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SOIL CO_2 FLUX ACROSS MANAGEMENT ZONES IN AN OIL PALM PLANTATION ON PEAT IN PAHANG, MALAYSIA

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ABSTRACT

Soil respiration is a significant contributor to the soil carbon (C) balance. However, knowledge of how it varies between management zones in oil palm plantation, and how it influences peat C loss rate, is still lacking. Therefore, a study to investigate the variations of soil CO_2 *flux* (R_s) *in different management zones was conducted in a 14-year-old oil palm plantation on peat soils.* R_s *was monitored over five months on a 1 ha plot located in an oil palm plantation in Pekan, Pahang, Malaysia using the closed chamber method. Spatial variability was considered by differentiating between C fluxes from each of three surface (management) zones (i.e., harvest paths, frond piles and inter-row). The mean* R_s *from the plantation was evaluated at 1.19 ± 0.09 g* m^{-2} hr^{-1} *across the three different surface zones, whose individual flux values were 0.68 ± 0.07, 1.19 ± 0.16 and 1.71 ± 0.19* m^{-2} hr^{-1}*, respectively. Highlighting* CO_2 *flux disparities among management zones provides insight into how surface management influences peat respiration. Additionally,* R_s *exhibited strong negative coherence with soil moisture. However, further information of the factors controlling soil* CO_2 *flux is required to assess the broader applicability of these findings.*

Keywords: CO_2 emission, oil palm plantation, soil respiration, tropical peat.

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INTRODUCTION

Peatlands offer a range of ecosystem services including carbon (C) storage, biomass production and climate regulation (Minasny et al., 2019). The peatlands of Southeast Asia (SEA) cover about 25 million hectares, are associated with tropical peat swamp forest (PSF) ecosystems, and have been attributed with the storage of a significant amount of soil C. The peat deposits can be up to 20 m thick and are estimated to store 68.5 Pg of C (Page et al., 2011).

Large tracts (up to 3.1 million hectares) of peatland in SEA have been converted into commercial oil palm plantations (Miettinen et al., 2016). In recent decades, the development of more oil palm plantations on tropical peatlands has significantly affected the global C budget because soil C sequestration rates are highly susceptible to changes in land use (Monson & Baldocchi, 2014). The compaction of peat soil before planting alters its biogeochemical and hydrological dynamics causing the degradation of peats, a reduction in water storage and subsidence (Hooijer et al., 2010; Tonks et al., 2017). Once the oil palm is established, deterioration of the peat can be accelerated by changes in land use practice and water management.

The agricultural use of tropical peatlands often requires drainage, which causes the aerobic mineralisation of peat soil and substantial carbon dioxide (CO_2) emissions (e.g., Couwenberg et al., 2010; Furukawa et al., 2005; Hooijer et al., 2012). Although measurements of CO_2 emissions from drained tropical peatlands commonly pertain to the drainage of peat for conversion to agriculture, they are significant for the global C cycle (Miettinen

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et al., 2017; Sjögersten et al., 2014) and can be used to predict future changes to tropical peat C sinks and stores, as well as the magnitude of transfers of peat-derived greenhouse gases (GHG) to the atmosphere. The most significant form of C released from drained peatlands is CO_2, which accounts for 98% or more of their total global warming potential (GWP) (Jauhiainen et al., 2012b). According to Ryan and Law (2005) and Hergoualc'h and Verchot (2011), only heterotrophic respiration, which is associated with bacterial and oxidation activities rather than with roots, is responsible for the emissions of peat C into the environment through soil respiration. Reports of previous study on the soil CO_2 flux from oil palm plantations on tropical peatlands include Dariah et al. (2014), Hergoualc'h and Verchot (2014), Ishikura et al. (2018), Matysek et al. (2018), Gusmayanti et al. (2019), Manning et al. (2019), Cooper et al. (2020) and Mos et al. (2021). Recent estimates of R_s from oil palm plantations on peat implies that these systems emit CO_2-C fluxes ranging from 4.1 to 104.0 Mg ha^{-1} yr^{-1}.

To conserve peatlands and contribute to realisation of the Paris Agreement targets, we must comprehend their magnitude, state and C stocks. Nevertheless, current apprehension on CO_2 emissions in tropical peatland remains scarce (Page et al., 2011). Due to the differences in environmental conditions, peat characteristics, vegetation and microbial diversity, the understanding of soil C flux based on studies in boreal and temperate peatlands is not directly applicable to tropical peat soils (Jauhiainen et al., 2012a). Most studies do not separate the components of autotrophic and heterotrophic respiration, which tends to make it challenging to understand how changing land use will affect decomposition processes and CO_2 losses from tropical peatlands, particularly oil palm plantations (Couwenberg et al., 2010). As a result, it is unclear how processes controlling the sources and dynamics of soil CO_2 flux (R_s) work. Furthermore, substantial uncertainty still exists on R_s and it responds to a variety of factors, including temperature and moisture, at different spatial and temporal scales (Webster et al., 2008).

Driven by ongoing economic development, oil palm is expanding rapidly in Malaysia (Parveez et al., 2021). A recent study by Basri et al. (2024) analysed CO_2 flux in oil palm plantation peatland in Sarawak, Malaysia across various management zones, reporting a bias-corrected upscaled annual plantation-level flux of 45.509 ± 3.322 Mg CO_2 ha^{-1} yr^{-1}. The highest emissions were observed in harvest path (HP) (37.155 ± 3.113 Mg CO_2 ha^{-1} yr^{-1}), followed by palm base, inter-row (IR) and frond pile (FP). However, despite such findings from East Malaysia, there is still minimal information on CO_2 fluxes in oil palm plantations on peat, especially in West Malaysia and on how they are affected by varying environmental conditions. It is hypothesised that CO_2 emissions from oil palm plantations on peat in West Malaysia will vary significantly among micro-sites and is driven primarily by differences in soil moisture, temperature, similar to patterns observed in East Malaysia.

This study aims to address the question of how soil CO_2 flux varies across different surface management zones within a mature oil palm plantation, specifically FP, HP and IR, and how these fluxes respond to site-specific factors such as soil temperature and moisture. Thus, its attempts to quantify the amount of soil respiration in the three surface (management) zones of oil palm plantation in tropical peatland (i.e., FP, HP and IR). *Figure 1a* shows location of CO_2 flux sampling points at different management zones (Mos et al., 2021).

In this article, we report the results of measuring CO_2 fluxes from mature oil palm plantation on peat soil together with soil temperature, soil moisture for a period of five months in September and October 2019; January, February and July 2020. By observing these spatial and environmental patterns, this study contributes to a better understanding of the processes influencing CO_2 losses from oil palm cultivation on tropical peatlands.

MATERIALS AND METHODS

Study Site

The study was conducted between 2019 and 2020 in an oil palm plantation on peatland in Pekan District, Pahang, Malaysia (03º 26′N, 103º 23′E), where mean annual rainfall is approximately 2,997 mm. The area consists of beach ridges, marine/estuarine deposits and organic deposits. The soils of the plantation belong mostly to the Teraja Series and consist of deep (150–300 cm) and very deep (>300 cm) organic soils. Soils of the Teraja Series deep phase occupy 472.3 ha or 31.2%, while the very deep phase occupies 347.3 ha or 22.9% of the plantation. The soils are dark brown in colour with severely decomposed sapric organic soil material below 60 cm depth and undecomposed wood fragments in the subsurface (50–100 cm) tier. These soils are very acidic with a pH of 3.09–3.42 and contain >40% organic C with a loss on ignition of about 91% (Paramananthan, 2016). The total area planted with oil palm within the estate is approximately 1,515 ha, comprised entirely of first-generation oil palm plantation that was established (planted) between 2005 and 2006.

Field and Laboratory Measurements

A 1 ha plot was established in an area with a planting density of 160 palms ha^{-1}, where the water table was maintained at a depth of about 0.5 m. Soil CO$_2$ efflux sampling were located at three different surface (management) zones; 1 ha plot was divided into 25 numbered subplots with dimensions of 20 × 20 m, presented schematically in *Figure 1b*.

Three soil CO$_2$ flux sampling points were established within each subplot. These encompassed the three different management zones of oil palm plantation, i.e., FP, HP and IR. The sampling points (HP, FP and IR) were about 3.5 m from the base of the nearest palm to avoid effects from fertiliser inputs to the weeded circle around each tree and to ensure minimal influence of root respiration on the flux measurements. Dariah et al. (2014) found that the root contribution at 2.5 m distance from a mature palm is less than 35%, meaning the sampling point locations had low root density.

Soil CO$_2$ flux was quantified using a closed chamber and EGM-4 Environmental Gas Monitoring System (PP-System, United Kingdom). Measurements were taken between 10:00 and 12:00 hr, when soil CO$_2$ fluxes were expected to be at their highest daily levels (Luo & Zhou, 2006). Each measurement was made at the soil surface using a soil collar made from PVC (10.5 cm diameter × 15 cm length), which was sunk 10 cm into the soil. The effective volume of the chamber was estimated in accordance with the different collar lengths caused by soil subsidence. To determine the CO$_2$ efflux, CO$_2$ levels were monitored over 2 min enclosure duration, with concentrations recorded every 3 s or until 100 ppm CO$_2$ was observed. Due to equipment malfunction, measurements were collected over a duration of two days in January and July. In contrast, the measurements for the remaining months were taken using two EGM-4 on a single day.

Soil temperature, air temperature and soil moisture were measured in conjunction with the soil CO$_2$ flux measurements. Soil temperature was determined at 5 cm depth by a sensor (STP-1, Campbell Scientific Inc., USA) attached to the EGM analyser. A digital thermometer positioned in the shade about 1 m off the ground was used to manually record the air temperature. Soil moisture content was determined volumetrically using the time domain reflectometer (TDR) sensor HydroSense soil water measurement system (CD620 and CS620, Campbell Scientific Inc., USA).

One month before the start of the flux measurements, nine PVC pipes 3.0 m in length and 5.0 cm in diameter with wall perforations spaced 10 cm apart were pre-installed into the peat soil to a depth of 2.5 m. After each set of flux measurements was completed in January, February and July of 2020, the water level relative to ground level (water table depth [WTD]) in the PVC pipes was determined by inserting a pipe of diameter 2.5 cm with a measuring tape attached (Manning et al., 2019).

Bulk density (BD) was measured as an indicator of soil compaction, according to Agus et al. (2011). Soil samples were collected using a stainless soil

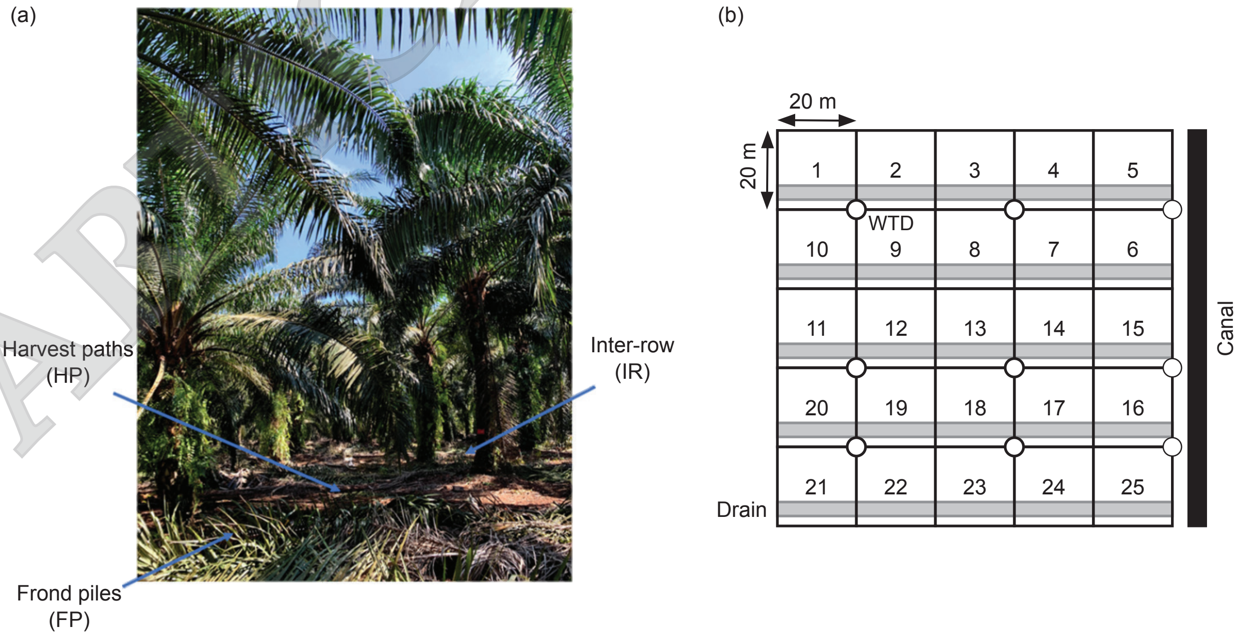


Figure 1. (a) *Plantation in Pekan, Pahang, Malaysia showing the three surface zones and (b) schematic representation of subplots in oil palm plantation, with drain indicated by grey shading. The open circles indicate the positions of the nine dip wells.*

core cylinder (98.125 cm^3), at three depths (0–15, 15–30, 30–35 cm) in the three different surface zones (FP, HP, IR) within each subplot. To determine the BD, 225 soil samples were weighed and dried to constant weight at 105°C. Ash content (%) was evaluated using the loss-on-ignition method for 6 hr at 550°C. A portable pH meter (EXTECH ExStixII) was used to take several measurements of the soil pH in July 2020.

Statistical Analysis

All statistical analyses and graphs were carried out using Microsoft Excel and R (version 4.1.2). The Kruskal-Wallis test (one-way ANOVA) was performed for multiple comparisons to test the significant variations in CO$_2$ fluxes on the different surface zones, where significant effects were detected, Dunn's post-hoc tests with Bonferroni correction were conducted to identify pairwise differences. Results are reported with test statistics (H-values), degrees of freedom and exact *P*-values.

RESULTS AND DISCUSSION

Based on *Table 1* the BD measurements showed that the near-surface peat in the plantation was more compact than the deeper peat and near to the surface BD was 0.16 ± 0.008 g cm^{-3} at FP, 0.22 ± 0.03 g cm^{-3} at HP and 0.20 ± 0.03 g cm^{-3} at IR with an overall mean of 0.19 ± 0.01 g cm^{-3}. The pH of the soil in the plantation ranges from 3.13 ± 0.02 to 3.44 ± 0.01 and the soil's C content was greater than 40% (Paramananthan, 2016). Mean WTD across all measurement points (n = 27) fluctuated between -0.54 and -0.96 m with an average of -0.63 m (relative to the peat surface) at all measurement points.

The average results of the CO$_2$ flux sampling and simultaneous environmental measurements are shown in *Table 2* and *Figure 2*. IR returned the highest mean R_s value of 1.71 ± 0.19 g m^{-2} hr^{-1} followed by FP at 1.19 ± 0.16 g m^{-2} hr^{-1} and HP at 0.68 ± 0.07 g m^{-2} hr^{-1}. Mean R_s was 1.19 ± 0.09 g m^{-2} hr^{-1}. The difference in R_s amongst surface zones was significant (Kruskal-Wallis chi-squared = 40.107; df = 3, $p<0.0001$) although the Kruskal-Wallis multiple comparison test revealed that there was no difference in R_s between FP and IR while R_s was significantly lower in HP ($p \leq 0.05$). Mean soil temperature was the highest in HP and declined in the order of HP (27.04°C) > IR (26.93°C) > FP (26.80°C). Soil temperature varied significantly amongst the different surface zones (Kruskal-Wallis: chi-squared = 6.206, df = 2, $p<0.05$) although there was no significant difference between HP and IR (Kruskal-Wallis multiple comparison test, $p \geq 0.05$). Soil moisture also varied significantly amongst the surface zones (Kruskal-Wallis chi-squared = 10.714, df = 2, $p<0.005$), decreasing in the order of HP (44.80%) > FP (44.02%) > IR (43.20%). The difference between soil moisture in IR and the other two zones was significant (Kruskal-Wallis multiple comparison test, $p \leq 0.05$). Similarly, air temperature varied amongst zones (Kruskal-Wallis chi-squared = 12.158, df = 2, $p<0.005$), with a significant difference in air temperature between IR and the other two zones (Kruskal-Wallis multiple comparison test, $p \leq 0.05$). In *Figure 3*, mean R_s is plotted against the mean values of soil moisture, soil temperature, and air temperature. Whilst *Figure 3* suggests that R_s declines with increasing soil moisture, no clear trends in R_s are discernible in relation to soil temperature or air temperature.

The soil in the plantation shows typical attributes of peat soils, which generally have low BD and ash content (Safford & Maltby, 1998). The low pH and high C content are typical for ombrotrophic peat. According to Mohd Haniff et al. (2011), the optimum water table level in peat soils is between -0.3 and -0.6 m relative to the surface. The water table level at our study site is often within this range, although sometimes higher because of seasonal variability. Nonetheless, WTD exceeds the Malaysian recommended optimum level of -0.3 to -0.5 m.

Soil CO$_2$ flux values reported by other studies employing the closed chamber technique in oil palm plantations on tropical peat soil range from 67.85 t ha^{-1} yr^{-1} (Mos et al., 2021) to 104.00 t ha^{-1} yr^{-1}

TABLE 1. MEAN VALUES (± SE) OF SOIL PROPERTIES AND WATER TABLE DEPTH (WTD)

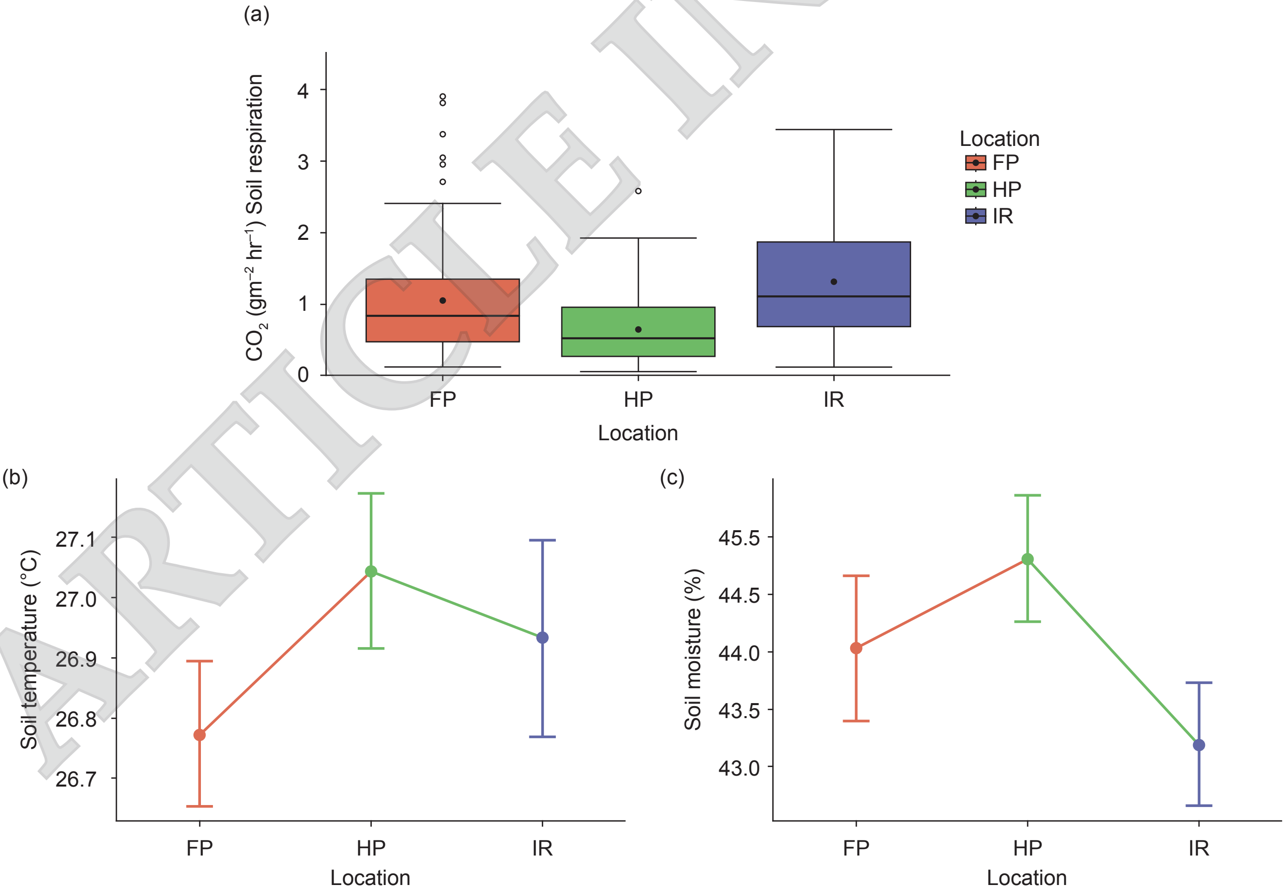
Variable	Depth (cm)	n	Surface zone		
			FP	HP	IR
Bulk density (g cm^{-3})	0–15	75	0.18 ± 0.01	0.26 ± 0.05	0.21 ± 0.04
	15–30	75	0.16 ± 0.01	0.20 ± 0.05	0.19 ± 0.05
	30–45	75	0.14 ± 0.02	0.19 ± 0.05	0.18 ± 0.05
	all	225	0.16 ± 0.008	0.22 ± 0.03	0.20 ± 0.02
pH	all	9	3.44 ± 0.01	3.13 ± 0.02	3.37 ± 0.02
WTD (m)	all	27		-0.63 ± 0.03	

Note: FP - frond pile; HP - harvest path; IR - inter-row; n - number of observations.

TABLE 2. MEAN VALUES (± SE) OF CO_2 FLUX (R_S) AND ENVIRONMENTAL FACTORS MEASURED IN THE PEKAN OIL PALM PLANTATION AT MONTHLY INTERVALS

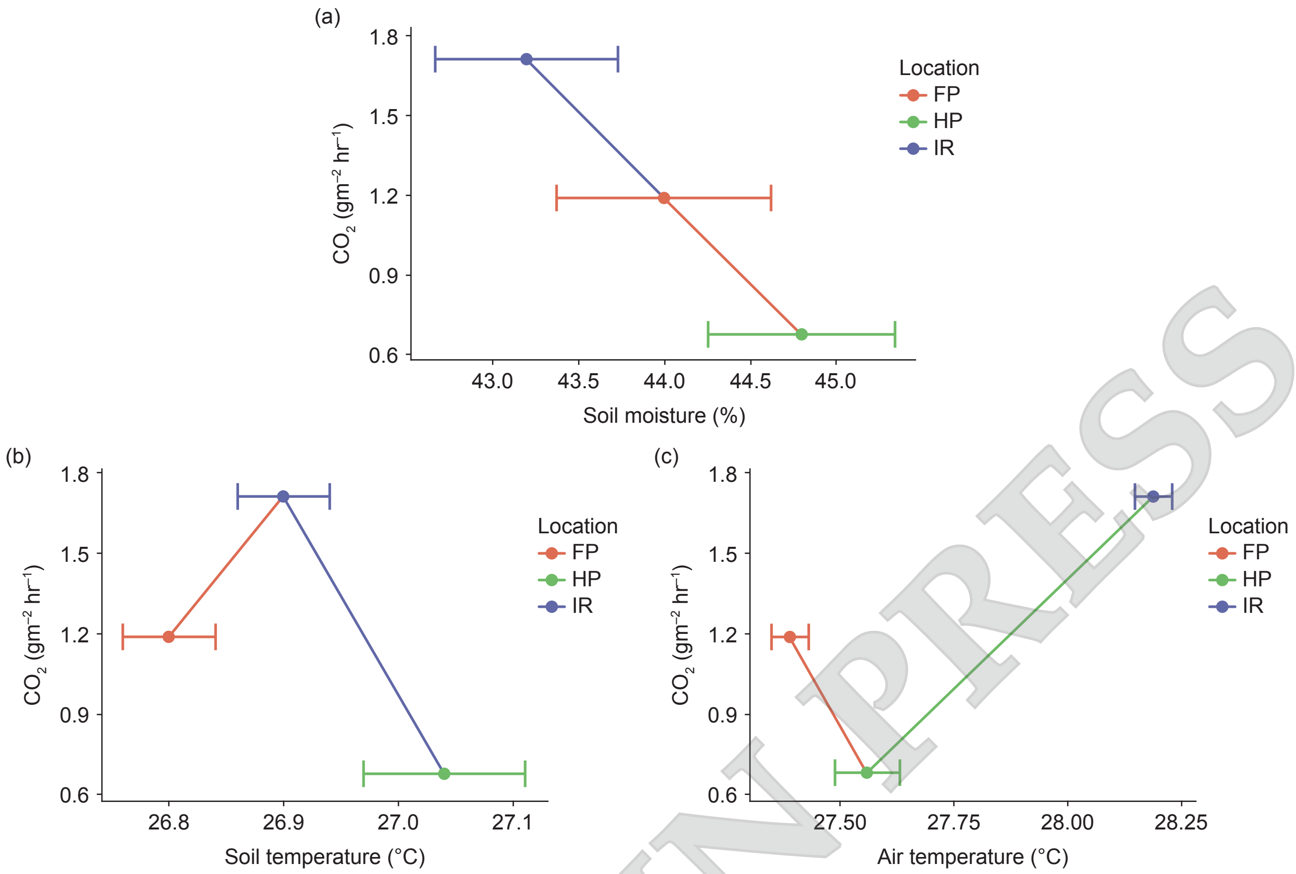
Variables	Surface zone	n	Mean values ± SE
CO_2 flux (R_s) (g m^{-2} hr^{-1})	All	225	1.19 ± 0.09
	FP	75	1.19 ± $0.16^{a,b}$
	HP	75	0.68 ± 0.07^{a}
	IR	75	1.71 ± $0.19^{a,b}$
Soil temperature (°C)	All	225	26.92 ± 0.03
	FP	75	26.77 ± 0.04^{a}
	HP	75	27.04 ± $0.07^{a,b}$
	IR	75	26.93 ± $0.04^{a,b}$
Soil moisture (%)	All	225	44.01 ± 0.33
	FP	75	44.02 ± 0.62^{a}
	HP	75	44.80 ± 0.54^{a}
	IR	75	43.19 ± 0.53^{a}
Air temperature (°C)	All	225	27.72 ± 0.08
	FP	75	27.40 ± 0.12^{a}
	HP	75	27.57 ± 0.13^{a}
	IR	75	28.20 ± 0.16^{a}

Note: FP - frond pile; HP - harvest path; IR - inter-row; n - number of observations. Data with significantly difference (p<0.05) parameters have been denoted by suffix a, non-significantly difference (p>0.05) denoted by suffix b.



Note: FP - frond pile; HP - harvest path; IR - inter-row. Points represent mean values with error bars. Lines indicate visual trends among categorical locations only and do not represent statistical or inferential relationships.

Figure 2. Box-and-whisker plots of R_s - CO_2 flux for (a) soil respiration, (b) soil temperature and (c) soil moisture in the three surface zones from September, October 2019; January, February and July 2020.



Note: FP - frond pile, HP - harvest path and IR - inter-row. Points represent mean values with error bars. Lines indicate visual trends among categorical locations only and do not represent statistical or inferential relationships.

Figure 3. Relationships between mean values of (a) soil CO_2 flux (R_s) and soil moisture, (b) soil temperature and (c) air temperature from September, October 2019; January, February and July 2020.

(Comeau et al., 2016), and the mean soil CO_2 flux (104.20 t ha^{-1} yr^{-1}) found in our study lies at the top end of this range. The higher CO_2 flux in IR could be due to higher density of roots between the palm bases within the row. Study by Arifin et al. (2015) and Manning et al. (2019) showed that R_s was lower in FP compared to HP, and our results contradict these findings. However, high R_s in FP is not surprising because the ground here consists of piles of decomposing fronds with enhanced oxidation of fresh organic matter that may well lead to relatively high CO_2 efflux (Kuzyakov, 2006). It is crucial to highlight the differences in R_s between surface zones to gain understanding about the influence of oil palm management methods on the dynamics of CO_2 efflux.

Due to the low sampling frequency of our study, any seasonal pattern of soil CO_2 flux remains unclear. On the other hand, our results did show that the increased soil moisture in HP was associated with substantially reduced soil CO_2 efflux compared to the other two surface types, while FP was intermediate in terms of both soil moisture and CO_2 flux (*Figure 2* and 3). The moisture content of peat affects microbial activity, making it one of the essential components in the breakdown of organic matter. Furthermore, soil moisture influences soil microbial respiration by influencing the diffusion of soluble substrates at lower soil water levels and restricting the diffusion of oxygen at higher soil moisture levels thereby reducing CO_2 emissions from the soil (Susilawati et al., 2022). Near the peat surface, changes in groundwater level and associated environmental conditions may control the rate of CO_2 emission from the soil; and Hergoualc'h et al. (2017) suggested that soil moisture and WTD could serve as proxies for redox potential because raising soil moisture reduced the rate of R_s. In our study, however, although individual observations of soil moisture in the top 20 cm varied from 15%–58% (by volume), soil moisture showed no statistical correlation with CO_2 flux.

A possible explanation for sensitivity of R_s to air temperature was changes in soil surface layer metabolism as the temperature at the soil surface fluctuated in response to air temperature, which might affect the short-term temporal variation of soil CO_2 efflux (Ohashi et al., 2008). Higher temperatures may expedite the degradation of soil organic C by microbial activity (Liu et al., 2018), intensifying the CO_2 emissions.

The lowest average soil temperature was observed in FP, which did not have the lowest mean R_s value. Soil temperature in IR was higher than at FP, and here R_s was also higher. In contrast, although soil temperature in HP was also higher than in FP, R_s was lower. Generally, increasing temperature boosts the activation energy of biological processes, leading to increased respiration (Manning et al., 2024). The weak relationship of CO_2 efflux to soil temperature could be partially accounted for by the small amplitude of soil temperature fluctuations in the tropical environment (Wakhid & Hirano, 2021). The absence of a significant link between CO_2 flux and soil temperature suggests that soil temperature does not influence the CO_2 flux in any of the surface types. Conversely, Wang et al. (2017) and Jeyanny et al. (2021) reported a strong correlation between soil temperature and soil CO_2 fluxes. It is also crucial to note that the soil temperatures were lower in FP and IR than in HP. This result is contradictory as soil moisture content is highest in HP.

Based on *Figure 3*, neither soil temperature nor air temperature shows a significant relationship with CO_2 flux across the measured plots except for soil moisture. Drainage is required prior to converting the peatland into an oil palm plantation. Drainage regulates CO_2 dynamics through enhanced soil aeration, which enhances soil respiration rates by raising the amount of oxygen accessible to soil microbes. Therefore, since there is no seasonal variation in soil temperature in the tropics and no significant low temperature, the influence of soil moisture on soil respiration rates in tropical peatlands is most likely greater (Melling et al., 2005).

Table 1 reveals that HP has the highest BD for every depth and also has the lowest mean CO_2 flux. Heavy machinery is used to mechanically compress peatlands after draining. Soil particles are compressed during mechanical compaction, it increases the BD of the soil and reduces porosity (Busman et al., 2021) hence, enhance root anchoring to mitigate leaning issues in oil palm cultivation on peat (Ratai et al., 2024). Additionally, compaction can shrink bigger holes into smaller pores and limit fluid and gas transport pathways, all of which may disrupt soil biological activities resulting in a decrease in soil CO_2 flux (Pengthamkeerati et al., 2005).

CONCLUSION

This study provides preliminary evidence that CO_2 fluxes associated with soil temperature and moisture vary spatially in oil palm plantations on tropical peatlands. This suggests that CO_2 emission is a complicated process influenced by a variety of peatland characteristics and environmental variables. Further comprehensive and long-term study on tropical peatlands is critically needed in order to better understand the response of CO_2 efflux in different seasons as well as autotrophic vs. heterotrophic respiration, and thus provide more accurate predictions of future soil C balance. These early findings may be helpful in revealing the degree of variance in soil CO_2 efflux at various surface management zones to support the development of management practices to improve the sustainability of tropical agriculture.

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