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EFFECTS OF DIFFERENT COVER CROPS ON SOIL CO_2 EMISSION UNDER OIL PALM PLANTATION ON TROPICAL PEATLAND

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ABSTRACT

Cover crops have long been grown for soil erosion and weed control under oil palm plantations. However, field information on the cover crop effect on soil carbon (C) emissions is lacking for oil palm plantations established on peat soil. Therefore, we investigated soil carbon dioxide (CO_2) emissions under different cover crops in an immature and mature smallholder oil palm plantation on peat in Riau, Indonesia. Soil CO_2 efflux was measured three times a year, using a closed chamber system under different cover crops, between oil palm trees. The mean soil CO_2 emissions in immature plantations treated with Amorphophallus muelleri *(IM1),* Crotalaria juncea *(IM2),* Calopogonium mucunoides *(IM3), regularly cleaned (IM4) and* Nephrolepis biserrata *(indigenous plant, IM5) were 4.83 ± 1.76, 4.59 ± 1.44, 3.13 ± 0.17, 4.07 ± 2.20 and 6.24 ± 3.57 µmol m^{-2} s^{-1}, respectively. Meanwhile, in the mature plantations, soil CO_2 emissions were 2.96 ± 1.18, 3.66 ± 0.49, 4.36 ± 1.99, 2.20 ± 0.69, 4.05 ± 0.76 µmol m^{-2} s^{-1}, respectively, similar to the above treatments, except for (M4), where frond stack was utilised.*

Keywords: carbon emissions, closed chamber, immature oil palm, mature oil palm.

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INTRODUCTION

The oil palm has become a focus of global attention in recent years for its fast development on mineral and peat soils worldwide. In Southeast Asia, the expansion of oil palm (*Elaeis guineensis*) plantations is blamed for deforestation, including tropical peat swamp forests (Afriyanti et al., 2016; Carlson et al., 2012). Although assembled from organic material, peat soil is classified as suboptimal land due to poor nutrient composition. Despite that, oil palm still produces high yields, making it as one of the few crops that can thrive on tropical peatlands.

The land use change in tropical peat swamp forests led to many scientific studies because peat soil, as an organic compound, stores a significant amount of carbon (C), of more than 60 Gt, only in Southeast Asia (Page et al., 2011). Therefore, tropical peatland plays an essential role in the global C cycle. Indonesia is the primary holder of peat soil in Southeast Asia with an estimated area of approximately 13.4 million hectares (Anda et al., 2021). However, over the past decades, some areas of peat swamp forest in Indonesia were estimated to have been converted to agricultural plantations, including oil palm (Miettinen et al., 2016). Conversion of peat swamp forest to agricultural plantations potentially turns peat soil function as a C sink into a primary C source due to the vegetation cover change and deep drainage construction

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(Hergoualc'h & Verchot, 2013). On that account, it is essential that a C dynamics study is conducted on oil palm, planted on tropical peatlands.

One of the common practices in oil palm plantations is the cover crop. Leguminous species such as *Pueraria phaseloides*, *Centrosema pubescens*, *Calopogonium mucunoides*, *C. caeruleum* and *Mucuna bracteata* are frequently grown as an essential agroecological practice during the immature stage of the plantation (Corley & Tinker, 2016; Mathews & Saw, 2007). Initially, cover crops were grown to control soil erosion in plantations (Turner & Gillbanks, 2003). However, studies about cover crops have increased as cover crops are also used to increase soil fertility through nitrogen (N) fixation (McSwiney et al., 2010; Pardon et al., 2016), as organic weed control (Baumgartner et al., 2008; Gago et al., 2007; Samedani et al., 2015), and to increase the soil C stock (Jian et al., 2020; Kotowska et al., 2015; Wakhid et al., 2022). Generally, without planting cover crops, weeds would naturally cover some areas of the plantation. In oil palm plantations, there are four main areas of soil surface plantation management: 1) Harvesting path: A clean area for workers' access and subject of compaction; 2) frond stack: A heap area of pruned fronds; 3) root circle: Ring area of oil palm tree where the fertiliser is usually applied and 4) cover plants (understorey vegetation): Unused area for weeds to grow freely (Manning et al., 2019; Wakhid & Hirano, 2021). The impacts of different soil surface management under oil palm plantations on soil carbon dioxide (CO_2) emissions have also been studied during the last few years (e.g., Dhandapani et al., 2019b; Manning et al., 2019; Wakhid & Hirano, 2021). However, there is only one study which tried to reveal the impact of cover crops (with two leguminous types) on CO_2 emissions under oil palm plantations on tropical peatlands (Arifin et al., 2015). Thus, there is a general lack of study on the effect of various cover crops on soil CO_2 emissions under oil palm plantations on tropical peat. Therefore, the objective of this study was to estimate the soil CO_2 emissions under different cover crops in oil palm plantations on tropical peat soil.

MATERIALS AND METHODS

Study Site

The study was conducted from June to November 2021 in two different smallholder oil palm plots established on tropical peat. The selected immature and mature oil palm plots were in Pelalawan, Riau, on the east coast of Sumatra Island, Indonesia (*Figure 1*). The information on the study sites is summarised in *Table 1*.

TABLE 1. STUDY SITE INFORMATION

Item	Smallholder sites	
	Immature (IM)	Mature (M)
Location	Bandar Sei Kijang, Pelalawan, Riau (0°20′33″N, 101°41′11″E)	Bandar Sei Kijang, Pelalawan, Riau (0°20′57″N, 101°41′14″E)
Tree age (yr)	1	8
Tree density (palm ha^{-1})	138	
Tree distance (m x m x m) (in triangular design)	8 x 9 x 9	
Soil type	Typic haplohemists	
Peat depth (m)	5.5-6.0	5.0-6.0
Peat maturity	Hemic, sapric	
Water management	Drainage ditch	

Experimental Design

The measurement was conducted in five different cover crops in immature (IM) and mature (M) plots. The types of cover crops were

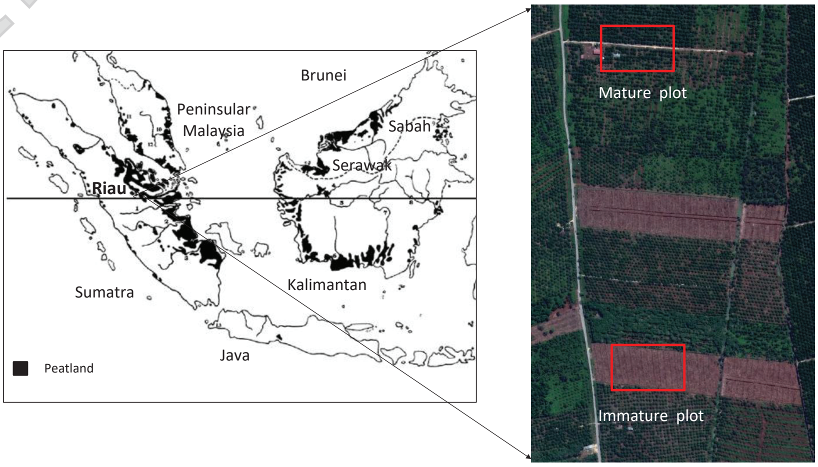

Figure 1. Map of the study area. The mature (currently being harvested) and immature plots were located adjacent to each other at about 1 km.

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selected based on availability, potential growth and the potential benefits for soil and emissions. In addition, *Amorphophallus muelleri* (porang) is a cover crop that has the potential as a source of high-quality food production. In the IM plot, the cover crops consisted of *A. muelleri* (IM1), *Crotalaria juncea* (IM2), *C. mucunoides* (IM3) and *Nephrolepis biserrata* (indigenous plant, IM5). A regularly cleaned area is labelled as IM4. Similarly, the M plot consisted of *A. muelleri* (M1), *C. juncea* (M2), *C. mucunoides* (M3), frond stacks (M4) and *N. biserrata* (indigenous plant, M5). The experimental design was different because the frond stack is only established in the M plot. *Amorphophallus muelleri*, *C. juncea* and *C. mucunoides* were newly planted cover crops in June 2021. These cover crops were planted in the understorey area of the plantation. Before planting, the soil was cultivated and manure fertiliser was applied to ensure good growth of the cover crops. *Calopogonium mucunoides* is the most common cover crop in the oil palm plantations (Sumaryanto et al., 2024). *Crotalaria juncea* is also a common cover crop, but usually does not grow much in oil palm (Bokhtiar et al., 2003), while *A. muelleri* is one of the industrial crops that require shading plants for their production (Nurshanti et al., 2023).

Soil CO_2 efflux was measured inside the cover crop plots established in the middle of palm trees or about 2.5 m from the base of oil palm trees (*Figure 2*). Hence, the oil palm root respiration is expected to be excluded from the measurement (Wakhid & Hirano, 2021). However, the roots of cover crops might still be involved in this measurement. Thus, the result of the CO_2 efflux measurement is still indicated as total soil respiration.

Soil CO_2 Efflux Measurement

Soil CO_2 efflux was measured three times in June, September and November 2021. However, the measurement in June was conducted only in IM1, IM2 and IM5 for IM plots and under M1, M4 and M5 for M plots. The measurement in June 2021 was conducted just after the soil tillage and manure application without cover crops because the crops had not grown yet. Soil CO_2 efflux was measured using a closed chamber system made of opaque PVC with a 25 cm diameter and 20 cm height. The chamber was installed in the cleaned area (without plants) in the cover crop plots. The area of the chamber was regularly cleaned before the measurements. CO_2 concentration in chamber headspace was measured using a portable infrared CO_2 analyser (LI-820, Li-Cor, Inc, USA). CO_2 concentrations were measured in accordance with air temperature every second for 2.5 min with three replications for each plot.

Soil CO_2 efflux (μmol m^{-2} s^{-1}) was calculated from the increase in CO_2 concentration in the chamber headspace using the Equation (1) (Sano et al., 2010):

$$CO_2 \text{ efflux} = (\frac{dC}{dt}).\frac{(V/(V'(273.2+T_a)/273.2)}{A} \quad (1)$$

where, dC/dt (μmol m^{-2} s^{-1}) is the increasing rate of CO_2 concentration during the last 2 min of measurement that was determined using the least-square method, T_a (ºC) is air temperature, V is chamber volume (0.0115 m^3), V' is molar volume of air at 0°C (0.0224 m^3 mol^{-1}), and A is covered ground area by the chamber (0.0510 m^2). To control the data quality of soil CO_2 efflux, the increasing rate of CO_2 concentration should have a significant slope of Pearson's correlation coefficient higher than 0.661376, with P<0.01, and n = 14 (Ishikura et al., 2019).

Peat Soil and Water Level Measurements

To analyse peat soil properties before measurements, a composite soil of five peat samples from each cover crop plot was collected at a depth of 20 cm in February 2021. Peat soils were analysed in the laboratory for chemical properties, including pH and total macronutrients (*Table 2*). Also, the peat depth was estimated from five points at each plot, using a peat auger. Data

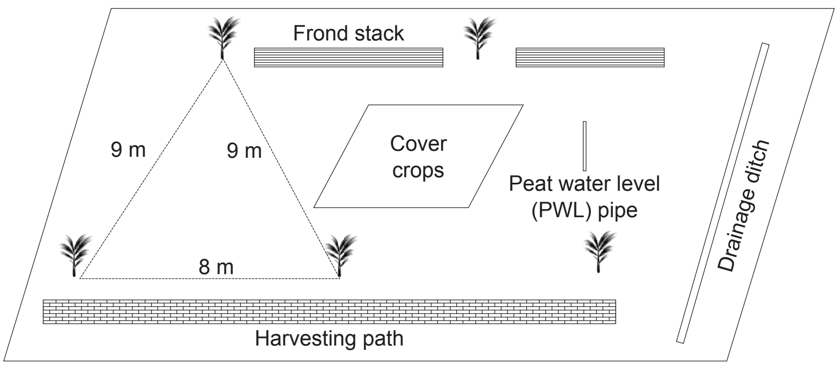


Figure 2. *Design of experiments for each immature (IM) and mature (M) plots. However, the area of the frond stack in IM is left empty as the frond is not pruned yet. Peat water level (PWL) was also measured during soil CO_2 emissions measurement.*

on precipitation were collected from the station about 10 km from the plot site (the Indonesian Meteorological, Climatological, and Geophysical Agency [BMKG], station climatology of Riau). Peat water level (PWL), the relative elevation of the water surface to the soil surface, was measured manually once a week using perforated PVC pipes inserted vertically into the peat. Also, PWL was measured manually in conjunction with the soil CO_2 emissions measurement. In addition, in a mature plot, PWL was measured using an automatic sensor (Hobo, U20, Onset, USA) from September to December 2021 in a perforated pipe. The automatic sensor displayed more detailed data than manual measurement and could be used as a control for manual measurements.

Statistical Analysis

Differences among the treatments were analysed using analysis of variance, and specific differences among groups were analysed using Tukey's multiple comparison test. The correlation between soil CO_2 emissions and PWL was analysed using the Pearson correlation method. Data analysis was conducted using Microsoft Excel and R software (R Development Core Team 2023; version 4.3.1).

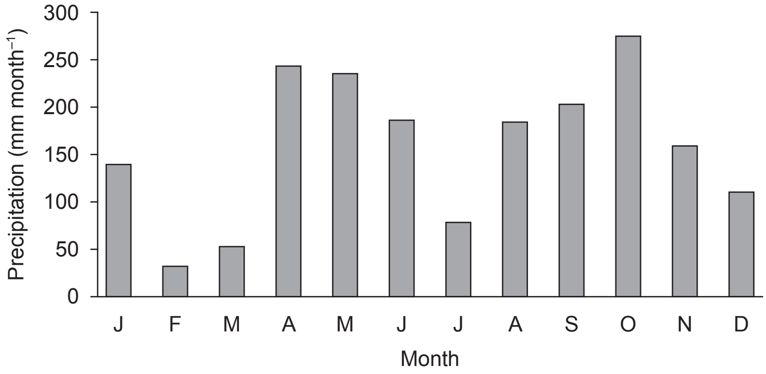
RESULTS AND DISCUSSION

Soil Environment

In IM and M plots, surface peat was dominated by hemic to sapric and included based on Typic Haplohemists soil classification taxonomy. The average peat depth was about 5.5 m in IM and M plots (*Table 1*). The mean soil pH was 3.49 and 2.96, respectively, in IM and M plots (*Table 2*). The dry season or months with monthly precipitation of less than 100 mm (Malhi et al., 2002) was recorded only in February, March and July (*Figure 3*). Based on the map of seasonal zones from BMKG, areas in Riau are characterised into two different zones, seasonal and non-seasonal zones. Seasonal zone means there is a clear difference between the dry and rainy seasons, while a non-seasonal zone does not have distinct wet and dry seasons. In the seasonal zone, there are two dry and rainy seasons in one year (rainy-dry-rainy-dry seasons, *Figure 3*) (BMKG, 2022). The mean PWL from May to November 2021, as a result of weekly manual measurement in the M plot, was -0.61 m, which varied from -0.33 to -0.98 m (*Figure 4a*). In the IM plot, mean PWL from May to November was higher than in the M plot at a level of -0.36 m and varied from -0.03 to -0.89 m. The lowest PWL was recorded in the middle of August 2021 in both IM and M plots. The highest PWL was also found in the same month, in early November 2021, for IM and M plots (*Figure 4a*). From hourly automatic measurement in the M plot, mean PWL from the middle of September through early December 2021 was -0.42 m, fluctuated between -0.09 to -0.73 m (*Figure 4b*). Mean PWL from automatic measurement was about 0.1 m deeper than that of manual measurement from September to November 2023 (*Figure 4b*). However, the trend of PWL was similar between manual and automatic measurements (*Figure 4*).

TABLE 2. PHYSICAL AND CHEMICAL PROPERTIES OF PEAT SOILS (0-20 CM DEPTH) IN THE PLOTS IN FEBRUARY 2021 BEFORE THE MEASUREMENTS

Properties	Plantation	
	Immature (IM)	Mature (M)
pH (H_2O)	3.49	2.96
pH (KCl)	2.58	2.67
Organic C (%)	58.0	47.5
Total N (%)	1.35	1.45
Available P (ppm)	20.9	27.1
P_2O_5 (cmol$^{(+)}$/kg)	34.3	358.4
K_2O (cmol$^{(+)}$/kg)	22.7	444.8
Ash content (%)	0.0	11.1



Source: BPS-Statistics of Pelalawan Regency (2022).

Figure 3. The variation of monthly precipitation from January to December 2021 in Pelalawan, Riau. Data was collected from the Meteorological, Climatological, and Geophysical Agency of Pekanbaru, Riau.

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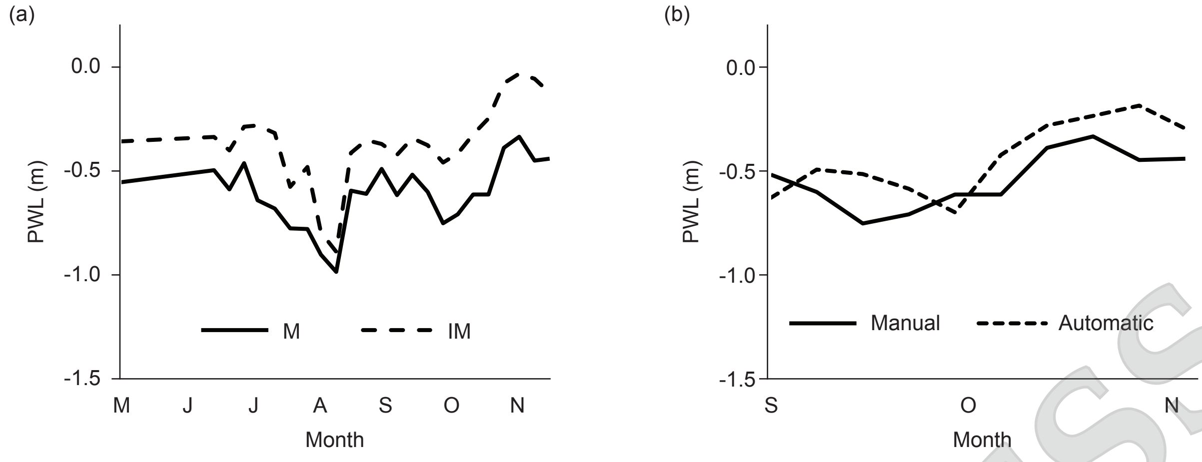

Figure 4. Variation of peat water level (PWL), (a) manual measurement every week from May to November 2021 in mature (M) and immature (IM) plots, and (b) comparison between manual and automatic measurements from September to November 2021 in the mature (M) plot.

Relationship Between Soil CO_2 Emissions and Peat Water Level (PWL)

Using the manual data of PWL during the measurement, soil CO_2 emissions showed no significant correlation with PWL in each plot of IM and M plots (P>0.05). The relationship between soil CO_2 emissions and PWL was also insignificant, even when the average PWL from three pipes was used for each plot of the IM and M plots. Generally, the CO_2 emissions had responded negatively to PWL (e.g., Itoh et al., 2017; Wakhid et al., 2017; Wakhid & Hirano, 2021), soil moisture (Ishikura et al., 2018) and temperature (Jauhiainen et al., 2014).

Soil CO_2 Emissions

In the IM plot, the measurement trend showed that the highest soil CO_2 efflux was measured under *A. muelleri* and *N. biserrata*, whereas there was a lower emission estimated under *C. mucunoides* (*Table 3, Figure 5a*). However, the CO_2 emissions under different cover crops in the IM plot were not significantly different (P>0.05). In the M plot, the highest and lowest emission was estimated at 4.36 ± 1.99 and 2.20 ± 0.69 μmol m^{-2} s^{-1} (mean ± 1 standard deviation (SD), n = 3), respectively, in *C. mucunoides* and frond stack (*Table 3, Figure 5b*). However, as in the IM plot, the CO_2 emissions in the M plot also showed no significant difference between cover crops. On average, the soil CO_2 emissions in the IM plot were higher than in the M plot (4.72 vs. 3.36 μmol m^{-2} s^{-1}, *Table 3*).

In June, the cover crops had not grown yet. However, soil CO_2 emissions in IM and M plots were not significantly different between June, September and November measurements. Except in the IM plot, where soil CO_2 emissions in September significantly differed from those in November (P<0.01).

Cover crops are one of the plantation management methods that have the potential to reduce the negative impact of land use change from forest to oil palm plantation and simultaneously improve the multiple ecosystem functions in the plantation, particularly on peat soil (Dislich et al., 2017). One negative impact of the land use change is the rise of CO_2 emissions from the peat ecosystem. The existence of cover crops affects the value of soil C emissions, likely due to two factors: Shading capability and root-plant activity in the soil. Shading capability results in different soil temperatures that indirectly influence the soil C emissions. The shaded area tends to have significantly lower soil C emissions than unshaded areas due to the lower temperature of the shading areas (Brady, 1997; Jauhiainen et al., 2014). Other evidence found that cover crops contribute significantly to amelioration of soil structure, increase in the soil organic content, which affect the soil microbial activity and biogeochemical processes (Ding et al., 2006; Gentsch et al., 2024; Hu et al., 2023; Lam et al., 2022; Strickland et al., 2018).

In this study, even though the CO_2 emissions were not significantly different between different cover crops, leguminous species such as *C. mucunoides* seem to show lower results of C emissions, particularly in the IM plot (*Table 3, Figure 5a*). In addition, we found that *C. mucunoides* as the most suitable cover crop that can easily grow under oil palm trees. However, some uncommon cover crops in oil palms, such as *A. muelleri* and *C. juncea,* also showed potential as cover crops in oil palm plantations. *Amorphophallus muelleri* is one of Indonesia's new highly demanded export commodities, but there are very limited studies under oil palm trees, particularly related to soil CO_2 emissions (Amalia et al., 2024; Yanuriati et al., 2017).

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TABLE 3. SOIL CO_2 EFFLUX UNDER DIFFERENT COVER CROPS (MEAN ± SD; *n* = 3) IN IMMATURE (IM) AND MATURE (M) PLOTS

Cover crop	Soil CO_2 efflux (µmol m^{-2} s^{-1})			
	June	Sept	Nov	Mean
Immature (IM)				
A. muelleri (IM1)	3.81 ± 1.03	3.81 ± 2.24	6.86 ± 0.56	4.83 ± 1.76
C. juncea (IM2)	5.75 ± 2.86	2.98 ± 0.13	5.05 ± 4.05	4.59 ± 1.44
C. mucunoides (IM3)		3.25 ± 0.25	3.01 ± 0.68	3.13 ± 0.17
Regularly cleaned area (IM4)		2.52 ± 0.66	5.62 ± 1.76	4.07 ± 2.2
N. biserrata (indigenous plant) (IM5)	8.07 ± 0.93	2.13 ± 1.25	8.53 ± 3.40	6.24 ± 3.57
Mean	**5.88 ± 2.13**	**2.94 ± 0.65**	**5.81 ± 2.06**	**4.72**
Mature (M)				
A. muelleri (M1)	1.87 ± 1.15	2.78 ± 0.28	4.22 ± 0.68	2.96 ± 1.18
C. juncea (M2)		4.01 ± 3.48	3.31 ± 2.14	3.66 ± 0.49
C. mucunoides (M3)		5.77 ± 0.66	2.95 ± 1.24	4.36 ± 1.99
Frond stack (M4)	2.96 ± 1.63	1.65 ± 1.33	1.98 ± 0.16	2.20 ± 0.69
N. biserrata (indigenous plant) (M5)	3.87 ± 0.50	4.88 ± 0.69	3.38 ± 1.02	4.05 ± 0.76
Mean	**2.90 ± 1.00**	**3.82 ± 1.64**	**3.17 ± 0.81**	**3.36**

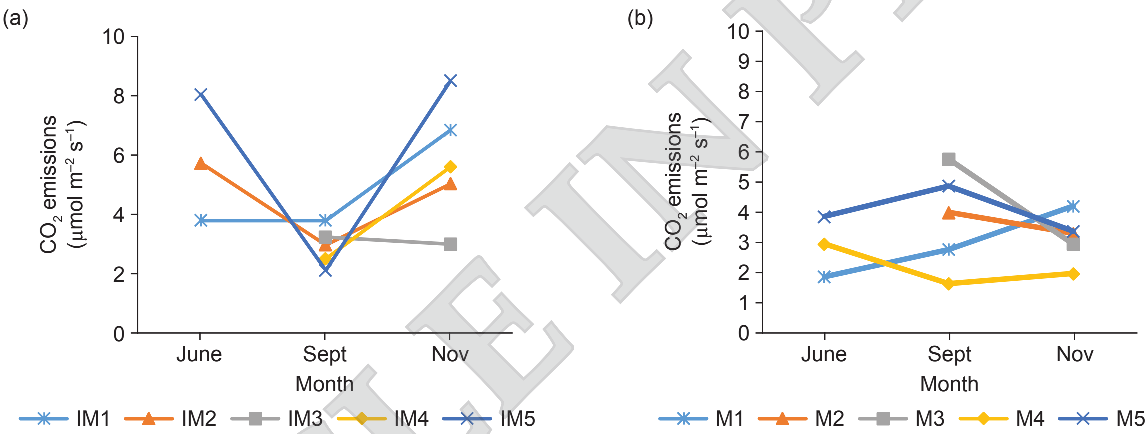

Figure 5. Variations in soil CO_2 emissions under different cover crops in (a) immature (IM) and (b) mature (M) plots from June-November 2021.

In the M plot, the CO_2 efflux under the frond stack also seems to result in the lowest emission with a low variation compared to cover crops (*Table 3, Figure 5b*). Like cover crops, the shading capability of the frond stack is likely to have the potential to maintain low C emissions from the peat soil under oil palm trees. A study by Manning et al. (2019) showed that peat soil C emissions in the open areas are significantly larger than under the frond stack. The results of this study emphasise that cover crops have the potential to reduce C emissions from peat soil developed for oil palm plantations. The lack of significance of CO_2 efflux under different cover crops might be due to the data limitation in this study.

Our study showed that soil CO_2 emissions were not significantly different under different cover crops, both in IM and M plots. This finding is in line with the result from a peat area in West Kalimantan, Indonesia. Which reported that soil CO_2 emissions under two different leguminous cover crops were not significantly different (Arifin et al., 2015). However, Arifin et al. (2015) also found that soil CO_2 emissions under six months of leguminous cover crops were significantly lower than those under one month of cover crops. More studies for comparison were not found; and the previous studies on cover crops' impact on soil CO_2 emissions were rather limited. Assuming that the understorey vegetation is similar to cover crops, there was another study at two sites of oil palm plantations in Malaysia which reported two different results: At the first site, soil CO_2 emissions below understorey vegetation were significantly lower than in the opened area (harvesting path), but in another site, it was not significant (Manning et al., 2019). Another study also found that soil CO_2 emissions under pineapple crop (in physical view, the pineapple crop is similar to understorey vegetation) between oil palm trees were relatively lower than without pineapple (Dhandapani et al., 2019a).

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These results indicate that more studies on soil CO_2 emissions from different soil surface management practices, including different cover crops, are recommended. An integrated mitigation is needed, as none of the single mitigation measures may be effective in reducing the rate of C loss from tropical cultivated peat soil.

If simply converted into annual emission, the average of soil CO_2 emissions in this study (IM: 17.9; M:12.7 Mg C ha^{-1} yr^{-1}) were higher than M (15 years old: 9.3 Mg C ha^{-1} yr^{-1}) and young smallholder plantations (six years old: 10.4 Mg C ha^{-1} yr^{-1}) in Jambi, Indonesia (Dariah et al., 2014). Their results were lower because they measured as heterotrophic respiration, while our estimation was total respiration which include the rate of root respiration. However, the pattern of emissions was similar, where younger plantation tends to have higher emissions than mature plantation. However, our results were lower than total respiration from smallholder oil palm plantation in South Kalimantan, Indonesia (23.1 Mg C ha^{-1} yr^{-1}), but near to the value of heterotrophic respiration (15.4 Mg C ha^{-1} yr^{-1}) (Wakhid & Hirano, 2021). Also, our results were similar to the total respiration in IM (one year old) and young (six years old) smallholder plantations in Central Kalimantan, Indonesia (11.7 and 13.8 Mg C ha^{-1} yr^{-1}, in one and six years old plantations, respectively) (Hergoualc'h et al., 2017). However, the pattern from their measurement was different where older plantation resulted in slightly higher emissions than immature plantation. Compared to industrial plantations, the emissions in immature plantation from this study were similar to total respiration from immature plantations under different soil peat characteristics in Sarawak, Malaysia (16.5-16.8 Mg C ha^{-1} yr^{-1}) (Mos et al., 2021). The time of measurement in this study was less than one year, but this comparison indicates that the results of emissions in this study are still within the range of soil CO_2 emissions results from oil palm plantations on tropical peat.

CONCLUSION

Soil CO_2 emissions under different cover crops were measured in oil palm plantations developed on tropical peat using the closed chamber method. Soil CO_2 emissions showed no significant difference under different cover crops in oil palm plantations. However, the existence of cover crops under oil palm trees might have the potential to reduce the CO_2 emissions from peat soil. More studies are needed to reveal the effects of cover crops on peat soil under agricultural plantations in mitigating soil CO_2 emissions.

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