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Dynamics of CO_2 fluxes from oil palm plantations on peatland

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Abstract*. The CO_2 flux from peat soil planted with oil palm is temporally and spatially dynamic related to various environmental factors. This flux can be partitioned into fluxes from oil palm root respiration, litter decomposition, and peat material decomposition. This study aimed to determine the temporal and spatial dynamics of CO_2 fluxes, the contribution of oil palm roots respiration, the contribution of litter decomposition, and the relation between flux and environmental factors in oil palm plantations on peatland. The measurements of CO_2 flux using an infrared gas analyzer (IRGA) were carried out in harvesting path and inter-row of oil palm plantation and nearby shrubs. Flux measurements were replicated three to four days for almost five months. The results showed the dynamics of the CO_2 fluxes temporally and spatially. Temporally, the CO_2 flux in oil palm plantation and shrubs ranged from 10.5-40.0 to 2.0-23.3 Mg C-CO_2 ha/year, respectively. Spatially, the flux in oil palm plantation and shrubs ranged from 17.0-32.0 to 9.9-12.4 Mg C-CO_2 ha/year, respectively. The contribution of oil palm roots respiration and litter decomposition were 47.6 and 6.1%, respectively. The CO_2 flux in oil palm plantations was significantly and negatively correlated with soil moisture content in the range of 145-450% (w/w), but not significantly correlated with groundwater level, air humidity, air temperature, soil temperature, and solar radiation.*

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INTRODUCTION

Peatland for plantations has received international attention regarding environmental issues, namely the potential release of carbon in large quantities. The release of carbon in the form of CO_2 from peatlands is also associated with increasing global temperatures. The oil palm plantations on the peatlands area have reached 1.7 million ha of Indonesia's 13.4 million total peatlands (Ritung *et al*., 2019; Gunarso *et al*., 2013). With this total area, peatland for oil palm plantations is considered a source of carbon emissions. Drainage development in oil palm plantations on peatlands is also considered an important factor influencing the release of carbon from the soil surface due to the decrease in groundwater levels. CO_2 flux from the soil surface does not directly contribute to CO_2 gas emission in the atmosphere, but plants have a process of CO_2 absorption. Oil palm plants will utilize CO_2 in the air for the photosynthesis process.

The CO_2 flux from oil palm plantations is generally estimated from CO_2 flux measurements in inter-row areas but not much from the harvesting path. According to Manning *et al*. (2019), the CO_2 flux in the harvesting path, frond piles, and cover crops in the inter-row resulted in varying CO_2 fluxes. A harvesting path is an area that has little grass growing and is always used as a farmer's path for plant care and harvesting. Meanwhile, the inter-row is an area that is rarely used and is not cleared of growing plants (understory cover crop). The harvesting path, which is slightly overgrown with grass, causes less litter than the inter-row. Wakhid and Hirano (2021) showed that litter from oil palm fronds contributed to CO_2 flux by 8-13%. Litter in oil palm plantations does not come from oil palm fronds but can be from other plants growing in the inter-row. In another study, oil palm plantation areas with exposed soil surface produced different fluxes from the soil surface with cover crops (Arifin *et al*., 2015).

For this reason, it is necessary to measure the CO_2 flux at the harvesting path. Measurement of CO_2 flux on these two surfaces needs to be done to obtain a more precise value of CO_2 flux in estimating CO_2 flux from oil palm plantations. Repeated daily measurements and tight daily measurement ranges allow the dynamics of the CO_2 flux to occur and its relationship to environmental factors to be seen to obtain more precise data.

The CO_2 flux from oil palm plantations on peatlands is generated from soil respiration which can be partitioned into fluxes from oil palm root respiration, litter decomposition, and peat material decomposition. The contribution of oil palm root respiration to CO_2 flux varies from 14 to 82%, influenced by environmental factors and plant age (Agus *et al*., 2010; Hergoualc'h and Verchot, 2011; Dariah *et al*., 2013; Matysek *et al*., 2017). Meanwhile, the contribution of peat material decomposition varies from 50 to 89% of the CO_2 flux measured at a distance of 3.5-4.5 m from the oil palm trunk by plot trenching or root cutting method (Hergoualc'h *et al*., 2017; Ishikura *et al*., 2018; Manning *et al*., 2019; Addianto *et al*., 2020). At such a distance, it is still possible for the plant root respiration to contribute to flux. Consequently, oil palm root length can reach 25 m, although root density decreases with increasing distance from the oil palm trunk (Henson and Chai 1997; Jourdan *et al*., 2000).

Cutting roots can minimize the effect of root respiration. However, dead roots can be a new source of organic matter for microbial activity, thereby contributing to the measured CO_2 flux. Hergoualc'h *et al.* (2017) suspected that the cut roots would completely decompose after one year. Separation of the flux source, which is only from microbial activity in decomposing peat material by measuring flux in a site far from oil palm, can minimize the influence of the contribution of plant roots. This site is determined by shrubs that are still in the oil palm plantation area. Flux data obtained from oil palm plantations will be compared with flux data from shrubs, leading to more precise data on the contribution of root respiration, litter, and peat material decomposition to flux obtained.

This study aimed to determine the temporal and spatial dynamics of CO_2 flux, the contribution of root respiration and litter decomposition to flux, and their relationship with environmental factors in oil palm plantations on peatlands.

MATERIALS AND METHOD

Time and Location

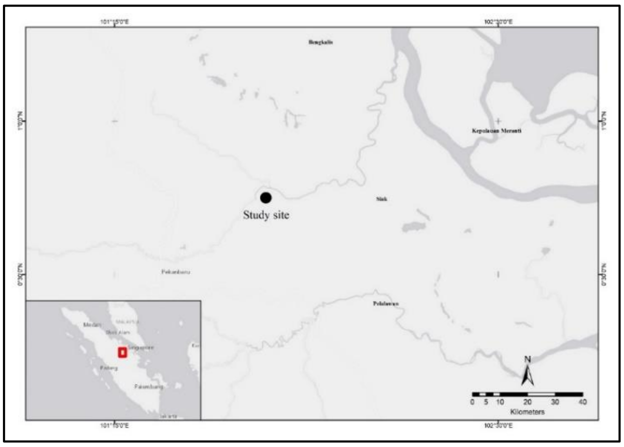

Figure 1 Location of the research site

The study was conducted in Pangkalan Pisang Village ($0^0$44’45.5” N, $101^0$45’13.1” E), Koto Gasib District, Siak Regency, Riau Province (Figure 1), from May to September 2019. Measurements of CO_2 fluxes were carried out in oil palm plantations with a plant age of 14 years and shrubs in adjoining locations dominated by ferns (*Nephrolepis sp*). There were 136 plants in one hectare.

Experimental Design

Measurement of CO_2 flux used the closed chamber method. The materials used are standard CO_2 gas, soda lime, and soil samples to analyze soil physical properties. The primary tool for measuring CO_2 flux consists of chamber base and chambers (Figure 2) and other supporting tools, namely 12 V and 6 V batteries, thermometer, stopwatch, meter, and ABH-4224.

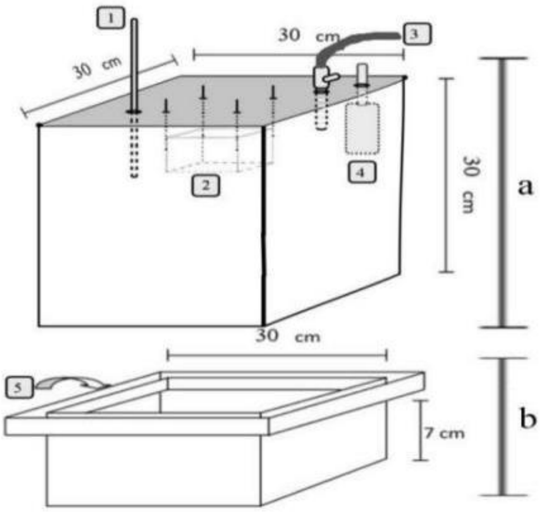

Figure 2 Design of chamber (a) and chamber base (b), including thermometer (1), mini fan (2), hose system (3), pressure compensation bag (4), and water reservoir (5)

Observation sites were determined on oil palm plantations (OP) in harvesting path (HP) and inter-row (IR) (Figure 3) by installing a chamber base at a distance of 4.5 m from the oil palm trunk. At a predetermined observation site, the soil surface is cleaned of understory cover crops without removing litter. Separation of litter contribution to flux is also carried out by installing a chamber base at the observation sites with litter (OP-l) and without litter (OP-nl) on the peat surface on inters row oil palm. Chamber bases installed on the harvesting path and inter-row were repeated at three locations ± 300 m apart, resulting in nine observation sites in oil palm plantations (OP). Observation sites were also determined on shrubs (SR) in the oil palm plantation area, and there were no root disturbances of oil palm plants. The surface of the shrubs is cleaned of litter and cover plants. At the site, SR describes a flux that only comes from microbial activity in the decomposition of peat material. The chamber base is mounted on the SR as many as two observation sites. The CO_2 flux measurement sites were 11, with nine observation sites in oil palm and two in shrubs.

Gas measurements were carried out using a CO_2 analyzer, namely the Infra-Red Gas Analyzer (IRGA) ZFP9GC11, Fuji Electric, Tokyo, Japan. The instrument is first calibrated with soda-lime and standard CO_2 gas. Before measuring flux, water is filled on the side of the chamber base serving to prevent gas leakage. Next, the chamber that has been connected to the IRGA is placed at the chamber base. Gas measurements were carried out for 6 minutes at 0, 3, and 6 minutes. Gas measurements at 0 minutes were carried out immediately after the chamber was installed and then measured at 3 and 6 minutes.

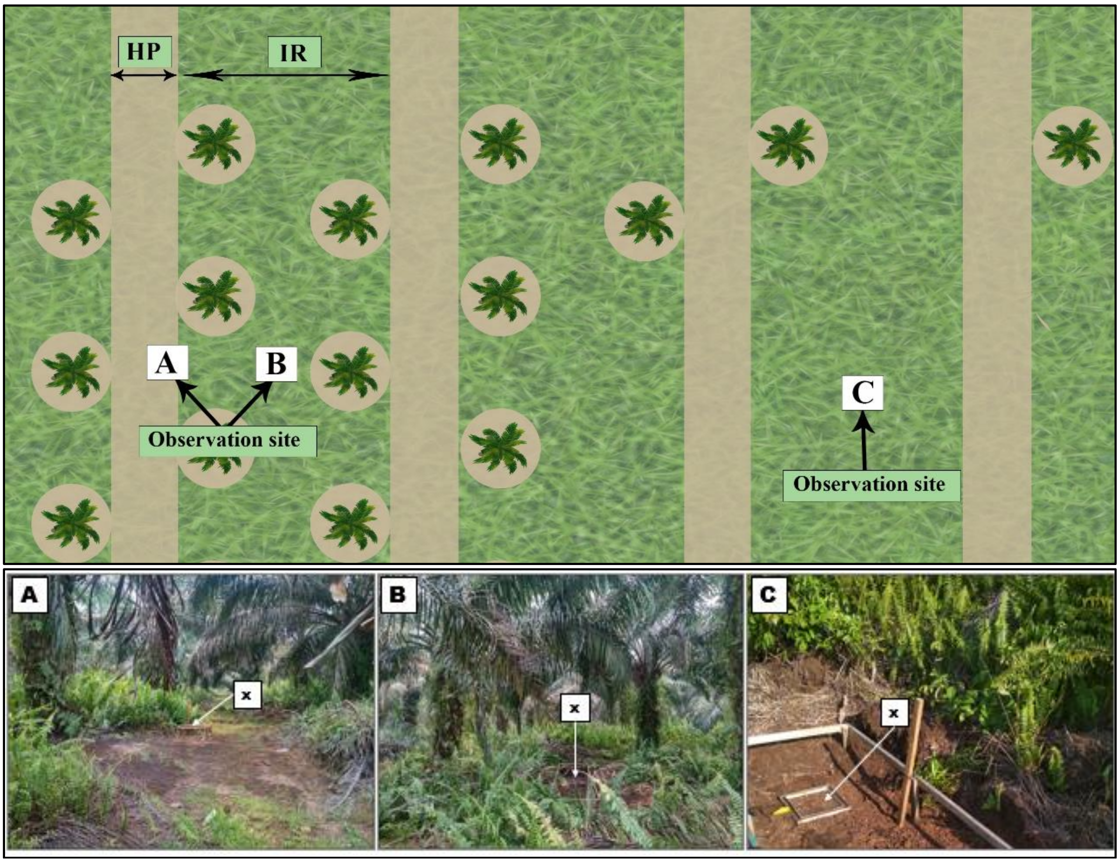

Figure 3 Observation site (x) in harvesting path (A), inter-row (B), and shrubs (C)

After the CO_2 gas concentration figure (ppm v) is obtained, the study proceeds with finding the dC/dT value obtained by linear regression analysis. After the dC/dT value is obtained, the CO_2 flux is calculated by the following equation:

$$\frac{F}{A} = \rho \times \frac{V}{A} \times \frac{dC}{dT} \times \frac{273}{273+T} \times \alpha$$

Where:
F / A = flux g C-CO_2/m^2/min
ρ = density of CO_2 under the standard condition (1.96 x 10^3 g/m^3)
V / A = volume (m^3) and the bottom area of the chamber (m^2), respectively
dC/dT = change in the CO_2 concentration in the chamber during the period (ppm/min)
T = absolute temperature in chamber (^{0}C)
α = conversion factor for CO_2 to C (12/44)

Measurement of the CO_2 flux was carried out in the morning between 06.00-10.00 (a.m.) and in the afternoon at 12.00-16.00 (p.m.). Measurements were repeated every three to four days from May to September 2019, leading to 26 days of observation in oil palm plantations and 22 days in shrubs.

Observations of environmental factors were carried out every time, and the CO_2 flux was measured, including groundwater level, soil water content, soil temperature, air humidity, and solar radiation. Soil water content was measured using the gravimetric method at a depth of 0-10 cm. Measurements of air humidity and the air temperature were carried out at the height of 1 m above the surface of the chamber base using ABH-4224. Rainfall data and solar radiation data were obtained from an automatic weather station (AWS) at the research location.

Data Analysis

The flux data on oil palm plantations (OP) and shrubs (SR) are presented temporally based on the date of observation from each observation site. The CO_2 flux data is also presented spatially, namely the accumulated value of each day of observation and the average value of each observation site. The average CO_2 flux data were obtained from linear regression analysis (y=ax) of the increase in flux accumulation in each observation. Spatial average flux data is used as the basis for calculating the contribution of roots and litter to CO_2 flux in oil palm plantations. The CO_2 flux from OP was obtained by combining the flux values in the harvesting path and inter-row with litter on the peat surface. The harvesting path (HP) covers 27% of the oil palm plantation area, while 73% inter-row (IR) is obtained using a spatial approach. Calculation of HP area also includes weeded circle oil palm because of similar conditions on the soil surface, namely the absence of vegetation on the peat surface overlooked by the farmers. The following equation obtains CO_2 flux from OP:

$$\text{OP flux} = ((\text{HP flux}) \times (27\%)) + ((\text{IR flux}) \times (73\%))$$

Where:
OP = oil palm plantation
HP = harvesting path
IR = inter-row

The percentage of litter contribution to the CO_2 flux of an oil palm plantation is calculated based on the IR area. This is because flux measurements with litter and without litter are carried out in IR. The calculation of the litter contribution in oil palm plantations is carried out using the following equation:

$$\text{Litter contribution} = \frac{(\text{OP-l flux}) - (\text{OP-nl flux})}{(\text{OP-l flux})} \times 100\% \times \%\ \text{IR area}$$

Where:
OP-l = oil palm with litter on the peat surface
OP-nl = oil palm without litter on the peat surface
IR = inter-row

The flux data from OP is used to calculate the root contribution by comparing it with the flux data from SR. The flux data in OP results from root respiration, decomposition of litter, and peat material decomposition. The SR site is far from oil palm, so the flux data produced only comes from microbial activity in decomposing peat material. By comparing these fluxes (OP and SR), the contribution of root respiration includes litter on the soil surface to flux, will obtain. This value must be reduced by the value of the litter contribution on the soil surface to get the contribution value only from the root respiration. The contribution of oil palm roots to CO_2 flux in oil palm plantations is obtained by the following equation:

$$\text{Root contribution} = \frac{\text{OP flux} - \text{SR flux}}{\text{OP flux}} \times 100\% - \%\ \text{litter contribution}$$

Where:
OP = oil palm plantation
SR = shrubs

The environmental factor component data in each observation is processed into data adjusted to the CO_2 flux data. The environmental factor data also correlated with the CO_2 flux data for each observation by Pearson correlation analysis.

RESULTS AND DISCUSSION

This study obtained CO_2 flux from oil palm plantations based on the flux, including litter on the peat surface. As there is always litter on the peat surface in oil palm plantations, litter is also included from the flux part of the soil surface. The value of CO_2 flux in OP results from root respiration, decomposition of litter, and peat material decomposition, which is different from flux from SR, only coming from microbial activity in decomposing peat material. Temporarily, The CO_2 flux measurements in OP and SR are presented in Figure 4. Figure 4 shows the distribution of data on each day of observation. The CO_2 flux at the SR observation site showed a smaller variation between the repetitions of the observation site compared to the observation at OP. In the OP, the CO_2 flux was in the range of 10.5-40.0 Mg C-CO_2/ha/year, while in the SR, it was 2.0-23.3 Mg C-CO_2/ha/year.

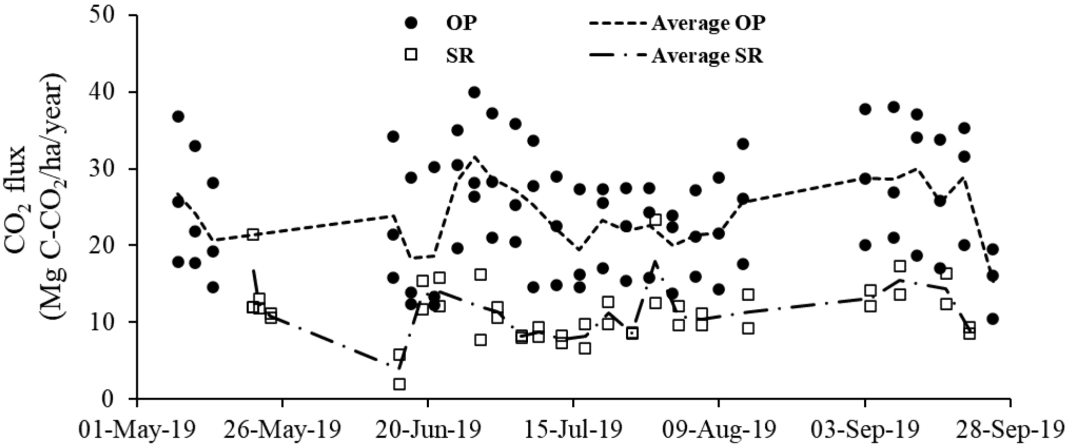

Figure 4 Temporal variation of flux in oil palm plantation (OP) and shrubs (SR)

Figure 4 shows that the CO_2 flux produced in SR is always smaller than that of OP. This result indicates that the amount of CO_2 flux is determined by the respiration activity of plant roots and the decomposition of organic matter from the litter on the soil surface. The CO_2 flux produced in a field is mostly a gas released from root respiration, increasing plant age (Sumawinata *et al*., 2012; Matysek *et al*., 2017).

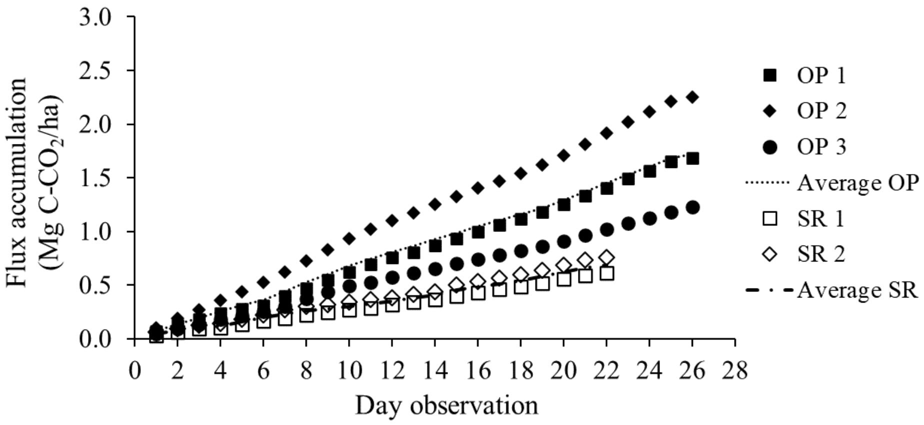

Figure 5 Spatial variation of CO_2 flux in oil palm plantation (OP) and shrubs (SR)

Spatially, different sites of flux observation have different values of CO_2 flux. The spatial variation resulting from the increase in flux accumulation of daily observation at three locations in OP and two locations in SR is presented in Figure 5. The CO_2 flux in the OP at the observation sites with replicates one, two, and three resulted in flux accumulation values for 26 days of observation, i.e., 1.68, 2.25, and 1.23 Mg C-CO_2/ha, respectively. Meanwhile, the SR at the site of observation of replications one and two were 0.61 and 0.76 Mg

C-CO_2/ha for 22 days of observation. The difference in flux values indicated that even though they are on the same stretch of land with plant age, air humidity, air temperature, soil temperature, and groundwater level, which are relatively the same, the flux values produced at each measurement site differed both in magnitude and pattern of CO_2 flux. The average CO_2 flux at each observation site obtained by linear regression analysis of the accumulation of each observation is presented in Table 1.

Table 1 Average CO_2 flux in oil palm plantation and shrubs

Observation site	CO_2 flux (Mg C-CO_2/ha/year)	
	Oil palm plantation	Shrubs
Site 1	23.2	9.9
Site 2	32.0	12.4
Site 3	17.0	-
Average	24.1	11.1

- = not measured

The difference in the average flux values in OP and SR (Table 1) is used as the basis for calculating the root contribution of oil palm plants. The contribution of oil palm plant roots, including litter on the peat surface, is 53.7% of the CO_2 flux. The type of vegetation affects the respiration rate of the soil by influencing the microclimate and the quality of the litter that falls on the soil surface. At the SR site, CO_2 flux is only affected by environmental factors. However, at the OP site, there is a contribution of CO_2 from the respiration activity of plant roots and litter decomposition on the peat surface. In addition to producing CO_2 from respiratory activity, plant roots also release exudates, free oxygen, enzymes, carbohydrates, and amino acids (Bais *et al*., 2006). Land with plant roots will accelerate the turnover of organic matter caused by exudates of plant roots (Girkin *et al*., 2018).

The resulting temporal flux variation is thought to be due to differences in the sensitivity of microbes as a source of respiration in the soil to environmental and soil components. CO_2 flux can be affected by a combination of soil moisture, soil temperature, drainage, and litter on the soil surface interacting with each other, including the observation site (Hermans *et al.*, 2021). The contribution of roots in oil palm plantations is obtained by reducing the contribution value of the litter on the soil surface. CO_2 flux measurements with (OPds) and without litter (OPts) on the peat surface are presented in Figure 6.

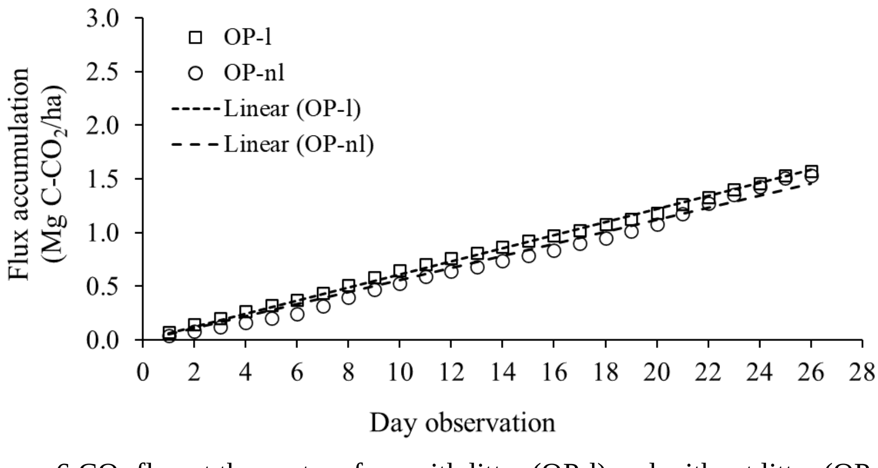

Figure 6 CO_2 flux at the peat surface with litter (OP-l) and without litter (OP-nl)

Figure 6 shows that the soil surface with litter has a higher flux accumulation and average daily flux values than without litter. The accumulated CO_2 flux for 26 days of observation was 1.57 Mg C-CO_2/ha with litter and decreased without litter, about 1.53 Mg C-CO_2/ha. The average CO_2 flux from the soil surface with and without litter obtained by linear regression analysis was 22.3 Mg C-CO_2/ha/year and 20.4 Mg C-CO_2/ha/year, respectively. From the difference in the value of the CO_2 flux, the contribution of litter to the

CO_2 flux is 8.4%. This measurement was carried out in inter-row, only covering 73% of oil palm plantations, so that the contribution of litter to CO_2 flux in oil palm plantations is 6.1%. Therefore, oil palm roots respiration contributes to flux amounting to 47.6%, and the contribution of peat material decomposition is 46.3%. In simple terms, the results of the contribution of each source of flux are presented in Table 2. The contribution of peat material decomposition in this study is below those of studies by Hergoualc'h et al. (2017); Ishikura et al. (2018); Manning *et al*. (2019); Addianto *et al.* (2020). In research in primary forests (Minkkinen *et al.*, 2018), the contribution of respiration from forest plant roots was 16%, roots from plants above the surface 8%, litter 22%, and peat material 53%.

Table 2 Average CO_2 flux and contribution to the total flux

Source of CO_2 flux	Flux CO_2 (Mg C-CO_2/ha/year)	% Contribution
Litter	1.5	6.1
Root respiration	11.5	47.6
Peat material	11.1	46.3

CO_2 flux can be affected by a combination of soil moisture, soil temperature, drainage, and litter on the soil surface interacting with each other, including the observation site (Hermans *et al*., 2021). The CO_2 flux from the soil surface is complex, influencing various factors, resulting in varying CO_2 fluxes. Variations in fluxes are thought to be due to differences in the microbial environment as a source of respiration in the soil to environmental and soil factors. The environmental factor data is presented with CO_2 flux data with linear regression in Figure 7. The environmental factor data also correlates with CO_2 flux data using Pearson correlation. The results of the Pearson correlation analysis are presented in Table 3.

Table 3 Correlation of CO_2 flux with environmental factor using Pearson correlation

Environmental factor	Oil palm plantation (*n* = 78)		Shrubs (*n* = 44)	
	P correlation	P value	P correlation	P value
Ground water level	-0.067^{ns}	0.558	0.010^{ns}	0.947
Soil water content	-0.595*	0.000	-0.104^{ns}	0.502
Relative humidity	-0.168^{ns}	0.141	-0.046^{ns}	0.766
Air temperature	0.170^{ns}	0.138	0.209^{ns}	0.173
Soil temperature	0.102^{ns}	0.372	0.032^{ns}	0.835
Solar radiation	0.107^{ns}	0.353	0.060^{ns}	0.701

n = amount of data; ^{ns} = no significant; * = significant

Table 3 shows that the CO_2 flux in OP was negatively correlated ($P<0.01$) with soil water content but did not significantly correlate with other environmental factors. In the range of water content of 145-450% (w/w), CO_2 flux decreases with increasing soil water content (Figure 7). It shows a strong relationship between soil water content and CO_2 flux. However, at the SR, the CO_2 flux was not significantly correlated with all components of environmental factors. Several studies directly correlate the CO_2 flux with the groundwater level. A decrease in groundwater level causes increments in CO_2 flux (Furukawa *et al*., 2005; Couwenberg *et al*., 2010; Hooijer *et al*., 2010; Hirano *et al*., 2014; Wakhid *et al*., 2017; Ishikura *et al*., 2018). However, in this study, the decrease in the groundwater level was not followed by an increase in CO_2 flux (Figure 7). The deeper the groundwater level does not always produce a high flux. This result is in line with the findings by Sumawinata *et al*. (2012), stating that there is no positive correlation between CO_2 flux and groundwater depth. The level of CO_2 flux produced in peatlands is influenced by peat water content. Manning *et al*. (2019) showed the opposite effect between CO_2 flux and groundwater level at two different observation sites. It further confirms that the depth of the groundwater level is not always consistent in influencing the CO_2 flux. Soil water content can be a better predictor of CO_2 flux than the groundwater level.

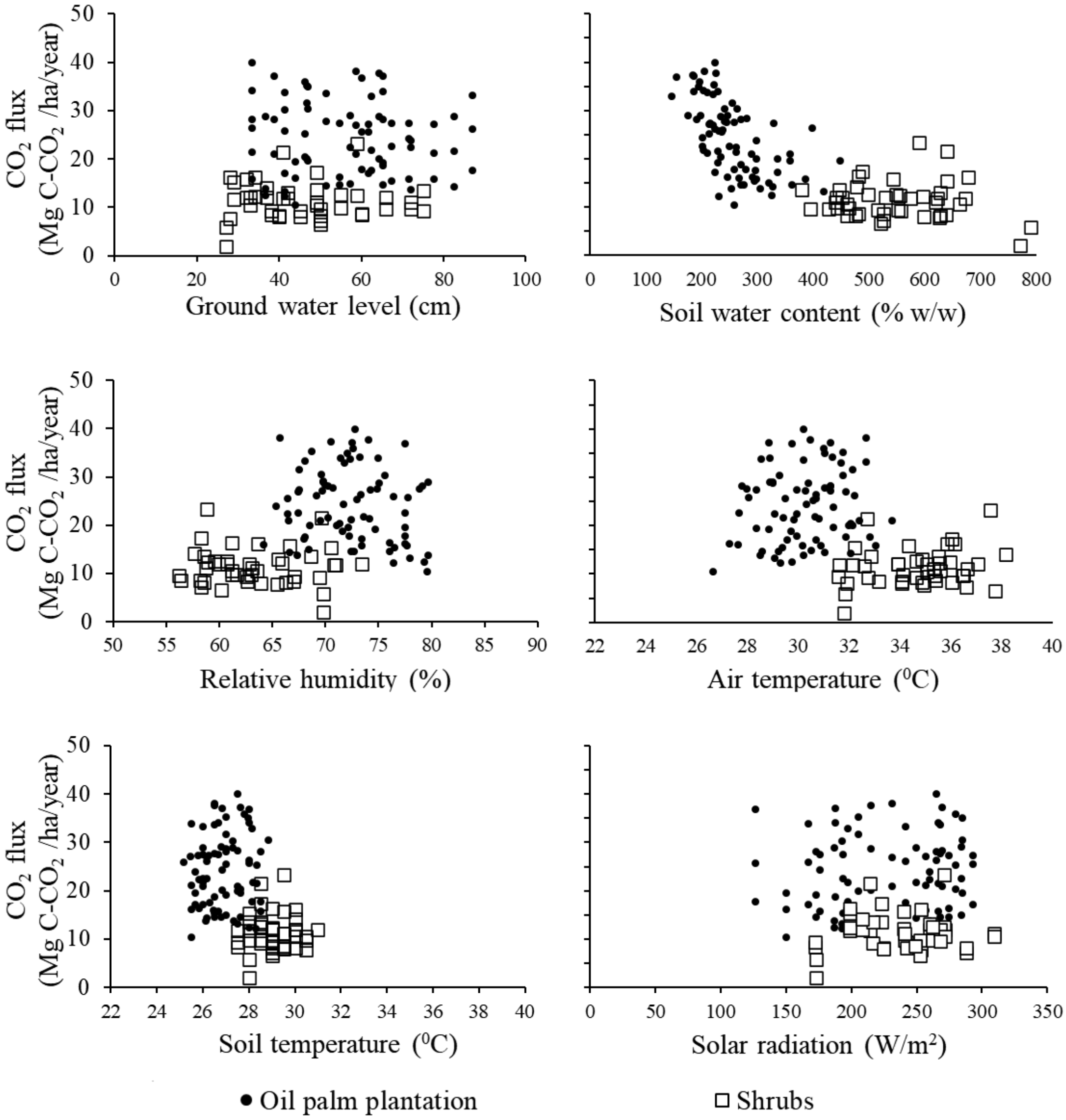

Figure 7 The relationship between the components of environmental factors and flux

Figure 8 shows that the daily average of CO_2 flux in OP observations decreased CO_2 flux during the 5th, 13th, 24th, and 26th observation days and at the 4th and 22nd observation days SR site. This flux pattern is caused by the effect of changes in soil water content due to rain. The addition of water from rain causes soil conditions to become wetter so that the soil water content increases. Waterlogged conditions of peatlands may limit CO_2 flux by generating anaerobiosis and reducing peat oxygenation, while very dry conditions and water deficit may also restrain microbial respiration (Jauhiainen *et al.*, 2005; Marwanto and Agus, 2013). The decrease in CO_2 flux does not always occur in observations after rain. The 8th OP flux and 15th at SR site show that an increase in flux occurs. It is influenced by soil infiltration, which compresses the air in the soil so that the CO_2 flux increases.

CO_2 flux cannot always be related to soil temperature, air humidity, and air temperature. The results of the Pearson correlation analysis showed no significant correlation between CO_2 flux and soil temperature, humidity, and air temperature (Table 3). Likewise, in Figure 7, at the same temperature and humidity values,

CO_2 fluxes show highly variable values. It reveals that the CO_2 flux produced from the peat soil surface does not always increase with increasing soil temperature, air temperature, and relative humidity. Because the relationship between the components of environmental factors and CO_2 flux is the combined effect. Increased solar radiation causes air temperature and soil temperature to increase, and air humidity decreases. Other environmental factors that are recorded are daily rainfall data. Rainfall data adjusted for flux data on each observation day are presented in Figure 8.

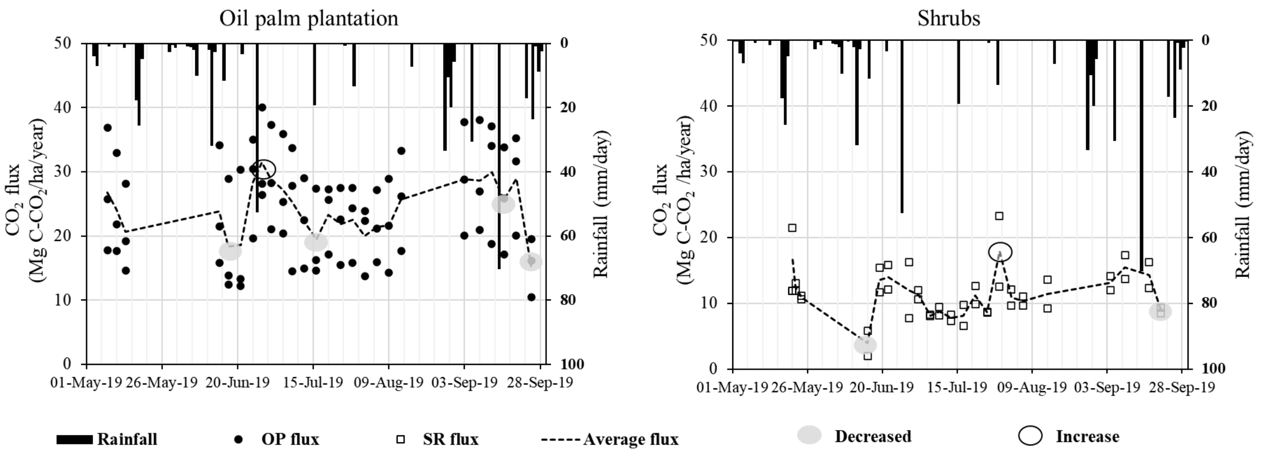

Figure 8 Temporal variation of CO_2 flux, and rainfall in oil palm plantation and shrubs

CONCLUSION

There are temporal and spatial flux dynamics at each time and site of observation. The CO_2 flux in oil palm plantations is more significant than that in shrubs. The contribution of oil palm roots respiration and litter decomposition were 47.6 and 6.1%, respectively. The remaining 46.3% is the contribution of microbial activity in decomposing peat material obtained from measurements in shrubs. These results further confirm that plant roots play an essential role in releasing carbon from the soil surface. The CO_2 flux in oil palm plantations was significant and negatively correlated with soil moisture content in the range of 145-450% (w/w) but did not significantly correlate with groundwater level, air humidity, air temperature, soil temperature, and solar radiation.

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