Assessment of CO\textsubscript{2} flux from peat soil under simulated groundwater level and monthly rainfall for sustainable water management in a tropical oil palm plantation

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Abstract. Sustainable production of oil palm plantation in tropical peat land is determined by groundwater level and rainfall as the important factors controlling the carbon balance. It is not easy to set up a stable groundwater level (GWL) in the field and even more impossible for the monthly rainfall (MRF) to get CO\textsubscript{2} flux data as the basis for determining technical aspects of water management. This research was aimed to obtain basic CO\textsubscript{2} flux data under simulated stable GWL and MRF from tropical peat materials of an Indonesian oil palm plantation. The experiment was conducted by applying CRD with those 2 factors as the treatments for 3 months period of greenhouse experimentation. There was no significant interaction effect of the GWL and MRF treatments. The single effect of GWL treatment at −40 cm produced the significant lowest monthly CO\textsubscript{2} flux with an average of 18.26 t.ha\textsuperscript{-1}.year\textsuperscript{-1} after 3 months experimentation, while that of MRF at 300 mm.month\textsuperscript{-1} resulted in the significant lowest CO\textsubscript{2} flux of 24 t.ha\textsuperscript{-1}.year\textsuperscript{-1} after 2 months experimentation. It can be recommended that the GWL should be set up in the field at around −40 cm to get the best control on CO\textsubscript{2} flux.

1. Introduction
Peatlands are wetlands and carbon stores of global importance. Peat with a thickness of 100 cm is estimated to have the potential to contain carbon reserves of 400–700 t.ha\textsuperscript{-1} [1]. Peatlands are characterized by acidic groundwater conditions, high waterlogging, low oxygen levels, and low nutrient status [2]. The total area of peatland in Indonesia in 2019 was 13,430,517 Ha and is mainly spread over four islands. Sumatra Island has the most extensive peatlands, which are around 5,850,561 Ha (43.56%), followed by Kalimantan Island of around 4,543,362 Ha (33.83%), Papua Island of around 3,011,811 Ha (22.43%), and Sulawesi Island of around 24,783 Ha (0.18%) [3].

The present land use of peatlands is not only as forest areas but is also widely used for agriculture and plantations. Miettinen \textit{et al.} [4] estimated that 0.4 million Ha of peat swamp-forest area in Southeast Asia were converted to industrial oil palm plantations between 2007 and 2015. Szajdak and Szatylowicz [5] stated that the use of peatland for agriculture and other forms of exploitation over a long period of time can lead to a decline groundwater level, increased aeration, land subsidence, and carbon emissions. Organic carbon in the soil can be lost in the form of carbon dioxide gas (CO\textsubscript{2}) and methane (CH\textsubscript{4}) that is released into the atmosphere and can cause greenhouse effect.
Emission of CO$_2$ from peatlands that are converted into other uses in Southeast Asia contributes substantially to the global anthropogenic CO$_2$ emissions [6]. It can occur as a result of the construction of drainage networks, in the context of conversion to agricultural land, as a consequence of a decrease in organic matter input and an increase in the rate of decomposition of peat matter [7].

Groundwater level (GWL) affects the storage and release of soil carbon from tropical peatland ecosystems [8]. It is determined by rainfall, evapotranspiration, and drainage that subsequently affects the decomposition and maturity of the peat matter [9]. In dry season CO$_2$ emissions will increase due to the decreasing GWL. Drainage also reduces the GWL of peatlands and allows for a greater absorption of rainwater. Factors that affect CO$_2$ emissions include air temperature and rainfall. Increasing air temperature and decreasing rainfall accelerate the process of peat decomposition, thereby increases CO$_2$ emissions. Thus, GWL and rainfall are the two important factors affecting CO$_2$ emissions from cultivated peatlands. However, it is not easy to set up a stable GWL in the field and even more impossible for the monthly rainfall (MRF) to get CO$_2$ flux data as the basis for determining technical aspects of water management. This research was aimed to obtain basic CO$_2$ flux data under simulated stable GWL and MRF from peat materials of an Indonesian oil palm plantation.

2. Methodology

Columns of peat material of the top 100 cm layer were sampled from peatland area of an oil palm plantation in Siak Regency, Riau Province, Indonesia using PVC pipes of 12.7 cm diameter and 110 cm length that were perforated at positions or with hole number as depicted in Fig. 1 and 2, which were then transported with care to the greenhouse and placed in glass containment of 30 cm x 30 cm base dimension. The experiment was carried out at the greenhouse of the Department of Soil Sciences and Land Resources, IPB University by applying completely randomized design (CRD) with simulated stable GWL and MRF as the treatments. The GWL and MRF treatments consisted respectively of 3 and 4 levels with 3 replications, i.e. −40 (L1), −60 (L2), and −80 (L3) cm for GWL (Fig. 1 and 2), while for MRF were of 30 (R1); 120 (R2); 210 (R3); and 300 (R4) mm.month$^{-1}$ (Table 1).

![Figure 1. Design of the groundwater level simulation.](image)

![Figure 2. Pore hole design of the pipes.](image)

| Treatment$^a$ (mm.month$^{-1}$) | Volume of water$^b$ |
|-------------------------------|---------------------|
| 0.381                         | 95                  |
| 1.524                         | 381                 |
| 2.667                         | 667                 |
| 3.810                         | 953                 |

$^a$based on the monthly rainfall at the peat material’s sampling area recorded using Automatic Weather Station (AWS) in year 2019 (min: 33.6 and max: 263.5 mm.month$^{-1}$).

$^b$Given by pouring exact volume of distilled water as the treatments into the peat columns.
The close chamber method was used to measure monthly CO₂ flux by measuring the accumulation or depletion of CO₂ in the main chamber that placed close above the peat column using portable infra-red gas analyzer (IRGA Li-Cor 830). The CO₂ level was measured every second and finished reading after 420 seconds. The CO₂ flux is calculated based on the following equation [10]:

\[ \frac{dc}{dt} = \frac{P h}{RT} \]

Where \( fc \) is the CO₂ flux (\( \mu \text{mol.m}^{-2}.\text{sec}^{-1} \)), \( P \) is the atmospheric pressure (Pa), \( h \) is the close height (m), \( R \) is the gas constant (8.314 Pa.m³.K⁻¹.mol⁻¹), \( T \) is the absolute temperature (°K), and \( dC/dt \) is the linear change in CO₂ concentration over time. Measurement of the Month 0 experimentation was carried out before providing MRF simulation, but has been given stable GWL simulation treatment.

The experimental data were analyzed statistically using Analysis of Variance and Pearson correlation. For the treatment or treatments with significant effect further tests were carried out using the Duncan Multiple Range Test (DMRT) at 5% or 10% test level.

### 3. Results and Discussion

Greenhouse gases (GHG) are atmospheric constituents, both natural and anthropogenic, that can absorb and emit radiation at certain wavelengths in the terrestrial radiation spectrum emitted by the earth's surface, atmosphere, and clouds. The main greenhouse gases are CO₂, CH₄ and nitrous oxide (N₂O).

Carbon emissions are the result of oxidation of carbon-containing compounds. Carbon emissions in peat soils occur when the peat material is oxidized as a result of a decrease in the water table and decomposition of organic matter. [11] explained that greenhouse gas emissions could increase due to drainage. This is related to the oxidation-reduction of organic matter from the peat. Peat land drainage increases CO₂ emissions as a result of reduced organic matter input and increased rates of peat decomposition [12]. CO₂ emissions are related to the moisture condition of the peat soil. When soil moisture increases, CO₂ emission decreases and vice versa. Apart from soil moisture condition, CO₂ emissions are also affected by changes in land use and fires which are closely related to changes in water levels.

Based on the results of statistical analysis (not shown), there was no significant interaction effect between the GWL and MRF simulation treatments. This was presumably due to the differences in air temperatures during the 3 months period of measurement and in the height of the IRGA chamber from the surface of peat column due to subsidence for different GWL treatments (Fig. 1). Different levels of subsidence of the peat materials at the uppermost part of the peat column were observed. As a single factor, the GWL treatment resulted in significant effects at p<0.05 on CO₂ flux after Month 0 and Month 3 experimentation (Table 2), while that of the MRF treatment gave significant effect at p<0.1 only after Month 2 experimentation (Table 3).

### Table 2. Effects of simulated stable groundwater level (GWL) on CO₂ flux from column of peat material sampled from an oil palm plantation in Riau, Indonesia.

| Treatment | CO₂ flux (t ha⁻¹ year⁻¹) after experimentation period of |
|-----------|----------------------------------------------------------|
|           | Month 0 | Month 1 | Month 2 | Month 3 |
| GWL -40 cm | p=0.011 | p=0.005 | p=0.056 | p=0.001 |
| GWL -60 cm | 21.85ᵇᵃ | 23.01ᵇ | 19.21ᵇ | 18.26ᵇ |
| GWL -80 cm | 25.02ᵇ | 38.06ᵇᵃᵇ | 35.18ᵇᵃᵇ | 31.51ᵃ |

*Number followed by different letter is significantly different at 5% test level (p<0.05)
Table 2 shows that the ~40 cm GWL treatment produces the lowest CO$_2$ flux after Month 3 experimentation. This is because the ~40 cm GWL treatment provides the highest moisture condition and therefore results in the lowest CO$_2$ flux due to the lowest rate of aerobic decomposition processes occurring on the peat materials.

**Table 3.** Effects of simulated monthly rainfall (MRF) on CO$_2$ flux from column of peat material sampled from an oil palm plantation in Riau, Indonesia.

| Treatment          | CO$_2$ flux (t.ha$^{-1}$.year$^{-1}$) after experimentation period of |         |
|--------------------|---------------------------------------------------------------------|---------|
|                    | Month 1 $p=0.759$                                                  | Month 2* $p=0.093$ | Month 3 $p=0.800$ |
| MRF 30 mm.month$^{-1}$ | 45.19                                                              | 45.95$^a$ | 30.55 |
| MRF 120 mm.month$^{-1}$ | 35.69                                                              | 24.78$^b$ | 34.21 |
| MRF 210 mm.month$^{-1}$ | 36.52                                                              | 24.00$^b$ | 27.47 |
| MRF 300 mm.month$^{-1}$ | 36.45                                                              |          | 32.33 |

$^a$Number followed by different letter is significantly different at 10% test level ($p<0.10$)

The accumulation and loss of tropical peat is controlled by GWL dynamics. If the GWL is further away from the land surface, the aerobic decomposition of the peat material will be higher and releasing CO$_2$, while on the other hand if it is closer to the land surface it will inhibit the aerobic decomposition due to the lack of oxygen thereby the production or accumulation of peat material will exceed its loss due to the decomposition process. The rate of peat accumulation is determined by the time fraction of the peat is exposed to oxygen at low GWL condition. Apart from peat decomposition, GWL can also affects irreversible dryness of the peat material that is influenced by drainage and climatic factors, especially rainfall. The closer to the drainage channel, the deeper the GWL is as a result of the higher groundwater movement. This results in a reduction in the water content of the peat due to drying that further reduces the groundwater retention [13].

[14] showed a significant relationship between GWL and CO$_2$ emissions from tropical peatlands in Palangkaraya, Central Kalimantan, Indonesia where any decrease in GWL of 0.1 m will increase CO$_2$ emissions by 89 g C.m$^{-2}$.year$^{-1}$. [15] reported the average CO$_2$ flux at a plot 4.5 m from the oil palm trees cultivated on peatland in Riau, Indonesia was of 20.62 t CO$_2$.ha$^{-1}$.year$^{-1}$, which contributed 50.53% to the total soil respiration. The reduction in GWL also affects CO$_2$ emissions around the palm oil trunks due the increase in the activity of root respiration and peat decomposition by soil microbes. The relationship between GWL reduction and CO$_2$ emissions, however, is not continuous as it only occurs at a certain depth and time [16].

Rainfall is one of the main factors affecting C emissions. A decrease in rainfall during the dry season can lead to a decrease in the GWL or the occurrence of aerobic conditions, which can increase the decomposition of peat materials and emission of CO$_2$ [17]. Rainfall affects the forming process of peat soil profile. According to [18], the increase in GWL due to increased rainfall is a complex function of permeability, evapotranspiration, vegetation, lateral groundwater flow, and rainfall volume. Low rainfall causes peat soil to be aerobic and increase in soil acidity. This condition causes faster rate of organic matter decomposition and release of CO$_2$ through oxidation reactions at low rainfall conditions. Low rainfall indirectly causes a peatland that initially absorb or as a sink of CO$_2$ to turn into a source of emissions. Conversely, high rainfall will create an anaerobic environment and allow the peatland ecosystem to function as a C sink and store [19]. Hence, rainfall and GWL are two important factors that influence the formation of CO$_2$ in peatlands and have a major contribution to CO$_2$ emissions. Maintaining groundwater at high levels will reduce CO$_2$ emissions from peatlands [20].

In this study, the effect of rainfall simulation treatment as a single factor are only significant after Month 2 experimentation (Table 3) in which MRF treatment of 300 mm.month$^{-1}$ gave the lowest CO$_2$...
flux of 24 t.ha\(^{-1}\).year\(^{-1}\) compared to the other three MRF levels. This was related to the amount of water given that described the wet or rainy season. Meanwhile, the 30 mm.month\(^{-1}\) MRF treatment level that described the dry season gave the highest CO\(_2\) flux of 45.95 t.ha\(^{-1}\).year\(^{-1}\).

Based on the results of statistical analysis, the Pearson correlation for CO\(_2\) flux vs air temperature \((r= 0.132; n=108; p= 0.448)\) and CO\(_2\) flux vs lid height \((r= 0.087; n=108; p= 0.613)\) were not significant. Hence, the relationships among CO\(_2\) flux and air temperature and lid height of the IRGA chamber were weak, meaning only unsignificant part of the CO\(_2\) flux variability that was explained by variations in these two variables due to peat subsidence at the surface of the peat column. Higher air temperature and lower lid height of the chamber will cause the release of CO\(_2\) flux to be greater than its absorption. However, it was not the case in this experimentation condition.

4. Conclusion

There was no significant interaction effect between groundwater level and monthly rainfall simulation treatments. The ~40 cm groundwater level treatment as a single factor produced the lowest and significant CO\(_2\) flux at 5% test level after the Month 0 and Month 3 experimentation. Monthly rainfall simulation treatment of 300 mm.month\(^{-1}\) describing the rainy season produced the lowest CO\(_2\) flux but only significant at 10% test level after the Month 2 experimentation. It can be recommended that to get the best control on CO\(_2\) flux, the groundwater level should be set up in the field at around ~40 cm.

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