CONCLUSION

CO₂ emissions from frond decomposition were investigated in mature oil palm plantations on tropical peat, industrial and smallholder plantations, in Riau and Jambi. Using decomposition rate constant (k), initial carbon (C) amount, and pruned frond production, CO₂ emissions from frond decomposition were estimated to be 1.48 and 1.12 Mg C ha⁻¹ yr⁻¹, respectively, in Riau and Jambi. These CO₂ emissions accounted for 10%-14% of heterotrophic respiration in oil palm plantations on peat. The contribution of frond decomposition is not large but should be considered in peat soil respiration calculation.

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