

Research Article

Seasonal litter contribution to total peat respiration from drained tropical peat under mature oil palm plantation

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Abstract

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The amount of CO₂ gas emissions in drained peatland for oil palm cultivation has been widely reported. However, the research addressing the contribution of litter respiration to peat and total respiration and its relationship with several environmental factors is found rare. The aim of this study was to measure peat and heterogeneous litter respiration of drained tropical peat in one year at a distance of 2.25 m and 4.50 m from mature oil palm trees of 14 years using the chamber method (Licor Li-830). In addition to CO₂ efflux, we measured other environmental parameters, including peat temperature (10 cm depth), air temperature, groundwater table (GWL), and rainfall. Results showed that the mean total peat respiration (R_t) was 12.06 g CO₂ m⁻² day⁻¹, which consisted of 68% (8.24 g CO₂ m⁻² day⁻¹) peat (R_p) and root (R_r) respiration and 32% (3.84 g CO₂ m⁻² day⁻¹) of litter respiration (R_l) at the distance of 2.25 m from the palm tree. Meanwhile, at a farther distance, the R_t was 12.49 g CO₂ m⁻² day⁻¹, the contribution of R_p was 56% (6.78 g CO₂ m⁻² day⁻¹), and R_l was higher than the closest distance (46%; 5.71 g CO₂ m⁻² day⁻¹). Thus, one-year observation resulting the mean R_t and R_r was 0.07–0.08 Mg CO₂ ha⁻¹ day⁻¹, while R_l was 0.04–0.06 Mg CO₂ ha⁻¹ day⁻¹. The means of R_t, R_p, and R_l were significantly different in the dry season than those recorded in the rainy season. The climatic-related variable such as peat and air temperature were chiefly governing respiration in peat under mature oil palm plantation, whereas the importance of other variables present at particular conditions. This paper provides valuable information concerning respiration in peat, especially for litter contribution and its relationship with environmental factors in peatland, contributing to global CO₂ emission.

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Introduction

Sumatera Island possesses the most considerable extent of peatland area in Indonesia. Covering around

5.85 million ha or 43.6% of Indonesian peatlands, Sumatran peat is distributed mainly in Riau and South Sumatera province (3.57 and 1.12 million ha, respectively). Around a half fraction of peatland in the

Riau area is occupied by very deep peat (>3 m thick), and another portion was identified predominantly as moderately deep and deep peat (1-3 m thick) (Anda et al., 2021). Regarding its extensive coverage and high carbon content, the peatland in this area is considered critical to sequester huge C reserve (Warren et al., 2017; Leiffield et al., 2019).

Being utilized extensively for the agricultural sector, such as oil palm plantation with an alarming rate, the uprising risk of C emission in peatland has raised global concern (Wijedasa et al., 2017; Leiffield et al., 2019; Dadap et al., 2021). Recent reports revealed that a large peatland area in the Riau region had been cultivated by oil palm plantations (Ramdani and Hino 2013; Adrianto et al., 2020), ranked Riau as the largest holder and producer of oil palm plantation over the country (BPS, 2021). Despite its importance as a profitable and efficient oil producer that outperformed other crops (Murphy, 2014), oil palm transformed the peat landscape (Sayer et al., 2012) and was believed to aggravate a considerable amount of C emission from peat (Hooijer, 2010; Page et al., 2011). Since CO₂ emission from drained tropical peatland is recognized as a pivotal part of the global C cycle (Sjögersten et al., 2014), the research that encompasses peat respiration in this area must be conducted.

Naturally, peat undergoes the reduction state during prolonged saturation due to the lack of oxygen availability, resulting in a slower rate of organic matter decomposition (Andriese, 1988; Law et al., 2019). Radically shifted condition from its natural state, causing significant peat changes from C sink to source (Miettinen et al., 2017). Emitted from roots and heterotrophic respiration, C emission in peat constituted mainly of CH₄ and CO₂ gasses, depending on the oxygen availability and also peat material. Under the waterlogged and strong reductive condition, peat can emit CH₄. However, some researchers pointed out that high lignin content in Southeast Asian peatlands inhibits CH₄ production (Hirano et al., 2009; Arai 2014), notably with oxic (Swails et al., 2021) and compacted conditions (Busman et al., 2021) in drained oil palm plantation. Oppositely, a considerable amount of CO₂ emanates in the peat surface after clearing and draining the peat for cultivation purposes (Prananto et al., 2020) owing to enhanced aerobic microorganism activity under excessive O₂ presence (Xu et al., 2021). This condition, hence, also generates CO₂ as prominent gas emitted from drained and cultivated peatland.

There is a large body of knowledge discussing CO₂ emission and peat respiration in tropical peatland, particularly for oil palm plantations (Murayama and Bakar, 1996; Melling et al., 2005; Hooijer et al., 2010; Sabiham et al., 2011; Dariah et al., 2014; Comeau et al., 2016; McCalmont et al., 2020). The total peat respiration represents a mixture of autotrophic and heterotrophic components (Epron, 2010). Their reported value varies widely among many sources with high discrepancies. In Indonesian peat, total

respiration recorded around 13.8 to 178 Mg CO₂ ha⁻¹ yr⁻¹ (Hooijer et al., 2012; Hergoualc'h et al., 2017); meanwhile, heterotrophic respiration ranges from 5.2 to 66.3 Mg CO₂ ha⁻¹ yr⁻¹ (Dariah et al., 2014; Husnain et al., 2014; Marwanto and Agus, 2014; Comeau et al., 2016; Hergoualc'h et al., 2017). Estimated the relative autotrophic or root respiration was contributed around 62 to 74% to total CO₂ flux (Meiling et al., 2013; Sabiham et al., 2014). Among these myriad-spreading reports, research concerning the contribution of litter to the total soil respiration had received little attention.

With respect to their difference in origin, heterotrophic respiration from litters may release a different magnitude and pattern of CO₂ fluxes compared to peat and root-related respiration. The litter in tropical peat swamp forest is composed predominantly of woody debris, coarse and fine roots, and leaf litter (Miyajima et al., 1997), contributing a remarkable portion for total and heterotrophic respiration on the surface (Hirano et al., 2009; Sundari et al., 2012), also similar within the mineral soil rainforest (Zhou et al., 2013). However, different species are grown as primary plants and understory cover in oil palm plantations (Sabiham et al., 2012; Ashton-Butt et al., 2018; Novita et al., 2020). Peatland monoculture ecosystem sequestered C with a broad range (Khasanah et al., 2015; Novita et al., 2020), releasing heterogeneous C sources ranging from pruned palm fronds with high lignin content (Moradi et al., 2014; Pulunggono et al., 2019) to the easily degraded understory cover material (Amatangelo and Vitousek, 2009). This is a clear indication that CO₂ emissions measured from the decomposed litter will give different records.

In oil palm plantations, litter roughly consisted of oil palm decomposing fronds and understory cover crops. Different litter source had their own space following the widespread best practice (Corley and Tinker, 2016). Moreover, the mixing between both sources is generally found in all plantations, as observed in this study. Respiration from fronds pile and understory cover row as well as total, root, and collection drains respiration of Malaysian peat at Kalimantan had been studied and reported well by Manning et al. (2019), although, with no reference to the peat maturity stage. They found that around 6% of the total soil respiration came from understory cover litter, while oil palm fronds contributed around 4.7%. Using the litter bag method, Wakhid and Hirano (2021) reported that the decomposition of an oil palm frond in Indonesian peat released 109 g C m⁻² year⁻¹, accounting for approximately 13 and 8% of heterotrophic and soil respiration, respectively. Despite the fact that no references pinpointed the CO₂ emission of heterogeneous litter composed of palm fronds and understory cover dead material, we hypothesized that their value and contribution to the total or heterotrophic respiration in tropical peat are somewhat higher than both previous authors' denoted. One of the reasons is favorable microhabitat and

microclimate that occur in the dense understory cover on fronds pile, promoting more diverse and abundant decomposer than the adjacent microsite close to the oil palm tree (Eisenhauer 2016; Ashton-Butt et al., 2018;). Fast-growing and ubiquitous ferns might act as nutrient accumulators, providing detrital materials that decompose at a rapid rate (Amatangelo and Vitousek 2009; Talbot et al., 2011), which are potential to enhance microbial respiration in high-lignin content tissue, e.g., palm leaflets, rachis, and fronds (Khalid et al., 2000; Pulunggono et al., 2019).

The dynamic of CO₂ efflux under oil palm plantation at tropical peatland is considered a function of various environmental factors, closely linked to the source, site, and season (Dariah et al., 2014; Manning et al., 2019; Dhandapani et al., 2019). Current reports demonstrated that CO₂ flux in peat at oil palm plantations primarily emanates from root/autotrophic respiration in less than three meters of oil palm radius. Oppositely, the heterotrophic respiration was found to contribute predominantly at a farther distance due to the decline in palm root density (Khalid et al., 1999; Dariah et al., 2014; Sabiham et al., 2014). Several researchers found that water table level (GWL) dictated CO₂ flux (Hirano et al., 2009; Sundari et al., 2012; Itoh et al., 2017), intensifying particularly during its rise near the peat surface (Ishikura et al., 2017). Otherwise, opposite (Couwenberg et al., 2010; Marwanto and Agus 2014; Ishikura et al., 2018) and obscured effect (Husnain et al., 2014) of GWL in governing CO₂ flux were also observed. Notwithstanding that, Meiling et al. (2005) and Ishikura et al. (2018) reported that peat temperature was significantly related to CO₂ flux, albeit its effects might be restricted under dense canopy cover of the

mature oil palm tree (Jauhainen et al., 2014). Therefore, to fill the knowledge gap in this field, this paper investigates the seasonal peat, heterotrophic, and litter respiration observed from drained tropical peatland located at a mature oil palm plantation in Indonesia. This paper also presents valuable information regarding the relationship of observed respiration with several environmental factors.

Materials and Methods

Study site

The study was conducted in the mature oil palm plantation (around 14 years old) of the drained peatland dominated by ± 5 m thick peat. The decomposition stage consisted of hemic-sapric, and the bulk density is around 0.10 to 0.18 g cm⁻³, according to Pulunggono et al. (2019). Astronomically, the study area is located at 0°44'55.89" N dan 101°45'14.04" E in Koto Gasib, Siak Regency, Riau Province, Indonesia, as shown in Figure 1. The oil palm trees in this plantation were grown in a triangular grid spacing system, with a planting distance of approximately 9 m resulting in around 140 to 143 palms per hectare. The soil was left bare with minimum understory cover on the fertilizer circle with a radius of around 2.5 to 3 meters from the palm tree. The fertilizer was broadcasted consistently every semester (six months) inside the fertilizer circle with the dosage of 3.5 kg NPK 15-6-24, while 1.5 kg dolomite was added in semester 2, 2020. Understory cover crops grew in the rows outside the fertilizer circle and consisted predominantly of *Nephrolepis bisserata* (Figure 2).

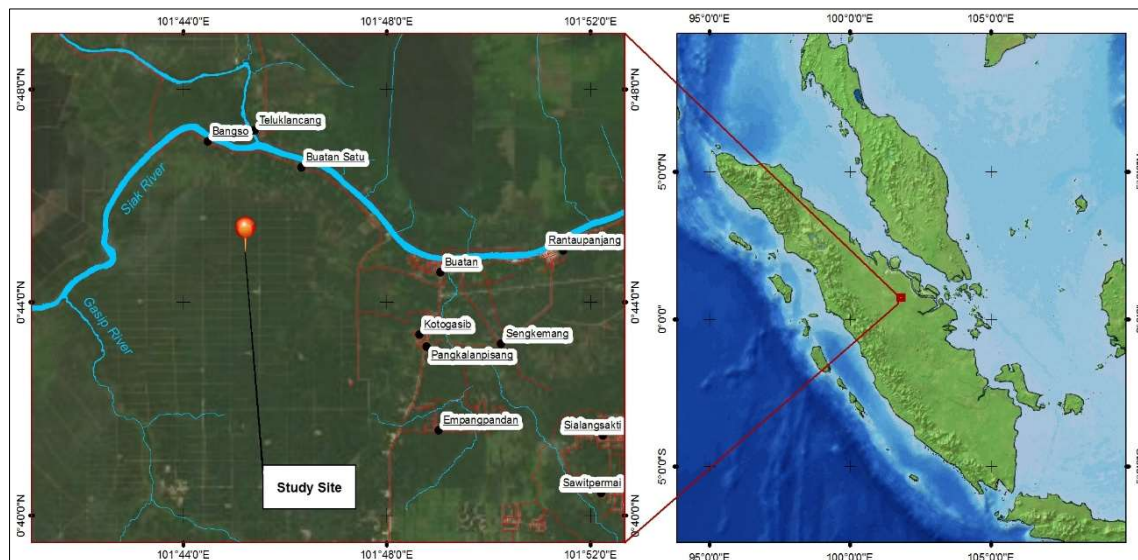


Figure 1. The study site location.

CO₂ flux monitoring: sampling location, design, and measurement

To calculate and characterize the CO₂ flux partition emitted from total peat respiration (Rt), a CO₂ flux measurement tool was installed inside the trenched peat (established on October 24, 2019, in three palm trees) located at two distances from the oil palm tree. The closest distance is located 2.25 m from the oil palm tree and inside the fertilization circle. The farther was 4.50 m from the oil palm tree, located at the fronds pile. However, a dense understory cover, mainly *N. bisserata*, was observed covering the piles. More heterogeneous litter was found here, consisting of newly pruned and decomposed leaflets, rachis, and petioles combined with fern's dead materials. In this

study, Rt was considered as the combination of peat or heterotroph respiration (Rp), root or autotroph respiration (Rr), and litter respiration (Rl). The observation was done in three treatments (T1, T2, and T3) using trenching collars made from PVC pipe (6 inches in diameter), which were placed at both distances from the oil palm tree (Figure 2). Each trenching collar was covered with the perforated hood with one mesh hole diameter to avoid insects or other animals. The cap was opened when measuring the CO₂ flux. The trenching collar installation followed Jovani-Sancho et al. (2018) method. In the T1 treatment that represents Rp + Rl, trenching collars of 35 cm long were penetrated 30 cm into the peat, cutting the active root inside and leaving 5 cm height above the surface.

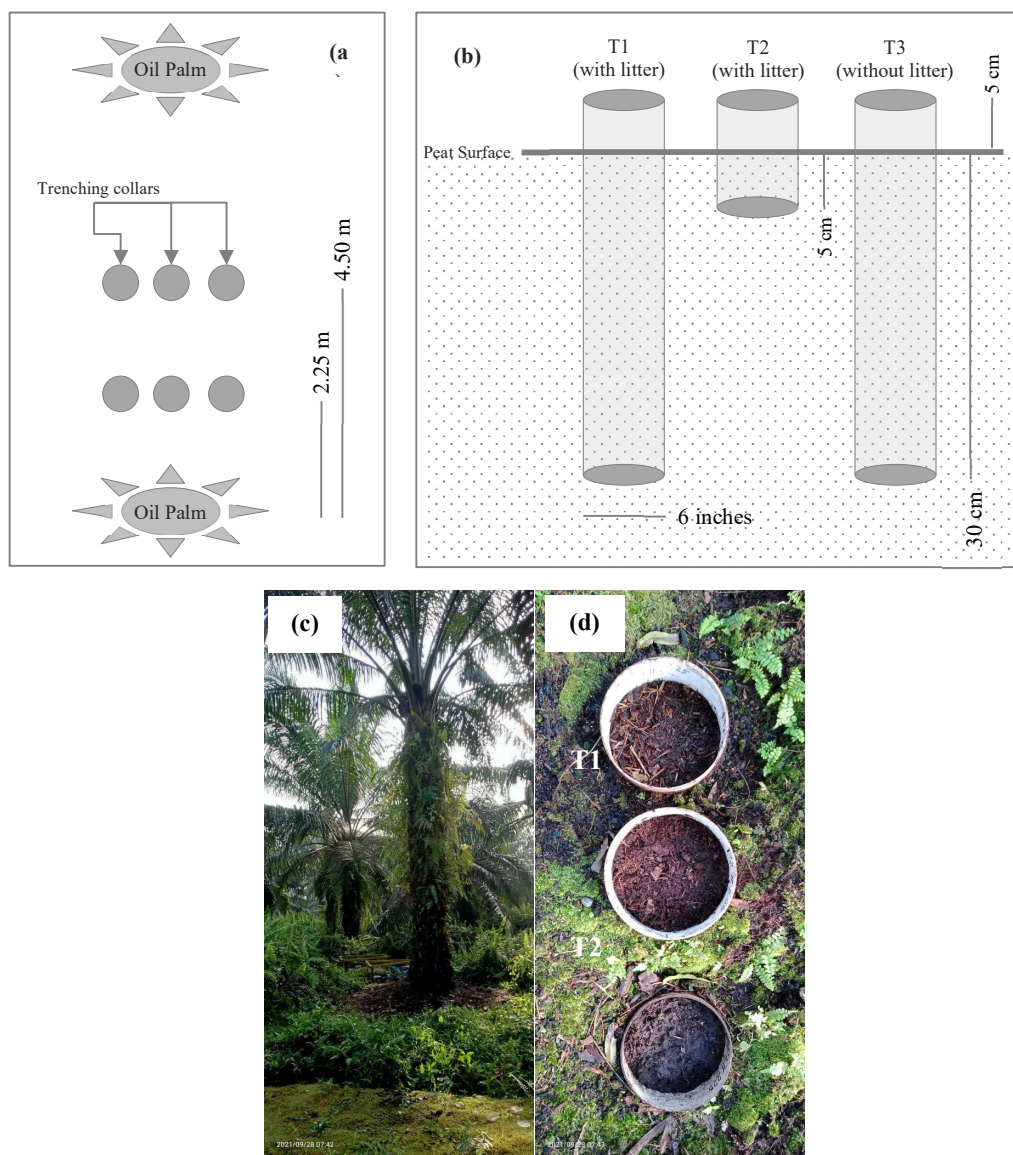


Figure 2. Experimental design of the study: (a) sampling location of trenching collars, (b) the trenching collars design, (c) and (d) field photos depicting the location and design of the trenching collars.

The litter that originated from decomposed parts of fronds and understory cover was then inserted into the collars' headspace. T2 treatment represents total soil respiration ($R_t = R_p + R_l + R_r$). In this treatment, trenching collars of 10 cm long were inserted into the peat without cutting the root inside, leaving 5 cm height above the surface for litter. T3 treatment was considered heterotroph/peat respiration (R_p), was done by inserting 30 cm long trenching collar, cutting the root inside, and leaving 5 cm of the headspace unoccupied by litter. The entire weeds that grow inside the trenching collar were removed in the initial and during the research. The litter respiration (R_l) was calculated by subtracting T1 with T3. Measurements

were taken at a depth of 30 cm due to the concentration of tertiary root biomass in this area (Khalid et al., 1999). CO_2 flux was measured consistently every 1 second for 2 minutes in the morning between 8.00–10.00 a.m., using the close chamber method with a portable Infrared Gas tool Analyzer (IRGA) LICOR Li-830. The observation was executed periodically between the 25th–28th once every month for 13 months from May 2020 to May 2021 (Figure 3). From this time range, a total of 120 measurement data were obtained. Other environmental parameters were measured simultaneously: peat and air temperature, chamber temperature, headspace's height level, and the groundwater table (water table level/GWL).



Figure 3. Measurement of CO_2 flux at the study site using a portable LI-COR 830 Gas Analyzer.

CO_2 flux was calculated following Madsen et al. (2009) equation:

$$F_c = \frac{V}{A} \frac{P_0}{R(T_0 + 273.15)} \frac{dC}{dT} \quad (1)$$

F_c : CO_2 flux ($\mu mol^{-1} m^{-2} s^{-1}$); V : chamber volume (m^3); A : chamber area (m^2); P_0 : initial atmospheric pressure; R : gas constant ($8.314 Pa m^3 K^{-1} mol^{-1}$); T_0 : air temperature inside the chamber; dC/dT : the change of CO_2 concentration per unit time ($mol ppm m^{-2} sec^{-1}$).

Statistical analyses

Datasets collection and compilation were conducted using Microsoft Excel; meanwhile, statistical analyses were done using Minitab 19. Prior to the analysis, all outliers (entire and subsequent datasets) were removed. The sqrt-transformation was employed to the CO_2 flux to normalize its distribution after being tested using Kolmogorov-Smirnov normality test. The relationship between CO_2 efflux and several environmental factors was assessed by applying linear regression (LR), multiple linear regression (MLR), Pearson correlation (R_p), and Spearman correlation (R_s). Meanwhile, the mean and median differences of environmental variables and CO_2 fluxes at each treatment, distance, and season were evaluated using the nonparametric Kruskal-Wallis test, continued by Mann-Whitney test at 99% confidence interval.

Results and Discussion

Seasonal and spatial change on environmental variables

The annual rainfall collected at the weather station of PT KTU from May 2020 to April 2021 is 2,045 mm per year, averaging around 170.4 mm per month. The difference between the dry and rainy seasons is not very clear, which is typical for tropical climates. The relatively dry and firm months are only January and February 2021. The number of rainy days varies between 12 days month⁻¹ (June 2020), and the highest is 26 days month⁻¹ in November 2020, averaging around 16 days month⁻¹.

The trends and magnitudes of soil and air temperatures are relatively similar during the observations, accounted at the range of 23 to 28 °C. During the study from May 2020 to May 2021, the mean air temperature and soil temperature were relatively almost similar and stable, varying between 25–28 °C. The lowest mean soil temperature in January 2021 is 23.31 °C, and the highest in July 2020 is 26.61 °C. The lowest mean air temperature in May 2020 and January 2021 is 24.31 °C and 23.31 °C, and the highest in July 2020 is 26.89 °C. During the 13 months of observation, the mean soil temperature was 25.50 °C, while the mean air temperature was 25.66 °C. According to the Kruskal-Wallis test, there are no significant means differences of soil and air

temperature in both distances ($p = 0.675$ and $p = 0.094$; respectively), as the previous reports denoted (Comeau et al., 2016). Seasonal change slightly

affected the mean of soil temperature ($p = 0.053$); however, having a strong impact on the mean difference of the air temperature ($p = 0.001$).

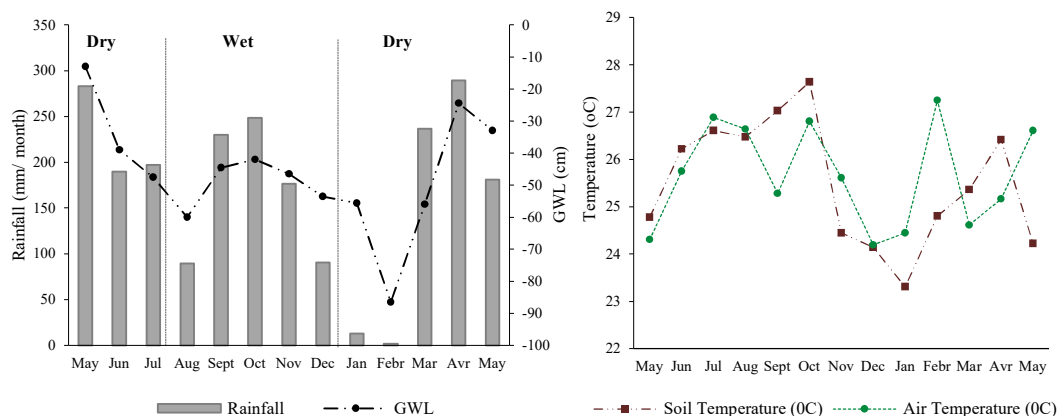


Figure 4. Annual rainfall, GWL, peat, and air temperature in the study area. Annual rainfall was collected at PT KTU's weather station; meanwhile, GWL, peat, and air temperature were measured simultaneously with CO_2 flux.

GWL was exhibited variation that seemingly related to the rainfall (Figure 4). The lowest GWL was around 10 cm from the soil surface in May 2020, then increased to around 60 cm until August 2020. A relatively stable GWL was observed for the next five months in the range of around 40 to 60 cm from the peat surface. That level was increased to 85 cm in February 2021 and then decreased to 20 to 30 cm in April and May 2021. The highest GWL (± 86.5 cm) occurred in February 2021, also indicated by very low rainfall at the beginning of the dry season. On the contrary, the highest rainfall recorded in both months (283.2 mm and 289.4 mm, respectively) also marked the lowest GWL in May 2020 and April 2021. The normal curve of GWL frequency distribution apparently follows a similar pattern in both distances from the oil palm tree. The contrary result was observed using season separation. However, means GWL were not significantly different either in both distances or seasons (Kruskal-Wallis: $p = 0.458$ and $p = 0.175$; respectively).

Spatiotemporal variability in peat and litter respiration

The importance of seasonal change governing total, peat, and litter respiration is demonstrated in this study. The monthly respiration in T1 (represent peat plus litter respiration) was fluctuated in a relatively similar trend in both distances following the seasonal pattern, as shown in Figure 5 and Figure 6. Higher CO_2 fluxes were recorded in the initial five months (dry season), then declined from October to December 2020 (rainy season). Moreover, CO_2 fluxes were increased again during the transitional and dry season (January 2021 to May 2021). Nonparametric analyses using Kruskal-Wallis, continued by Mann-Whitney test, revealed that means T1, T2, T3, T4, and all data

in the dry season were significantly different from those observed in the wet season ($p = 0.002$, $p = 0.006$, $p = 0.017$, $p = 0.042$, and $p < 0.001$; CI = 95%; respectively). On the other hand, the effects of distance from the oil palm tree were distinct, only observed at T1 ($p = 0.01$). In contrast, other treatments possessed similar means at both distances ($p > 0.05$).

Despite remarkable differences of T1 means recorded at both distances from the oil palm tree, a particular pattern variation was also observed, marked the contribution of litter to heterotrophic respiration on the onset of our measurement. CO_2 fluxes in T1 were recorded around 12.09 to 15.63 $\text{g CO}_2 \text{ m}^{-2} \text{ days}^{-1}$ (Figure 5 above) in the initial five months (May to September 2020; dry season). At the same period, the T1 respiration at the distance of 4.50 m was higher, in the range of 15.93 to 22.18 $\text{g CO}_2 \text{ m}^{-2} \text{ days}^{-1}$ (Figure 5c and 5d). Furthermore, the percentage of litter respiration (compared to T1) remained below the peat respiration at 2.25 m distant from the oil palm tree in the entire month. However, it accounted for more than 50% in 4.50 m at four initial observations (May to August 2020). The litter contributions in the following months were recorded relatively similar to the closest observation. Dariah et al. (2014) reported that the low total soil respiration in peat at the oil palm plantation is associated with low root densities; in this case, it is the farthest distance from the oil palm tree. Enhanced respiration observed at 4.5 m distant from the oil palm tree in the initial four months probably occurred due to the higher decomposition rate. In that distance, an improved microclimate occurs under fern *N. bisserata*, possibly promoting a higher abundance and more diversity of local macrofauna and microbial community compared to the closest distance (Prider and Facelli, 2004; Ashton-Butt et al., 2018; Yeo Joseph et al., 2020).

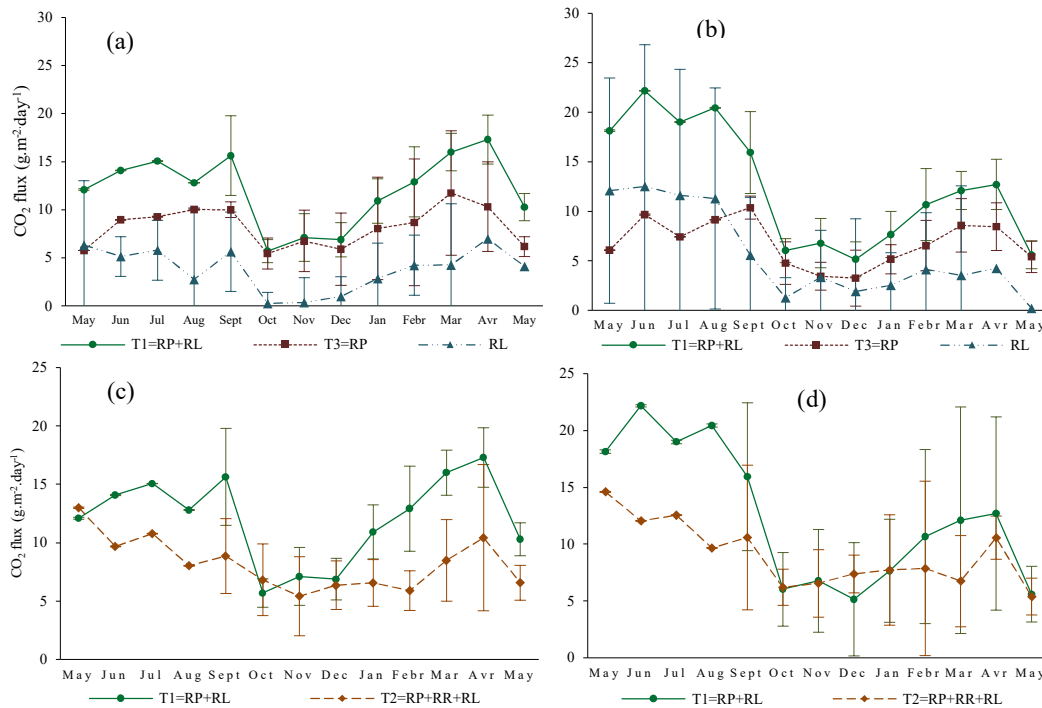


Figure 5. CO₂ efflux measured monthly at 2.25 m (left: a and c) and 4.50 m (right; b and d) from oil palm trees of T1, T2, T3, and T4 treatment from May 2020 to May 2021.

After high CO₂ production achieved on the fourth and fifth-month observations, steep declines of CO₂ fluxes were recorded at all treatments and distances from the oil palm tree. The cause was probably linked to the dynamic of water and O₂ availability. GWL had its lowest depth (-60 cm; Figure 4) during the first four months, indicating relatively lower water-filled pore spaces (WFPS) and higher O₂ availability inside the pores at the peat surface. Higher rainfall recorded in the following months (September and October; considered the peak of wet season) leads to the rise of GWL (-44.5 and -42 cm, respectively) and WFPS. Water-saturated pores limit O₂ supply, thereby shifting the peat oxygenation state from aerobic to anaerobic. This condition restricts O₂-dependent respiration, which generates lower CO₂ flux (Pezeshki and DeLaune, 2012; Busman et al., 2021).

Higher CO₂ fluxes exhibited at high rainfall rates (e.g., July 2020, March 2021, and April 2021; Figure 4) were attributed mainly to two reasons, i.e., enhanced microbial respiration and the water displacement of entrapped CO₂ gasses below the peat surface. As well as the rainfall, GWL (Figure 4) was ascended from its lowest depth (-86.50 cm) in February, culminating in April. Similar patterns were also observed on the respiration in both distances (Figure 5). Although the rainfall rate increased, the soil surface is still aerobic due to lower GWL depth. An increase in rainfall rates increases the soil moisture in the peat surface, which is considered favorable for microbial respiration. Furthermore, the displacement trends were

strengthened by low infiltration rates and hydraulic conductivity of compacted peat, which occurs mainly in drained and cultivated peatland (Melling and Henson, 2011; Kurnianto et al., 2019; Busman et al., 2021).

This study also captured the specific role of litter to peat/heterotrophic respiration during high monthly rainfall, which was subsequently affected by site-specific. As stated before, there were extreme dips in CO₂ fluxes observed during the fourth and fifth months. These changes occurred particularly around September-October 2020 in 2.25 m and August-October 2020 in 4.5 m for T1 and T4 treatments. Meanwhile, T2 and T3 treatments at both distances were similar to previous treatments located at a 2.25 m distance from the oil palm tree. According to Figure 5, the slope steepness in the entire T3 treatment (both distances) was relatively lower than T4, indicating the heterotrophic/peat respiration dynamics in that particular period was attributed more to litter respiration. The steepness on the T2 treatment was much flatter, suggesting a higher portion of a relatively stable root-related respiration obscured the litter respiration effect in total respiration. Since a lack of technical explanation directly related to litter contributed to peat respiration was found in this specific time range, we assumed that the major driven factor was chiefly associated with decomposition rate of fern's detrital material than pruned fronds. Fronds had a relatively high lignin content. Its main component, such as leaflet, rachis, and fronds,

accounted for 249.6-521.6, 209.6, and 224.5-607.6 g kg⁻¹ lignin, whereas having N content of 1.3-2.3, 0.4, and 0.2-1.2 %, respectively (Khalid et al., 2000; Pulunggono et al., 2019). The entire parts required more than eight months to lose around 60-86, 58, and 65-68%, respectively, of their original mass (Moradi et al., 2014; Pulunggono et al., 2019). Otherwise, as polypod ferns, *Nephrolepis* sp. had lower lignin:N ratio (Amatangelo and Vitousek, 2009) than oil palm fronds, which was induced a higher decomposition rate (Talbot et al., 2011).

Peat respiration (Rp) tended to fluctuate with lower variation (Figure 5), except after the peak of the rainy season in October (Figures 5 and 8). The observed Rp at 2.25 m distances from oil palm trees ranging from 5.77 to 11.75 g CO₂ m⁻² day⁻¹, while a slightly lower value was recorded at 4.5 m, ranging from 5.40 to 10.37 g CO₂ m⁻² day⁻¹. Furthermore, Rl tended to be higher in the dry season and decreased in the rainy season, at a distance of 2.25 m ranging from 5.77 to 11.75 g CO₂ m⁻² day⁻¹, while CO₂ fluxes at a distance of 4.50 m from the palm oil tree ranged from 5.40–10.37 g CO₂ m⁻² day⁻¹. In the dry season, the mean litter respiration at a distance of 2.25 m and 4.5 m were 5.05 and 7.92 g CO₂ m⁻² day⁻¹, respectively, while in the rainy season was recorded at 2.39 and 3.12 g CO₂ m⁻² day⁻¹, respectively. The mean contribution of litter respiration was detected higher at the farthest distance from the oil palm tree than the closest observation. At the distance of 2.25 m from the palm tree, the mean total soil respiration was 12.06 g CO₂ m⁻² day⁻¹ which is consisted of 68% (8.24 g CO₂ m⁻² day⁻¹) peat (Rp) and root respiration (Rr), and 32% (3.84 g CO₂ m⁻² day⁻¹) litter respiration (Rl). Meanwhile, the mean total soil respiration at 4.5 m distance was higher (12.49 g CO₂ m⁻² day⁻¹), consisting of 56% (6.78 g CO₂ m⁻² day⁻¹) Rp and Rr, and 46% (5.71 g CO₂ m⁻² day⁻¹) Rl. As previously stated above, the high respiration rate at a distance of 4.50 m compared to a distance of 2.50 m was due to the high organic matter content at 4.50 m, which is a pile accumulating decomposed part of fronds, as well as supporting fern, like *Nephrolepis* sp. without being targeted to eradicate. In the study site, *N. bisserata* weeds were deliberately allowed to grow, especially outside the fertilizer circles, to maintain soil moisture and return soil organic matter. This condition creates a favorable condition for the decomposition process, enhancing heterotrophic respiration. Sabiham et al. (2012) stated that understory vegetation such as ferns (*Nephrolepis* sp) in oil palm plantations on peatlands could absorb CO₂ of around 9.75 tons ha⁻¹year⁻¹. Maintaining the growth of *N. biserrata* or moss weeds in natural conditions helps to keep soil conditions moist and avoid irreversible drying in peat, preventing fires and reducing CO₂ emissions (Sabiham et al., 2012).

The total respiration/Rt, which is the sum of soil respiration (Rp), litter respiration (Rl), and root respiration (Rr), were presented as T2. The CO₂ flux

in this treatment varied between 5,42 to 13.00 g CO₂ m⁻² days⁻¹ (averaged at 8.22 g CO₂ m⁻² days⁻¹) and ranging from 5.39 to 14.60 g CO₂ m⁻² days⁻¹ (averaged at 9.07 g CO₂ m⁻² days⁻¹) in the distances of 2.25 and 4.50, respectively (Figure 5). CO₂ fluxes measured at T2 in 2.25 m distance in May and October 2020 and at a distance of 4.50 m from October 2020 to January 2021 were exhibited higher than T1. However, mostly identified fluxes showed contrary results. Theoretically, the measurement of CO₂ flux in T2 should be higher than in T1. The depth of T2's trenching collar inserted below the soil surface was shallower than T1 (5 cm compared to 30 cm), assuring no palm root was cut. Nevertheless, it is possible that the T2 trenching collar was undergone a leakage due to its limited length. This condition could lead to a diffusion of CO₂ flux out of the collar, resulting in lower measurement (Kutzbach et al., 2007). On the deep trenching collars (60 cm), Batubara et al. (2019) demonstrated that the mean annual CO₂ emission was lower than the shallower collar (20 cm deep).

The mean of Rp+Rl (T1) was recorded slightly higher at a distance of 4.5 m, although did not significantly different than the closer distance, accounting for 0.12 Mg CO₂ ha⁻¹ day⁻¹ (Figure 8). Oppositely, Rp was higher near the palm tree (0.08 Mg CO₂ ha⁻¹ day⁻¹) than at a farther distance (0.07 Mg CO₂ ha⁻¹ day⁻¹). On the other hand, the mean Rl was lower at a distance of 2.25 m (0.04 Mg CO₂ ha⁻¹ day⁻¹) than at 4.50 m (0.06 Mg CO₂ ha⁻¹ day⁻¹). These results probably occur due to the contribution of root respiration close to the palm tree, which is more significant than 4.5 m (Dariah et al., 2014). The tree spacing between oil palm trees is generally nine meters, and the distance of 4.5 m is considered the midpoint. The abundance and roots density in this site were considered minimal. According to Dariah et al. (2014), the effect of roots could be negligible at a distance of more than 3 m. Putri (2015) also reported similar results, who found that the density of oil palm roots decreased with increasing distance from oil palm trees and soil depth. The mean soil respiration (Rp) and root respiration (Rr) that presents as T1 of drained tropical peat in mature oil palm plantation aged 14 years for 13 months of observation were 0.07–0.08 Mg CO₂ ha⁻¹ day⁻¹ or 24.8–30.1 Mg CO₂ ha⁻¹ year⁻¹ while respiration from litter decomposition (Rl) was 0.04–0.06 Mg CO₂ ha⁻¹ day⁻¹ or 14.0–20.8 Mg CO₂ ha⁻¹ year⁻¹. The results of this measurement were slightly lower than those reported by Dariah et al. (2014), who found CO₂ emissions at a distance of 3.0 m from oil palm trees that are not affected by root respiration are 38.2 ± 9.5 and 34.1 ± 15.9 Mg CO₂ ha⁻¹ year⁻¹ on six years and 15 years old oil palm plantations, respectively. In addition, they stated that the measurement of CO₂ flux over a distance of 3.0 m from the oil palm tree could represent heterotrophic respiration. Marwanto and Agus (2013) reported that the mean 46 ± 30 Mg CO₂ ha⁻¹ year⁻¹ emanates from peat at 15 years old oil palm plantations in Jambi.

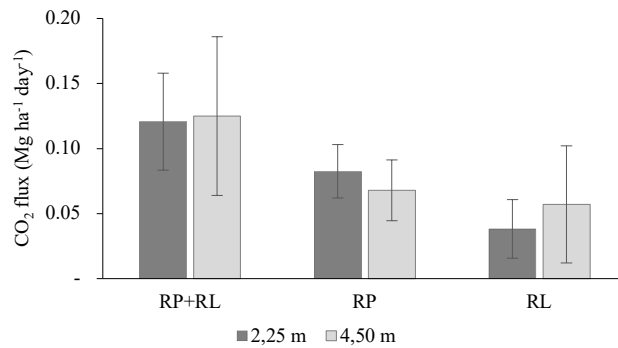


Figure 6. Partition of peat respiration (RP) and litter respiration (RL) at a distance of 2.25 m and 4.50 m from the palm tree.

Meanwhile, Marwanto et al. (2019) who measured CO₂ fluxes at various peat depths of 10, 30, and 50 cm in 14 years old oil palm plantations, showed that as the peat depth increases, the annual CO₂ fluxes also increase, which were 1032, 1209, 2304 Mg CO₂ m⁻¹ h⁻¹, respectively. Meanwhile, Batubara (2019) and Batubara et al. (2019) reported that in six years old oil palm plantations on peatlands, Muaro Jambi Regency, Jambi Province, mean annual CO₂ emissions from soil respiration ranged from 39.3 ± 2.2 Mg CO₂ ha⁻¹ year⁻¹ on a deep collar (60 cm depth) to 55.5 ± 2.6 Mg CO₂ ha⁻¹ year⁻¹ on the shallower collars (20 cm depth).

Measurement of soil respiration partition in afforested temperate peatland in South-west Ireland using the trenching method was reported by Jovani-Sancho et al. (2018). Mean root respiration was 44% of total soil respiration, varying between 1.10 and 2.05 Mg CO₂ ha⁻¹ year⁻¹. Heterotrophic respiration consisted of peat and litter respiration, accounted for 35 and 21% of the total soil respiration. Peat respiration varied between 0.77-1.49 Mg CO₂ ha⁻¹ year⁻¹, while litter respiration varied between 0.51-1.01 Mg CO₂ ha⁻¹ year⁻¹. Compared to the temperate peatland, annual litter respiration observed in our study is much higher (14.6 to 21.9 Mg CO₂ ha⁻¹). On the other hand, our value was 2.60 to 6.25 times higher than pruned frond litter respiration in tropical peatland reported by Wakhid and Hirano (2021). Moreover, CO₂ flux from frond piles and understory cover separately obtained by Manning et al. (2019) in tropical peat accounted 9.42 to 22.81 times lower than this study. Both previous authors used different sources, fronds (Wakhid and Hirano, 2021), both fronds pile and understory cover were measured separately at their specific site (Manning et al., 2019). For methods, litter bag method, C-reduction by time, loss of ignition (Wakhid and Hirano, 2021), static chamber approach using the collar and measurement tool (Manning et al., 2019), Thermolyne type 48000 muffle furnace (Wakhid and Hirano, 2021), Thermo TraceGC Ultra Gas Chromatograph (Manning et al., 2019). This study was used heterogeneous/mixed

fronds with decomposed understory cover, static chamber approach through the trenching collar, measurement using IRGA LICOR Li-830. Hence, this study is considered the pioneering research that exploited the heterogeneous litter contribution to total and heterotrophic respiration at tropical cultivated peatland.

The influence of environmental factors on CO₂ efflux

In agreement with the previous study conducted by Husnain et al. (2014), Marwanto and Agus (2014), and Batubara et al. (2019) in tropical peatland at oil palm plantations, the entire LR of CO₂ flux from the entire treatment and all data exhibited no strong relationship with GWL, peat, and air temperature (Figure 9). The low coefficient of determinations using LR did not surprise us since LR contains many confounding factors (i.e., dependency on the normal distribution of error/residual, heteroscedasticity, and collinearity) that restricts its capability to model CO₂ flux accurately. Furthermore, CO₂ flux relied on root and microbial respiration, which also had high variability (Nurzakiah et al., 2021). In order to capture specific role between CO₂ flux with environmental variables, many recurrent reports developed more sophisticated statistical models, e.g. hierarchical Bayesian regression (Ishikura et al., 2017), machine learning tree regression (Meiling et al., 2005), Gaussian linear mixed effect models (Manning et al., 2019), and backward elimination stepwise regression (Dhandapani et al., 2020) to predict CO₂ flux in tropical peatland. Nevertheless, besides only focusing on describing Rt, Rp, and RL, this paper preserves linear regression (LR and MLR) and correlation (Rp and Rs) to initially explain the general relationship between CO₂ flux and other environmental variables. Meanwhile, some complex statistical models will be explored in future manuscripts.

In Figure 7, CO₂ flux tended to increase along with the increase of soil temperature; however, an opposite trend was observed in relation to air

temperature. Under matured oil palm plantations, the slight variation of air and peat temperature occurred due to the densely overlapped leaves that spread across each other, hampering its effects on heterotrophic CO₂ flux (Jauhainen et al., 2014). Hence, CO₂ flux is mainly governed by soil moisture or WFPS, which is closely related to GWL (Jauhainen et al., 2008). LR in Figure 7 showed that maximum R² between CO₂ flux and GWL was reached at T2 (R² = 0.1211), representing total respiration, which consisted of heterotrophic (litter and peat) and autotrophic (root) respiration. However, in other treatments (T1, T3, T4, and all data), GWL had an invariable pattern with CO₂

fluxes. This is indicated that the relationship of total respiration and GWL were linked to root respiration. Generally, optimum peat and air temperature for respiration were achieved, ranging around 26 to 27 °C and 25 to 26 °C, respectively, as shown by each treatment's peak and concentration of CO₂ efflux data. A similar condition also coincided with GWL somewhere in between -60 to -40 cm. These results are in the range of -80 and -40 cm GWL in tropical peat reported by Ishikura et al. (2017), similar to WFPS between 0.54 to 0.75 m³ m⁻³. This condition was recognized as an optimum soil-water condition for aerobic mineralization (Linn and Doran, 1984).

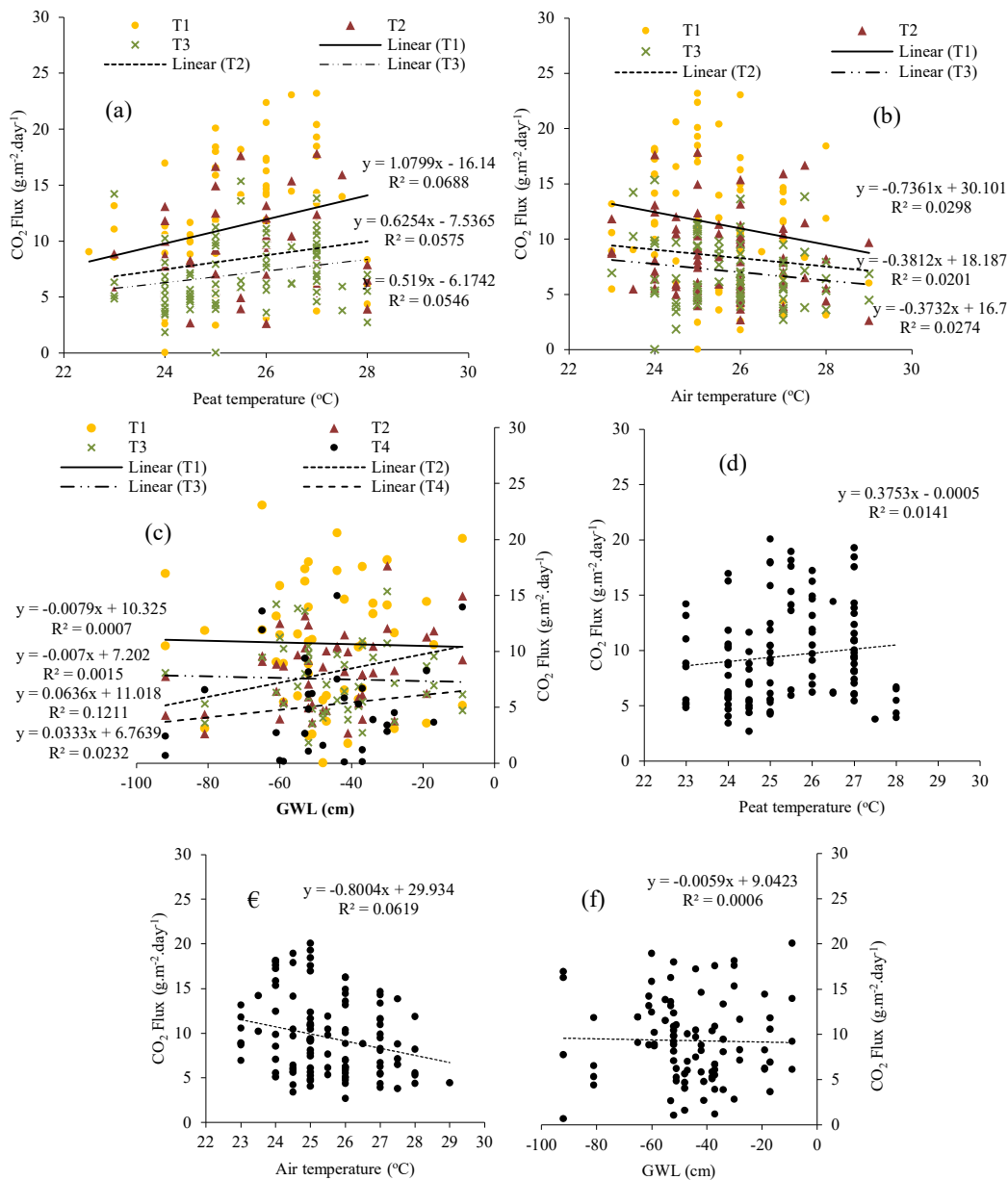


Figure 7. Linear regression between CO₂ fluxes in each treatment (T1, T2, T3, T4: a, b, c) and all data (d, e, f) with GWL, peat and air temperature.

A remarkable improvement was recorded regarding the relationship between CO₂ fluxes with distance, air and soil temperature using Spearman and Pearson correlation analyses (Rs and Rp; respectively; Table 2). Using all datasets, CO₂ flux gained the highest significant negative correlation with distance (Rs, Rp = -0.332; $p < 0.05$); moreover, it also marked similar relation in T1 and T3 datasets. CO₂ flux was denoted a significant negative relationship with air temperature; meanwhile, the opposite result was observed concerning the soil temperature. Previous researchers reported similar results, such as Meiling et al. (2005), Ali et al. (2006), and Ishikura et al. (2018) in tropical peatland and Berglund et al. (2010) and Kechavarzi et al. (2010) in temperate peatland. Although the relationship between CO₂ flux and climatic-related variables (soil and air temperature) exhibited a broad strength and p -value, their direction (positive or negative correlation) remained consistent. This pattern suggested the importance of climate variables controlling respiration in peat, regardless of the high variability presence among CO₂ flux datasets. GWL showed a notable positive relationship with CO₂ flux, observed in T3 (Table 2), indicating that the total respiration decreases with the deepening of GWL. The increase of GWL means a shallower water level from the surface, indicating the increase of WFPS at the peat

surface. Soil microbial and root activities could be enhanced by a higher WFPS level at a particular threshold. However, their respiration was found hampered under excessive WFPS (Kechavarzi et al., 2010). Some reports conducted in tropical peatland found that higher WFPS owing to the rise of GWL could increase CO₂ flux during the rewetting period (Ishikura et al., 2017). However, this finding was opposed by Couwenberg et al. (2010), Marwanto and Agus (2014), and Ishikura et al. (2018) studies, who suggested the CO₂ flux increased along with the deepening of GWL. These contradictory results might arise from various states of discontinuing capillary pores in peat (Ishikura et al., 2017). Discontinued capillary pores restrict the GWL capability to control WFPS or soil moisture at the peat surface. Macropores were commonly established by tropical peatlands' coarse woody material (Sabiham, 1989), which had poor capillary continuity compared to other peat types (Gabriel et al., 2018). Under natural tropical forest, Hirano et al. 2009 reported daily mean of peat respiration rate exhibited a significant linear relationship with GWL above -20 cm. Furthermore, deeper GWL level showed insignificant relation with CO₂ flux, apparently consistent with our study in a matured oil palm plantation, which mainly consisted of GWL deeper than -20 cm (Figure 7).

Table 2. Correlation (Rs and Rp) between CO₂ flux and each environmental variable.

| | Spearman Correlation (Rs) | | | | Pearson Correlation (Rp) | | | |
|--------------------------|---------------------------|--------------|---------------|--------|--------------------------|--------|---------------|--------------|
| | Distance | T peat | T air | GWL | Distance | T peat | T air | GWL |
| All_CO ₂ flux | -0.332 | 0.190 | -0.234 | 0.002 | -0.322 | 0.148 | -0.243 | 0.031 |
| T1_CO ₂ flux | -0.433 | 0.251 | -0.196 | -0.04 | -0.401 | 0.197 | -0.213 | -0.026 |
| T2_CO ₂ flux | -0.115 | 0.221 | -0.246 | 0.233 | -0.128 | 0.19 | -0.252 | 0.348 |
| T3_CO ₂ flux | -0.333 | 0.267 | -0.263 | -0.102 | -0.348 | 0.187 | -0.262 | -0.038 |
| T4_CO ₂ flux | -0.185 | | | 0.091 | -0.064 | | | 0.152 |

Note: number in **bold style** indicated significance in $\alpha = 0.05$.

MLR (Table 3) revealed that climatic-related variables such as season, air, and peat temperature were always presented as significant determinants for CO₂ fluxes in the entire treatment (T1, T2, T3, and all data), except for T4. The statistic for T4 treatment was negligible than others due to an incomparable amount of determinant variables (without air and soil temperature; $R^2 = 0.1419$). Moreover, GWL was stood as a remarkable predictor for CO₂ flux in T3; meanwhile, distance from the oil palm tree was detected notably governed CO₂ flux in T1, T3, and all data. In general, our finding is consistent with Meiling et al. (2005), which also attributed the climatic condition such as RH and peat temperature at 10 cm depth, besides the WFPS as the most critical variables controlling CO₂ flux in oil palm plantation. In other land uses, Hirano et al. (2009) also found that temperature had a greater effect dictating CO₂ flux than GWL. Similar to the previous LR using treatment

separation, very weak relationship between GWL, air and peat temperature with CO₂ fluxes were also shown by distance from the oil palm tree and season separation (Figure 8), which comes from the high variability of the data. A slightly higher relationship was observed at the dry season between CO₂ flux with air temperature ($R^2 = 0.1393$) compared to others ($R^2 < 0.01$). The linear relationships were also exhibited a similar pattern to those in treatment separation. Both CO₂ fluxes in the distances from the oil palm tree and season were tended to increase with the increasing peat temperature; meanwhile, opposite trends were recorded regarding the effects of air temperature. Correlation between CO₂ fluxes and several environmental variables based on the distance from the oil palm tree and season (Table 4) seemingly demonstrates more satisfactory results. Consistent with the previous separation, their direction remained the same, despite the significant differences.

Table 3. Regression equation for CO₂ fluxes based on treatment.

| Treatment | Categorical Separator | | Regression Equation | | | | R ² |
|---------------------------------|-----------------------|------------|---------------------|--------------|-----------------|-----------------|----------------|
| | Distance | Season | Intercept | T Peat | T Air | GWL | |
| T1 | 2.25 | Dry | 22.10 | 1.574 | - 1.960 | - 0.0501 | 0.4872 |
| | 2.25 | Wet | 16.90 | 1.574 | - 1.960 | - 0.0501 | |
| | 4.50 | Dry | 18.40 | 1.574 | - 1.960 | - 0.0501 | |
| | 4.50 | Wet | 13.20 | 1.574 | - 1.960 | - 0.0501 | |
| T2 | 2.25 | Dry | 19.30 | 0.892 | - 1.206 | 0.0415 | 0.3889 |
| | 2.25 | Wet | 16.84 | 0.892 | - 1.206 | 0.0415 | |
| | 4.50 | Dry | 19.07 | 0.892 | - 1.206 | 0.0415 | |
| | 4.50 | Wet | 16.61 | 0.892 | - 1.206 | 0.0415 | |
| T3 | 2.25 | Dry | 13.86 | 1.079 | - 1.327 | - 0.0532 | 0.4393 |
| | 2.25 | Wet | 11.54 | 1.079 | - 1.327 | - 0.0532 | |
| | 4.50 | Dry | 11.82 | 1.079 | - 1.327 | - 0.0532 | |
| | 4.50 | Wet | 9.49 | 1.079 | - 1.327 | - 0.0532 | |
| T4 | 2.25 | Dry | 7.62 | | | 0.0323 | 0.1419 |
| | 2.25 | Wet | 4.52 | | | 0.0323 | |
| | 4.50 | Dry | 7.87 | | | 0.0323 | |
| | 4.50 | Wet | 4.77 | | | 0.0323 | |
| All (SQRT CO ₂ flux) | 2.25 | Dry | 4.30 | 0.2112 | - 0.2567 | - 0.00458 | 0.3778 |
| | 2.25 | Wet | 3.71 | 0.2112 | - 0.2567 | - 0.00458 | |
| | 4.50 | Dry | 3.89 | 0.2112 | - 0.2567 | - 0.00458 | |
| | 4.50 | Wet | 3.30 | 0.2112 | - 0.2567 | - 0.00458 | |

Note: numbers and variables in **bold style** indicated significance in $\alpha = 0.05$

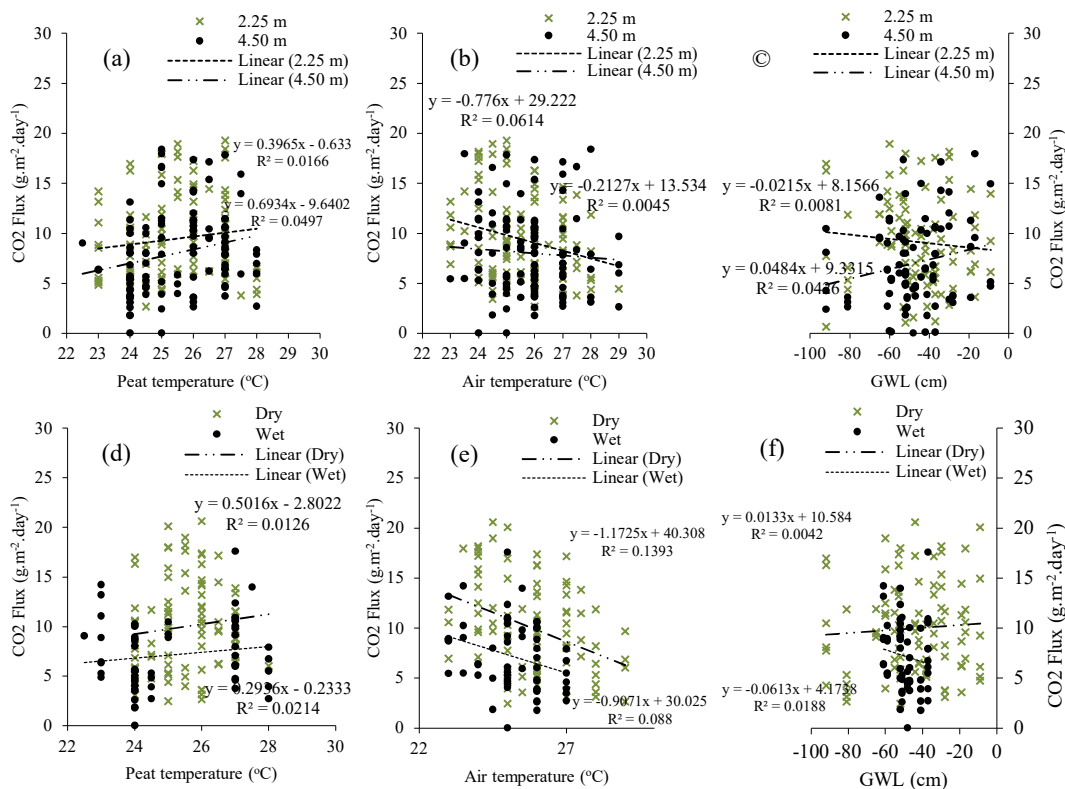


Figure 8. Linear regression between CO₂ fluxes with GWL, peat and air temperature based on distance from the oil palm tree (a, b, c) and season (d, e, f).

CO₂ fluxes were significantly increased along with soil temperature at a 4.50 m distance from the oil palm tree. Meanwhile, contrasting results were denoted on air temperature located at 2.25 m from the oil palm tree. As previously noted, there are no significant means differences of peat and air temperature based on the distance from the oil palm tree (Kruskal-Wallis: $p = 0.673$; $p = 0.225$; respectively), which seems to have an inconsistent interpretation with the finding in Table 4. The dynamic of air temperature was mostly related to atmospheric variation at the farthest distance from

the oil palm tree, 4.50 m in our case, which had the lowest shade from palm leaves.

The opposite condition was obtained in the full shadowed site at the nearest distance, having more stable and less disturbance for air temperature. This condition may lead to lower strength and insignificant correlation at 4.50 m distance from the oil palm tree than the nearest distance. On the other hand, soil temperature at the closest distance was more susceptible to disturbance due to minimum vegetation cover.

Table 4. Correlation (Rs and Rp) between CO₂ flux and each environmental variable.

| | Spearman Correlation (Rs) | | | | Pearson Correlation (Rp) | | | |
|----------------------------|---------------------------|--------------|---------------|---------------|--------------------------|--------------|---------------|---------------|
| | Distance | T peat | T air | GWL | Distance | T peat | T air | GWL |
| 2.25m CO ₂ flux | | 0.111 | -0.278 | -0.187 | | 0.062 | -0.271 | -0.149 |
| 4.50m CO ₂ flux | | 0.303 | -0.135 | 0.138 | | 0.272 | -0.137 | 0.217 |
| Dry CO ₂ flux | -0.332 | 0.135 | -0.359 | 0.021 | -0.314 | 0.112 | -0.373 | 0.065 |
| Wet CO ₂ flux | -0.335 | 0.062 | -0.309 | -0.286 | -0.319 | 0.101 | -0.313 | -0.240 |

Note: number in **bold style** indicated significance in $\alpha = 0.05$

Fronds and dense understory cover around the collar at 4.50 m distance from the oil palm tree prevent further direct exposure from the atmosphere, stabilizing the soil temperature, thereby generating a more significant relationship with CO₂ flux. During the dry season, CO₂ fluxes significantly showed a negative correlation with air temperature and distance from the oil palm tree. A similar relationship was also observed in the wet season with an addition of GWL (Table 4). Previous studies highlighted the critical role of GWL in governing CO₂ flux, which enlarges at a closer depth to peat surface, especially during the rewetting period (T3 treatment) (Hirano et al., 2009; Ishikura et al., 2017). The correlation in Table 4 exhibited a significantly opposite direction, which was consistent with Couwenberg et al. (2010), Sundari et al. (2012), Marwanto and Agus (2014), Itoh et al. (2017), and Ishikura et al. (2018). The GWL distribution in Figure 8 can explain this condition. Clear differences in GWL

distribution based on season were observed in relation to CO₂ fluxes. GWL was concentrated at -40 to -60 cm depth at the wet season, emitted around 2.5 to 12.5 g CO₂ m⁻² day⁻¹. Meanwhile, a wider range of CO₂ flux (2.5 to 20 g CO₂ m⁻² day⁻¹) emanates from a broader GWL range (-10 to -90 cm depth) during the dry season. These conditions result in a strong correlation during the wet season while lowering the correlation during the dry season.

Table 5 presented multiple linear regression based on distance from the oil palm tree and season. The entire variables (season, GWL, soil, and air temperature) were significant determinants for CO₂ flux at a 2.25 m distance from the oil palm tree. Meanwhile, GWL did not present as a significant determinant from the equation at 4.50 m distance, dry and wet season. As predicted before, the climatic variables exhibited a significant effect to determine the CO₂ fluxes at the entire datasets.

Table 5. The regression equation for CO₂ fluxes based on the distance from oil palm tree and season

| Categorical Separator | Regression Equation | | | | R ² | |
|------------------------------------|---------------------|--------|--------------|---------------|----------------|--------|
| | Intercept | T peat | T air | GWL | | |
| <u>Season</u> | | | | | | |
| 2.25 | Dry | 21.15 | 1.113 | -1.609 | -0.0675 | 0.3762 |
| | Wet | 17.25 | 1.113 | -1.609 | -0.0675 | |
| 4.5 | Dry | 10.87 | 1.234 | -1.281 | 0.0151 | 0.2880 |
| | Wet | 8.16 | 1.234 | -1.281 | 0.0151 | |
| <u>Distance from oil palm tree</u> | | | | | | |
| Dry | 2.25 | 11.30 | 1.505 | -1.519 | -0.0182 | 0.2966 |
| | 4.50 | 8.80 | 1.505 | -1.519 | -0.0182 | |
| Wet | 2.25 | 12.80 | 0.982 | -1.334 | -0.0797 | 0.3254 |
| | 4.50 | 11.20 | 0.982 | -1.334 | -0.0797 | |

Note: numbers and variables in **bold style** indicated significance in $\alpha=0.05$.

Conclusion

This research demonstrated the important contribution of litter to peat/heterotrophic and total respiration. One

year observation resulted in the mean peat and root respiration of 0.07–0.08 Mg CO₂ ha⁻¹ day⁻¹, while litter respiration was 0.04–0.06 Mg CO₂ ha⁻¹ day⁻¹. The litter contribution to total peat respiration in peat was

relatively higher in the peat at 4.45 m distant (46% or 5.71 g CO₂ m⁻² day⁻¹) than 2.5 m (32% or 3.84 g CO₂ m⁻² day⁻¹). The mean CO₂ fluxes of the entire treatment were remarkably different at each season, whereas only heterotrophic respiration (Rp + Rl) denoted a significant difference based on the distance from the oil palm tree. The means of Rt, Rp, and Rl were significantly different in the dry season than those recorded in the rainy season, whereas only Rp + Rl possessed remarkable means between both distances. The climatic variables (air and peat temperature) were significant determinants governing the peat and total respiration. Other variables are importantly related to CO₂ flux under a particular condition. Regarding the high variability of litter respiration in tropical peatland, more research must be conducted concerning its contribution to total and heterotrophic peat respiration.

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