Correlation of CO_2 flux to ground water level and soil water content in oil palm plantations on peatlands

Cut Rushayu Putri[1]*, *Fransisca* Simanjuntak[2], *Dian* Ari Kurniawan[2], *Suwardi*[3], and *Bandung* Sahari[2,4]

[1]Department of Natural Resources and Environmental Management, Faculty of Multidisciplinary, IPB University, Bogor, West Java, Indonesia
[2]PT. Astra Agro Lestrari, Tbk, East Jakarta, Jakarta, Indonesia
[3]Department of Soil Science and Land Resources, Faculty of Agriculture, IPB University, Bogor, West Java, Indonesia
[4]Center for Transdisciplinary and Sustainability Science, IPB University, Bogor, West Java, Indonesia

Abstract. Peatlands play a crucial role in Indonesia's agricultural sector and their use is often linked to environmental concerns, such as being a source of CO_2 emissions. This study analyses the relationship between CO_2 flux, ground water level, and soil water content in oil palm plantations in the tropical peat ecosystems of *Pangkalan Pisang* District, Riau Province. The research was conducted from October 2023 to March 2024, measuring CO_2 flux in three plots inside oil palm plantations: Bare plots, N. *biserrata* plots, and plots under oil palm trees. CO_2 flux measurements were carried out using a closed chamber method and an Infrared Gas Analyzer (IRGA); additional factors such as groundwater level and soil water content were also measured simultaneously with CO_2 flux. The results showed that the average CO_2 flux measured was 6,25±3,68 g m^{-2} d^{-1} in Bare plot, 8,25±4,30 g m^{-2} d^{1} in N. *biserrata*, and 9.80±5,75 g m^{-2} d^{-1} near oil palm trees. The results indicate that, except for bare plots, there is no significant correlation between Ground Water Level (GWL) and Soil Water Content (SWC) with CO_2 flux.

1 Introduction

Peatlands are formed by the continuous addition of fresh organic materials faster than their decomposition, which results in the accumulation of undecomposed organic material from time to time [1]. Indonesia has the most extensive tropical peatland in the world, with a total area of around 13,48 million hectares scattered throughout Sumatra, Kalimantan, Sulawesi, and Papua [2].

[1] Corresponding author: cutrushayuputri@apps.ipb.ac.id

One of Indonesia's largest peat distribution areas is located on the island of Sumatra, precisely in Riau Province, which has around 3,573,955 hectares or equivalent to 61% of the total province area [2]. The vast peat area in Indonesia, especially in Riau Province, makes peatland widely used for agricultural activities such as oil palm plantations. Several concerns about peatland utilisation have arisen, including CO_2 release from peatland to the atmosphere. Studies that measured CO_2 gases from oil palm plantations on peatlands showed different results. A study by [3] shows the CO_2 emissions of tropical peatlands in oil palm plantations are 48-86 tons ha^{-1} $year^{-1}$, and according to [4], the total CO_2 emissions of peatlands in oil palm plantations aged 5-6 years are 35.9 tons CO_2 ha^{-1} $year^{-1}$. A study by [5] mentioned that drainage formation greatly influences the peat decomposition rate, and every increase in drainage depth by one centimetre will be followed by increasing CO_2 emissions by 0.91 tons ha^{-1} $year^{-1}$. CO_2 emissions from peatland are influenced by several factors, namely microorganism populations and root respiration, as well as external factors, namely the availability of oxygen and nutrients, soil temperature and organic matter content, soil moisture, and ground water level.

One of the main parameters in peatland is water management by conducting Ground Water Level (GWL) monitoring [6]. In oil palm plantations, the condition of the water level can affect the yield [6-7]. The Indonesian government has regulated water management on peatlands in Government Regulation No. 57/2016, which states that ground water level should not be deeper than 40 cm. This regulation was released to prevent land fires on peatlands by keeping peatlands in a humid state and not prone to fires [7]. The factor that significantly affects the ground water level is rainfall [7]. In addition, ground water level also affects the soil water content. The study by [8] showed that the highest CO_2 emissions were achieved at soil water content around field capacity and decreased with increasing soil water content above the field capacity. Therefore, water management in the field should consider rainfall monitoring to manage the dynamic water level on the ground. However, limited studies have been done to evaluate the relationship between the dynamic of ground water level and carbon emissions [9].

With increasing concern about CO_2 emissions and water level management in cultivated peatlands, especially in oil palm plantations, this study is focused on evaluating CO_2 emissions and their relationship with Ground Water Level (GWL) and Soil Water Content (SWC).

2 Methods

The research was conducted from October 2023 to March 2024 in oil palm plantations in Pangkalan Pisang, Siak Regency, Riau Province. Several water management systems have been implemented at the research site, including the construction of overflow and water gates. Data was collected on two planting blocks, each encompassing approximately 40 hectares and equipped with drainage canals. Within each block, three distinct plots were selected based on varying conditions. Measurements were taken in triplicate for each plot, resulting in nine samples per research block. The variation of the conditions on the plots are:

1. Bare Plots. Plots were set up in areas without oil palms, and all weeds above the ground were removed to create a bare plot. Although above-ground plant removal was performed, underground root removal was not performed in this study.
2. N. *bisserata* Plots: The plots were set up in the shrub area dominated by N. *bisserata*, specifically at > 4.5 meters from oil palm trees. This placement was conducted to eliminate the influence of the CO_2 from oil palm trees within the plots. *N. biserrata* is a

fern species generally found under oil palms and useful as a ground cover plant and does not cause harm or disturbance to the oil palm planted.

3. Oil Palm Tree Plots. Plots were set up 1.5 m from the 19- and 27-year-old oil palm trees. 5 *Groundwater level data* were collected along with CO_2 flux measurements. In each block, three piezometers were set up at different points: 1) in the main ditch, 2) in the middle, and 3) at the end of the block. A piezometer is a device used to determine the height of groundwater levels. The piezometer is made of PVC pipe, 3 inches in diameter and about 150 cm long. In addition to observations during gas flux measurements, ground water level (GWL) measurements were conducted weekly to observe GWL trends in the research blocks.

2.1 CO_2 measurement

The CO_2 flux was measured using the closed chamber method. A chamber measuring 30 cm x 30 cm x 30 cm was used to capture gases released from the soil, and the speed was measured at 0, 3, and 6 minutes. Gases from the chamber were circulated to an Infrared Gas Analyzer (IRGA), specifically a model ZFP9GC11 from Fuji Electric, Tokyo, Japan. The CO_2 flux measurement time was carried out in the morning from 08.00 - 10.00 WIB and in the afternoon from 14.00 -16.00 WIB. Each oil palm block was observed twice a week for measurements, resulting in four days of measurements conducted over 12 weeks. However, there were a few days when measurements were not taken due to heavy rainfall, making it impossible to measure the oil palm plantation blocks.

The chamber is equipped with a thermometer to measure the air temperature, a fan for air circulation, and an air pressure holding bag. Measurements were recorded at intervals of 0, 3, and 6 minutes to stabilise CO_2 gas flow in IRGA, which was then examined using linear regression. Before using the IRGA for measurement, it was calibrated using soda lime and standardised CO_2 gas to ensure precision. The recorded CO_2 data values were then analysed using linear regression to obtain dC/dT values through the Microsoft Excel application.

After obtaining the dC/dT value of the concentration, the CO_2 flux is calculated based on the equation[10] :

$$fc = \frac{PH}{RT}\frac{dC}{dt} \tag{1}$$

Information :
fc: CO_2 flux (μmol m^{-2} sec^{-1})
P: Atmospheric pressure based on the average reading by the CO_2 analyser (Pa)
H: Cover height (m^3)
R: gas constant (8.314 Pa m^3 °K^{-1} mol^{-1}) T: Cover temperature (K) dC/dt: change in CO_2 concentration during time change (ppm sec^{-1})

2.2 Soil water content

The soil water content of peat was measured by collecting soil samples at the gas sampling points after the CO_2 measurement. The soil was cut at a 0-20 cm depth using knives. The soil samples are then sent to the laboratory for analysis using the gravimetric method.

2.3 Rainfall data

Historical rainfall from 2015-2024 was observed using an Ombrometer at the oil palm plantation, and data was recorded every day (08.00-10.00 AM).

2.4 Correlation among CO_2 flux, GWL, and soil water content

All data collected was then analysed to see the correlation between factors using Spearman correlation analysis. Statistical analyses were conducted using Mini tab software.

3 Result and discussion

3.1 Rainfall, ground water level, and soil water content in the study area

Riau Province has a tropical rainfall pattern, experiencing dry months twice a year, from January to February and from July to September. This pattern is supported by the rainfall distribution data record, as shown in Figure 1. Observations indicate that the study was conducted during the wet to humid months at the research site. As a result of these conditions, measurements could not be performed on certain days due to heavy rainfall. According to recorded rainfall data from 2015 to 2023, it is evident that October to December are the wet months at the study location, except for 2019 when El Niño occurred in Indonesia. Subsequently, from January to March 2024, the study location experienced humid months with rainfall exceeding 100 mm but less than 200 mm monthly.

Rainfall has a significant impact on groundwater levels in peatlands [7]. Weekly groundwater level measurements at the study location show that the groundwater levels in both blocks of the research site ranged from -40 cm to -60 cm (Figure 2). The optimum GWL depth for oil palm in drained peatland ranges from 60-80 cm [7]. According to the monthly rainfall data, the wet months are observed to occur from October to December. During this period, the groundwater level becomes shallower, particularly in the months of December and January (Figure 2).

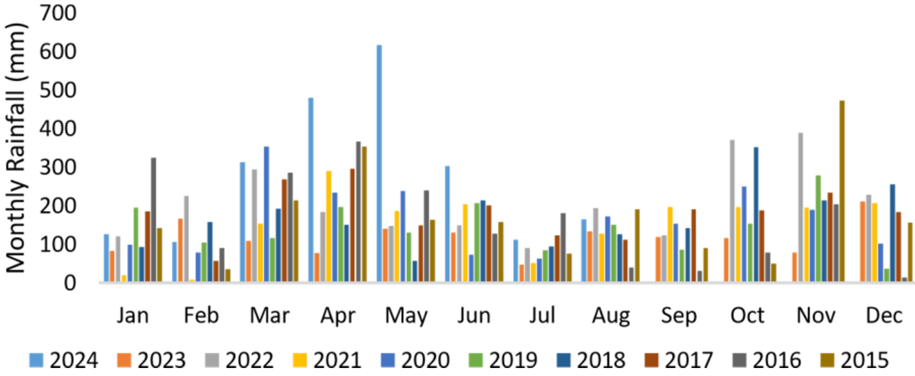

Fig. 1. Monthly Rainfall in the Research Location from 2015 to 2024

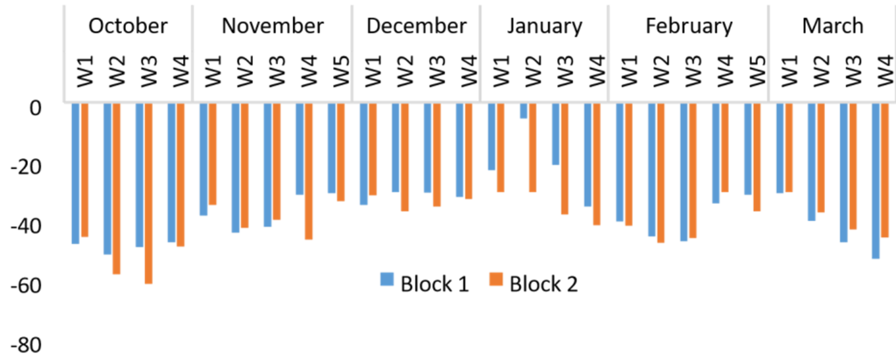

Fig. 2. Ground Water Level in Research Location October 2023 - March 2024

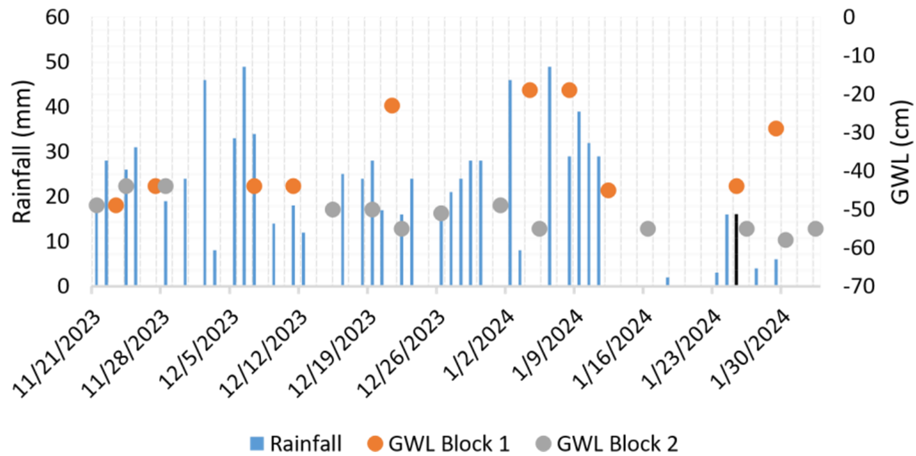

Fig. 3. Rainfall and Ground Water Level in Research Location

The observations of GWL during CO_2 flux measurements (Fig. 3) indicate that the GWL in both research blocks were no deeper than -60 cm. It is essential to observe GWL depth as this value subsequently affects the water content in peat soil [11]. The soil water content measured during the study indicated it was at field capacity, ranging between 200 to 300 (w/w%) (Table 1). Soil water content in peat soil affects the proportion of soil pores that can be filled with air, which is vital for root respiration [16]. When soil moisture exceeds field capacity, all soil pores are filled with water, resulting in a tiny proportion of pores filled with air, such as oxygen or carbon dioxide [13] .

Table 1. Ground Water Level and Soil Water Content During Measurement

Land Type	Ground Water Level (cm)	Soil Water Content (w/w%)
Bare plot	-49.00±3.69	255.95± 32.07
N. *bisserata*	-41.30±15.89	304.10±40.96
Oil Palm Trees	-39.68±7.74	287.68±50.42

3.2 Relationship of CO_2 flux with ground water level and soil water content

The highest CO_2 flux was recorded in plots with oil palm trees, 35,76 tonnes ha^{-1} $year^{-1}$, followed by N. *bisserata* plots, 31.23 tonnes ha^{-1} $year^{-1}$, and the lowest, 22,83 tonnes ha^{-1} $year^{-1}$, was recorded in bare plots (Table 2). The amount of CO_2 flux in oil palm measured in this study is supported by the values observed in the studies conducted by [4] and [5]. The CO_2 release in oil palm is triggered by the oil palm roots' respiration that releases CO_2 and the decomposition of peat soils through microbial activity.

The plot with the second largest flux is the N. *biserrata* plots. N. *biserrata* holds potential as a ground cover crop in oil palm plantations for its ability to aid soil and water conservation. Additionally, it serves as forage, enhancing the carbon and nutrient cycles. The effectiveness of N. *biserrata* in maintaining soil moisture is indicated by its highest average soil water content (SWC) (Table 1).

Land without vegetation or bare plots has the lowest CO_2 flux despite having the deepest average groundwater level (GWL) compared to other plots. This finding contradicts previous research, which suggests that deeper GWLs result in higher CO_2 flux. Additionally, considering the influence of plant root respiration on soil CO_2 flux, these results indicate that the low CO_2 flux observed in bare plots may relate to less organic matter decomposition by soil microorganisms and the reduced CO_2 release from root respiration. In this context, rather than the influence of GWL and SWC, other factors that influence soils' CO_2 flux were not observed in this study, namely root respiration and soil microorganism activity.

The bare plot has the lowest SWC compared to the other plots, as shown in Table 2. Since a bare plot has no vegetation above the ground, direct exposure to sunlight and wind may cause drier soil conditions, thereby reducing the activity of microorganisms and affecting CO_2 release. This is in accordance with [14] when peat soil is dry, the activity of microorganisms that decompose organic matter is inhibited, as is the release of CO_2. Fluctuations in the GWL level affect the soil water content in accordance with [15], a reduction in the GWL can decrease peat soil water content because it will affect the distribution of soil moisture in the entire peat soil profile.

N. *bisserata* plots were recorded to have the highest water content, with an average of 304.10%, followed by oil palm tree plots that have an average moisture content of 287.68%, and bare plots have the lowest content of 255.95% (Table 2). GWL also affects the increase in peat soil water content, other factors that affect the high water content of peat are the depth of the peat soil layer and the low maturity rate of peat [4].

Table 2. CO_2 Fluxes in plots of Oil Palm Trees, N. *bisserata*, and Bare Plot

Sampling Plots	CO_2 Flux ($t\ ha^{-1}$ y-1)	CO_2 Flux ($g\ m^{-2}\ d^{-1}$)	GWL (cm)	Soil Water Content (w/w%)
Bare plot	22.83±13.43	6,25±3,68	-49.00±3.69	255.95± 32.07
N. *bisserata*	31.23±15.76	8,25±4,30	-41.30±15.89	304.10±40.96
Oil Palm Trees	35.76±20.99	9.80±5,75	-39.68±7.74	287.68±50.42

The data shows that the GWL in the bare plot is the deepest compared to the others, but the SWC in that plot is not the lowest. This indicates that many environmental conditions in the field need to be further investigated, such as the maturity rate of peat. However, the results of this study should emphasise that the SWC conditions were at field capacity, and the resulting flux values varied greatly.

Shallow GWL may affect CO_2 emissions through soil moisture and microbial activity mechanisms. In soils with deeper water levels, the organic decomposition process increases. Thus, CO_2 flux tends to be higher, while in soils with shallow water levels, anaerobic conditions can reduce microorganisms' activity and CO_2 emissions. Some studies directly correlate CO_2 flux with GWL, that deeper GWL causes an increase in CO_2 flux [4-13].

3.3 Correlation of CO_2 flux with environmental factors

Table 3 presents the results of Spearman correlation analysis between GWL and SWC across three land use types: Bare plot, N. *biserrata*, and oil palm tree. GWL did not significantly correlate with the CO_2 flux measured across these plots, but SWC significantly correlated with the CO_2 flux on bare plots but not in other plots.

Further studies are needed to explore additional data to look at factors that affect the CO_2 flux from peat soil. In addition, a longer measurement duration should be able to show the correlation between these environmental factors and CO_2 flux. According to [6], CO_2 flux measurements in peatlands with land cover in the form of annual crops should be carried out for at least one year.

Table 3. The correlation of CO_2 flux with environmental factors with Spearman

Factors	Bare plot (n = 11)		N. *biserrata* (n = 33)		Oil palm tree (n = 25)	
	P Corr.	P value	P Corr.	P value	P Corr.	P value
GWL	0.311^{ns}	0.352	0.125^{ns}	0.490	-0.061^{ns}	0.771
SWC	0.612*	0.046	-0.076^{ns}	0.676	0.211^{ns}	0.312

ns = insignificant; *= significant

4 Conclusion

The highest CO_2 flux value was recorded at 9.80 g m^{-2} d^{-1} on the oil palm tree plot, while the lowest value in bare plots was 6.25 g m^{-2} d^{-1}. GWL and SWC do not significantly correlate with CO_2 flux, except for bare plots. More studies are needed to explore the relationship between CO_2 flux, GWL, and SWC.

Acknowledgements

We gratefully thank to PT. Astra Agro Lestari for funding the research. We also extend thanks to all company's members for providing full supports during observation and data collection in the field. The last, special appreciation extend to all team members for the hardwork, direction and constructive suggestion in the proccess of this article.

References

1. Masganti, K. Anwar, M.A. Susanti, Potensi dan Pemanfaatan Lahan Gambut Dangkal untuk Pertanian *J. Sumberd. Lahan* **11** 43 (2017)
2. M. Anda, S. Ritung, E. Suryani, Sukarman, M. Hikmat, E. Yatno, A. Mulyani, R.E. Subandiono, Suratman, Husnain, Revisiting tropical peatlands in Indonesia: Semi-detailed mapping, extent and depth distribution assessment *Geoderma* **402** 115235 (2021)
3. V.J. Yahya, S. Sabiham, B. Pramudya, I. Las, Identification of factors that influence carbon emissions in tropical peatland *Biospecies* **12** 20–7 (2019)
4. Jamaludin, E. Gusmayanti, G.Z. Anshari, Emisi Karbon Dioksida (CO2) dari Pertanian Skala Kecil di Lahan Gambut *J. Ilmu Lingkung.* **18** 582–8 (2020)
5. A. Hooijer, S. Page, J.G. Canadell, M. Silvius, J. Kwadijk, H Wösten, J. Jauhiainen, Current and future CO_2 emissions from drained peatlands in Southeast Asia *Biogeosciences* **7** 1505–14 (2010)
6. S. Sabiham, Winarna, H.B. Pulunggono, D. Novarina, B. Sahari. What Is The Way Forward on Indonesian Peatland?, 15th Internasional Peat Kongress 2016. A-454: 39-42 (2016)
7. Y.A. Adhi, H. Mubarak, R. Roland, P.P. Utama, N. Tambusai, I. Ismail, S. Anwar, Tarigan S.D. Tarigan, B. Sahari, Effects of rainfall and groundwater level on soil subsidence, water content, and yield of oil palm *IOP Conf. Ser. Earth Environ. Sci.* **771** 012029 (2020)
8. Winarna, H. Santoso, Karakteristik Emisi CO_2 Tanah Gambut di Bawah Tegakan Kelapa Sawit *J Pen. Kelapa Sawit*. **28** 1 (2020)
9. N. Novita, A. Asyhari, R.P. Ritonga, A. Gangga, G.Z. Anshari, J. Jupesta, J.C. Bowen, N.S. Lestari, J.B. Kauffman, A.M. Hoyt, C.R. Perryman, I. Albar, C.A.S. Putra, W.C. Adinugroho, B. Winarno, M. Castro, S. Yeo, T. Budiarna, E. Yuono, V.C. Sianipar, Strong climate mitigation potential of rewetting oil palm plantations on tropical peatlands *Sci. Total Environ.* **952** 175829 (2024)
10. R. Madsen, L. Xu, B. Claassen, D. McDermitt, Surface Monitoring Method for Carbon Capture and Storage Projects *Energy Procedia* **1** 2161–8 (2009)
11. Y.A. Adhi, S. Anwar, S.D. Tarigan, B. Sahari, Relationship between Groundwater Level and Water Content in Oil Palm Plantation on Drained Peatland in Siak, Riau Province, Indonesia *J.Trop.Agric.Sci.* **43** 3 (2020)
12. Rohaniah, A.R. Saidy, A. Kurnain, Hubungan Kadar Lengas Gambut dan Tinggi Muka Air pada Beberapa Tipe Tutupan Lahan Gambut *Acta Solum* **1** 7–10 (2022)
13. S. Marwanto, S. Sabiham, U. Sudadi, F. Agus, Pengaruh Kerapatan Akar, Pupuk, dan Kedalaman Muka Air Tanah terhadap Emisi CO2 dari Tanah Gambut pada Perkebunan Kelapa Sawit **37** (2013)
14. D. Simatupang, D. Astiani, T. Widiastuti, Pengaruh Tinggi Muka Air Tanah Terhadap Beberapa Sifat Fisik Dan Kimia Tanah Gambut Di Desa Kuala Dua Kabupaten Kubu Raya **6**, 4 (2018)
15. N. Wakhid, Zainudin, Pemantauan Dinamika Tinggi Muka Air Secara Otomatis Di Lahan Gambut *EnviroScienteae* 15, 374 (2019)