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Research Article

CO_2 emissions of tropical peat soils under controlled groundwater table depths: A laboratory-based experiment

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Abstract

The groundwater table (GWT) is widely recognized as a key factor influencing CO_2 emissions in tropical peatlands. However, previous studies investigating this relationship have reported diverse results. This variability likely stems from the dynamic nature of field-based groundwater conditions. To address this, this study investigated the relationship between controlled GWT and CO_2 emissions in a laboratory experiment using PVC columns filled with peat soil. GWT depths were adjusted to 20 cm, 30 cm, 40 cm, 50 cm, and 60 cm within a large container filled with peat pore water. CO_2 emissions were measured using an Infra Red Gas Analyzer - Environmental Gas Monitoring-4 instrument, with a closed-chamber system. This study revealed significant differences in CO_2 emissions between treatments, except for the transition from 20 cm to 30 cm GWT. Correlation analysis showed a positive correlation ($R^2 = 0.25$). Notably, CO_2 emission factor values based on average yearly emission rates displayed a substantial increase with decreasing GWT, exhibiting a strong exponential relationship ($R^2 = 0.99$). The specific CO_2 emission factors for each treatment, 20 cm, 30 cm, 40 cm, 50 cm, and 60 cm, were 2.39, 3.77, 9.34, 15.81, and 28.77 $MgCO_2\ ha^{-1}\ yr^{-1}$, respectively. Furthermore, the results of this study suggest an estimated value of 5.28 $MgCO_2\ ha^{-1}\ yr^{-1}$ for every 10 cm decrease in GWT.

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Introduction

Tropical peatlands are one of the largest carbon (C) storage ecosystems on Earth, with an estimated C stock of more than 75 Gt (Jaenicke et al., 2008; Kurnianto et al., 2015; Warren et al., 2017; Cobb et al., 2020). However, these ecosystems are highly vulnerable to disturbances caused by human activities (Nusantara et al., 2018). When disturbed, peatlands can switch from being a C sink to a C source due to peat decomposition (Turetsky et al., 2015; Hoyos-Santillan et al., 2016; Huang et al., 2021; McCalmont et al., 2021). A key accelerant of peat decomposition is lower groundwater table (GWT) depth. This creates a thicker aerobic layer (acrotelm), increasing the rate of organic matter decomposition (Webster et al., 2013; Anshari, 2021). Furthermore, decreased GWT also elevates soil surface temperature (Husnain et al., 2014), leading to increased microbial activity and significantly accelerated organic matter decomposition (Andersen et al., 2013; Webster et al., 2013).

Several prior studies have identified a correlation between GWT depth and CO_2 emissions emanating from peatlands, yet these studies have yielded disparate results (Jauhiainen et al., 2008; Couwenberg et al., 2010; Hooijer et al., 2012; Hirano et al., 2014; Carlson et al., 2015; Novita et al., 2021). The variability in findings regarding the relationship between GWT depth and CO_2 emissions from tropical peatlands highlights the complex and dynamic nature of GWT itself. Field-based studies often struggle to isolate the specific influence of GWT due to the multitude of interacting environmental factors. To address this challenge, further research is crucial to examine this relationship in more detail, particularly under controlled conditions with minimized external influences. Previous studies have reported that controlled environmental conditions provide clearer results regarding various environmental factors such as temperature and moisture content in influencing carbon emissions from peat soil (Strack and Waddington, 2007; Husen et al., 2014; Byun et al., 2021). Building upon this rationale, this study aimed to analyze the critical between controlled GWT depths and CO_2 emissions from tropical peatlands. Additionally, this study delves further by estimating the CO_2 emission factor associated with GWT drawdown, providing valuable insights into the potential consequences of GWT changes for peatland carbon dynamics.

Materials and Methods

Soil sampling and measurement period

Soil samples were collected from a drained peatland in Pontianak, West Kalimantan, Indonesia, at 0º4’25” N - 109º19’58” E. The soil samples were collected and placed in a PVC experiment to maintain a controlled GWT. The CO_2 emission measurement was conducted in an open area shaded by trees. The measurement was carried out for two months. Soil analyses were carried out at the Department of Biosciences Laboratory, University of Nottingham UK, and Laboratory of Soil Quality, Tanjungpura University, Indonesia.

Experimental design and variables

The equipment and materials used in this study were divided into several parts. The first part was the equipment for soil sampling and identification in the field, including a location map, auger drill, field tools, and PVC pipes with a length of 80 cm and a diameter of 4 inches (±12 cm). The design of the experimental PVC is shown in Figure 1. The equipment and materials required for measuring CO_2 emissions include the Environmental Gas Monitoring-4 (EGM-4, PP System, Amesbury, MA, USA) instrument with a closed chamber system. The PVC filled with peat soil was lined with fine mesh at the bottom as a retainer. The PVC was then placed in a casing (large container) filled with peat water. The soil sample in the PVC was acclimated for a month before the emission measurement was carried out. This was done to homogenize the microclimate conditions around the PVC with the surrounding environmental conditions. Peat water was also added if the GWT changed according to the initial conditions, and the surface layer was sprayed with peat pore water to maintain soil moisture.

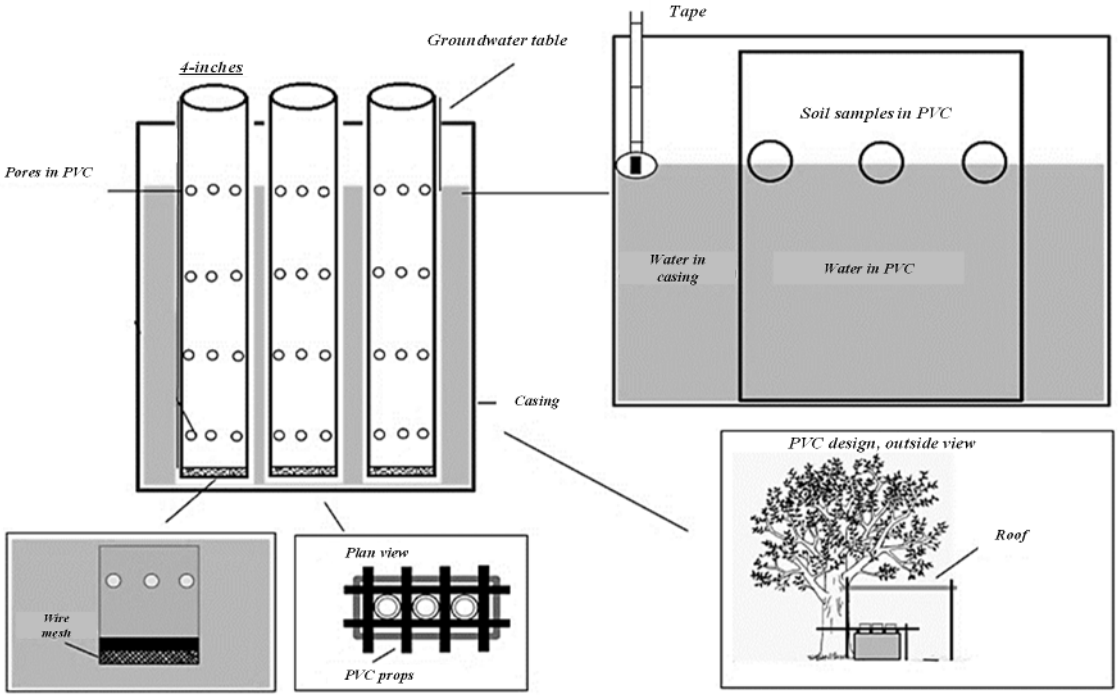

Figure 1. PVC design.

This study used a completely randomized design with five static GWT depth treatments (20 cm, 30 cm, 40 cm, 50 cm, and 60 cm) with three replications. CO_2 emission measurement was conducted for 125 seconds on each PVC, and every 5 seconds, the CO_2 concentration data was recorded and stored in the

EGM-4. The measurement data was quantified to obtain the emission value.

The measured soil peat properties included peat decomposition level (PDL), bulk density (BD), field water content (FWC), pH, total nitrogen, and soil organic carbon. Dry soil samples, BD, and FWC measurements were employed using the gravimetric method using a Memmert GmbH UN55 oven set to 70°C. For pH, a SenseLine F410 instrument was utilized. Total nitrogen was quantified using the Kjedahl method, while soil organic carbon was analyzed using the Loss on Ignition method.

Soil samples for BD and FWC were taken based on differences in the peat decomposition rate, which was measured using the Von Post Humification Scale method. After obtaining the differences in the PDL, soil samples were taken and analyzed according to the parameters to be tested. Each soil sample unit tested was duplicated, resulting in four soil samples in one plot. Soil pH was taken twice for each plot, and then the pH values were averaged.

Data analyses

CO_2 emissions were calculated using the equation proposed by Dossa et al. (2015) in equation 1 (en1). This equation is derived from the Ideal Gas Law and represents an improvement over previous methods for quantifying soil CO_2 emissions using a closed chamber system. Notably, variables included in this equation are measurable parameters within the EGM-4.

$$F = \Delta CO_2 \frac{P}{Pi} \frac{(Vc\text{-}Vs)}{Vi} \frac{Ti}{(Ti+Tc)} \frac{1}{Ws} \qquad \text{(en1)}$$

where: F is CO_2 emissions ($mgCO_2\ kg^{-1}\ hr^{-1}$). ΔCO_2 denotes the difference in CO_2 emission between two time points ($\mu mol\ mol^{-1}\ s^{-1}$). P represents the air pressure during the measurement in the chamber (kPa). Pi is the standard air pressure. Vc is the chamber volume. Vi is the volume of an air mole at 0°C. Ti is the standard temperature. Vs represents the base area of the chamber. Tc is the average temperature during the measurement (°C). Ws denotes the dry mass of the soil sample (g).

The following is an example of CO_2 emission quantification using measurement data from day 17 in GWT 60cm treatment. The first step is to find the ΔCO_2 value. ΔCO_2 is the slope of the concentration change between times during the measurement. The coefficient of determination (R^2) used from the ΔCO_2 measurement ranged between 95-100%. The ΔCO_2 result was 4 ppm s^{-1}, which means that for each change in measurement time, there was a change in CO_2 concentration of 4 ppm with an R^2 value of 1.00.

The ΔCO_2 value obtained in ppm s^{-1} equivalent to $\mu molCO_2\ s^{-1}$ was then entered into equation 1. The P value is the pressure in the chamber (SRC) during the measurement. Pi is the standard pressure (101.325 kPa), Vi is the molar volume of air at 0°C, is 22.4 L or 22,400 cm^3, Vc is the chamber volume (1,171 cm^3), Vs is the CO_2 volume value based on the treatment, mathematically formulated as follows: Vs (cm^3) = A (cm^2) x GWT (cm) x BD (g cm^{-3}), A is the chamber cross-sectional area with 78 cm^2 while GWT is the groundwater table depth for each treatment and BD is the average bulk density value for each treatment. Ti is the standard temperature (273 K) while Tc is the average temperature in the chamber during measurement (°C) and Ws is the dry mass of the soil sample in the PVC Experiment. The soil dry mass of the soil sample for each treatment was as follows:

- GWT 20 cm: 2,141.791 g
- GWT 30 cm: 2,262.413 g
- GWT 40 cm: 2,150.400 g
- GWT 50 cm: 2,191.857 g
- GWT 60 cm: 2,143.934 g

The CO_2 emission obtained from this calculation was 0.000028 $\mu molCO_2\ g^{-1}\ s^{-1}$ to convert to $\mu gCO_2\ g^{-1}\ s^{-1}$ then, 0.000028 $\mu molCO_2\ g^{-1}\ s^{-1}$ x molar mass of CO_2 (Ar C + 2 Ar O). Ar C = 12.01 and Ar O = 16, a value of 0.001219 $\mu gCO_2\ g^{-1}\ s^{-1}$ was obtained. The value obtained was then converted to mg $kg^{-1}\ hr^{-1}$ to 4.39 mg $kg^{-1}\ hr^{-1}$. This value was then statistically analyzed with ANOVA and a simple linear regression test. All statistical data were analyzed using SPSS Statistic 25 (IBM, NY, USA).

The equation 2 (en2) was used for calculating the estimated yearly CO_2 emission factor (${}_{E}fC$) in $MgCO_2\ ha^{-1}\ yr^{-1}$ for each GWT treatment. A_{PVC} is the area of PVC (cm^2), D_{peat} is the peat depth inside PVC (cm), BD is the average bulk density (g cm^{-3}).

$${}_{E}fC = \frac{F\ 10^{-6}}{A_{PVC}} * D_{peat} * BD * 365 * 1\ 10^{8} \qquad \text{(en2)}$$

Furthermore, the emission factor for each 10 cm GWT decreases was calculated using equation 3 (en3).

$${}_{E}fC_{10} = \frac{[(fC_{ii}\text{-}fC_{i})+(fC_{iii}\text{-}fC_{ii})+\ldots(fC_{nii}\text{-}fC_{ni})]}{nfC} \qquad \text{(en3)}$$

fC followed by a Roman numeral is the mean change in CO_2 emission for every 10 cm decrease in GWT.

Results

Peat properties are presented in Table 1. CO_2 emission analysis using one-way ANOVA showed significant differences by a p-value<0.05. The results of the LSD test (Table 2) showed that only the decrease in GWT from 20 cm to 30 cm did not exhibit a statistically significant (p=0.28). Conversely, comparisons with other GWT depths revealed statistically significant differences, with p-values less than 0.05. These results confirm that variations in GWT have a significant impact on CO_2 emissions. The results of the study showed a positive but weak correlation between GWT and CO_2 emissions (Figure 2). The strength of this relationship is indicated by a correlation coefficient (r) value of 0.5017. The linear regression test showed that the decline in GWT had a weak effect on the increase in CO_2 emissions. This effect is evidenced by the

R^2 value of 0.2517. This study presents the results of CO_2 emission measurements in units of mg CO_2 kg^{-1} hr^{-1} (Table 3). These measurements served as the basis for estimating the CO_2 emission factor (${}_{E}fC$). However, estimating the CO_2 emission factor due to declining GWT necessitates data on soil dry mass in a hectare, which can be obtained by measuring bulk density and peat depth. In this study, GWT was employed as a limiter for D_{peat}, resulting in unique soil masses for each GWT depth treatment (Table 3). The ${}_{E}fC$ estimations demonstrate a very strong exponential relationship between GWT drawdown and CO_2 emissions, with an R^2 value of 0.99 (Figure 3).

Table 1. Peat chemical and physical properties.

GWT (cm)	PDL	FWC (%)	BD (g cm^{-3})	pH	Total N (%)	Organic C (%)
20	Sapric H8	207.10	0.20	3.86	2.01	52.97
	Hemic H5	280.45	0.12		1.22	53.19
	Sapric, H8	230.19	0.18	4.15	1.42	53.92
	Hemic, H7	298.24	0.13		1.18	55.18
30	Sapric, H8	115.24	0.21	4.15	1.84	53.05
	Hemic, H6	235.35	0.16		1.36	56.39
	Sapric, H9	212.68	0.19	4.01	1.96	52.74
	Hemic, H5	281.18	0.11		1.53	53.18
40	Sapric, H9	123.70	0.17	4.12	1.67	53.51
	Hemic, H5	178.83	0.12		1.37	53.85
	Sapric, H9	110.36	0.18	4.16	1.89	52.50
	Hemic, H5	189.74	0.15		1.45	54.68
50	Sapric, H8	104.86	0.20	4.12	1.69	52.55
	Hemic, H6	184.08	0.13		1.38	54.34
	Sapric, H8	154.34	0.18	3.83	1.87	51.54
	Hemic, H5	205.60	0.15		1.42	55.04
60	Sapric, H8	106.76	0.22	4.15	1.53	53.84
	Hemic, H5	185.45	0.16		1.36	53.69
	Sapric, H9	113.46	0.21	3.98	1.65	49.71
	Hemic, H6	124.25	0.16		1.48	53.42

Notes: PDL-peat decomposition level; FWC-field water content; BD-bulk density.

Table 2. LSD test of CO_2 emissions.

GWT (cm)	Sign. difference	Test statistic	*p*-value
20 vs 30	-0.69	1.08	0.28
20 vs 40*	-1.97	3.08	0.002
20 vs 50*	-3.68	5.75	$2.64\ 10^{-8}$
20 vs 60*	-5.09	7.95	0
30 vs 40*	-1.28	2.01	0.04
30 vs 50*	-2.99	4.67	$4.98\ 10^{-6}$
30 vs 60*	-4.40	6.87	$4.92\ 10^{-11}$
40 vs 50*	-1.71	2.66	0.008
40 vs 60*	-3.12	4.87	$1.98\ 10^{-6}$
50 vs 60*	-1.41	2.21	0.03

*significance difference at a 95% confidence level.

Table 3. CO_2 emissions measurement results.

GWT (cm)	Avrg. F (mgCO_2 kg^{-1} hr^{-1})	${}_{E}fC$ (MgCO_2 ha^{-1} yr^{-1})
20	2.85 ±1.93 (n=51)	2.39 (fC_{i})
30	3.54 ±2.11 (n=51)	3.77 (fC_{ii})
40	4.82 ±2.91 (n=51)	9.34 (fC_{iii})
50	6.53 ±4.19 (n=51)	15.81 (fC_{iv})
60	7.95 ±4.25 (n=51)	28.77 (fC_{v})

Discussions

The ${}_{E}fC_{10}$ value in this study was 5.28 MgCO_2 ha^{-1} yr^{-1}. This value is relatively comparable to several other reports (Furukawa et al., 2005; Couwenberg et al., 2010; Hirano et al., 2014; Novita et al., 2021). The assumption used in this study is that all peat soil above the GWT, located in the acrotelm layer, undergoes decomposition and emits CO_2. Therefore, the CO_2 emitted increases as the GWT decreases. When calculating CO_2 emissions resulting from drainage processes, it is essential to consider the potential impact of the findings. For instance, the report from Hooijer et al. (2012)'s study, which serves as one of the standard methods for calculating carbon emissions during peatland rewetting, highlights the significance of this aspect. Another significant impact, perhaps the most widely recognized, is the implementation of national regulations mandating specific groundwater table (GWT) levels. While maintaining GWT at these levels has been proven to reduce CO_2 emissions, it may also lead to a decrease in plantation commodity production, as reported in the previous report (Othman et al., 2011). The advantage of this approach is that the CO_2 calculated originates purely from peat soil (heterotrophic respiration) with *Ws* or soil dry mass as the basis for calculating the carbon source. This minimizes the potential of calculation mistakes. For example, one widely used method to differentiate between heterotrophic and autotrophic CO_2 plots is the trenching method, which involves cutting roots at a specific depth. Plots with trenching are considered to be heterotrophic CO_2 emission sources, while those without trenching are considered to be total respiration.

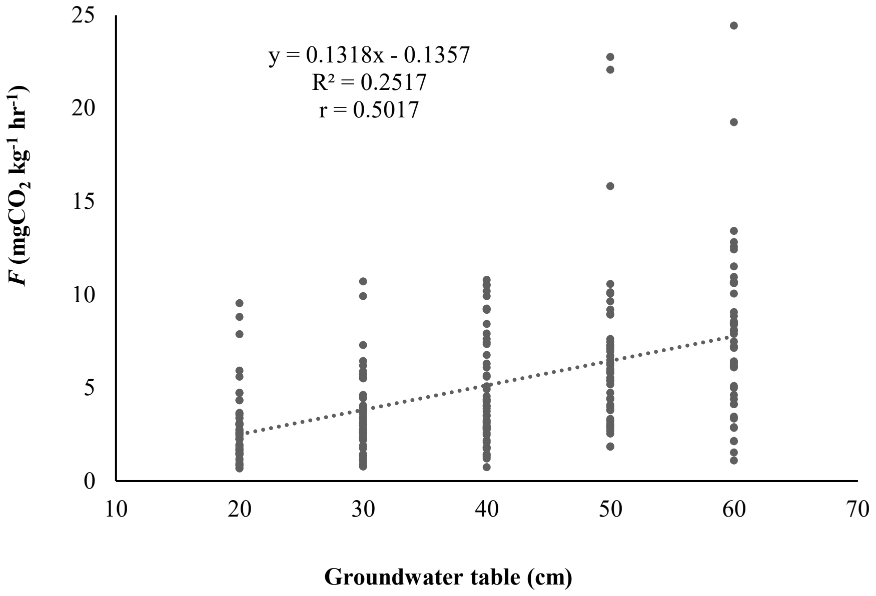

Figure 2. Linear regression of CO_2 emissions.

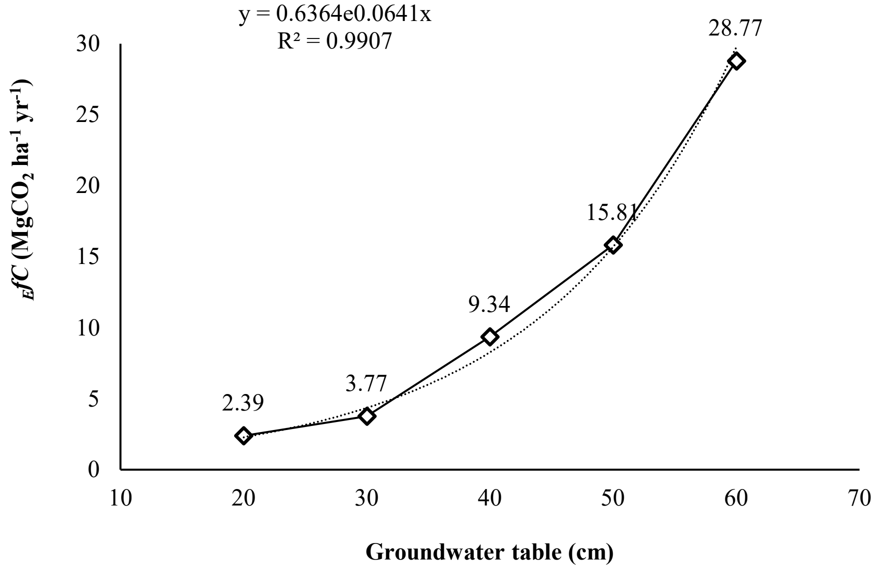

Figure 3. CO_2 emissions factor.

Subtracting the heterotrophic CO_2 emission value from the total CO_2 emission value yields the autotrophic emission value. This has been reported in several similar studies on peatlands (Melling et al., 2007; Murdiyarso et al., 2010; Dariah et al., 2014; Jamaludin et al., 2020). Groundwater table is considered important in regulating carbon emissions from peat ecosystems (Jauhiainen et al., 2008; Couwenberg et al., 2010; Hooijer et al., 2012; Carlson et al., 2015). These findings indicate the complexity of other factors that may influence carbon emissions. Previous research results have reported that temperature and humidity at the soil surface affect the increase in microbial activity in peat decomposition and CO_2 emissions (Teh et al., 2005; Hirano et al., 2009; Andersen et al., 2013; Webster et al., 2013 Husen et al., 2014; Husnain et al., 2014; Marwanto and Agus, 2014; Van Noordwijk et al., 2014; Saptomo et al., 2023). Furthermore, it should be noted that the results of this study may vary slightly when using peat soil with an immature decomposition level (fibric). The peat decomposition rate at the soil sampling location falls within the sapric and hemic categories, with a decomposition level of H5 to H9. Immature peat, the fibric, indicates early-stage decomposition, potentially contributing to relatively higher CO_2 emissions.

Conclusion

The controlled conditions in this study provide a clear description of the impact of anaerobic conditions on peat decomposition. It is evident that a positive decrease in GWT enhances CO_2 emissions, resulting in an overall increase in emitted quantities. This study also illustrates that under controlled conditions, emission factors can be quantified for every 10 cm decrease in GWT. Moreover, the findings of this research can contribute additional information to the understanding of ecosystem dynamics and serve as a reference for the improvement of regulations related to the protection and management of peatland ecosystems.

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