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RESEARCH ARTICLE

Effect of peat water levels on greenhouse gas production in different cropping land use

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ABSTRACT

Degraded peat has a high potential for use in agricultural production, especially food crops. The water table, which impacts the production of greenhouse gases (GHGs), is the main problem concerning peat utilization. The study aimed to determine the production of greenhouse gases at various peat water levels. The study was conducted in a laboratory setting utilizing the soil column of undisturbed peat soil. The factorial experiment was arranged in randomized block design, with three replicates, with the first factor was peat cropping use: Maize (*Zea mays* L.), pineapple (*Ananas comosus* (L.) Merr.), and scrubs. The second factor was water level (0, 10, 20, 30 cm depth). Variables measured were GHG flux (CO_2 and CH_4), pH, redox potential, total C content, and ash content. The peat cropping use interacted significantly with the peat water level on the potential for CH_4 and CO_2 production and the value of global warming potential. Water table depth significantly increased CO_2 flux and global warming potential (GWP) in all three peat cropping uses. The lowest GWP at a 0 cm peat water level was 944 (pineapple use), 961 (maize use), and 1097 mg CO_2e m^{-2} d^{-1} (scrub use). Peat for pineapple cultivation produces the lowest CO_2 production and GWP compared to maize cultivation and scrubs. The negative relationship between redox potential and GWP is significant in peat for scrub. The relationship between pH and GWP is significant in peat for pineapple and scrub.

Key words: Carbon dioxide, global warming potential, methane, peat soils, water level.

INTRODUCTION

Peatland is created by the gradual accumulation of organic material over hundreds of years in anaerobic and waterlogged conditions (Hairani et al., 2024). Peatland plays various roles, such as enhancing productivity, however, its utilization exerts an indirect impact on environmental factors such as the production of greenhouse gases (GHGs). In Indonesia, there are 14.9 million hectares of tropical peatland areas, primarily located in Sumatra, Kalimantan, and Papua (Wahyunto et al., 2014; Anda et al., 2021). Approximately 4.2 million hectares of this expanse have the potential for agricultural development. Effective management of peat hydrology is crucial for using peatland for agricultural purposes. Over the past three decades, peatlands have been actively utilized for agricultural activities, including cultivating food crops, horticultural crops, and estate plants. The rapid conversion of peatland forests to alternative land uses, particularly for agriculture, diminishes peat stability and accelerates peat degradation (Wigena et al., 2015; Surahman et al., 2018; Zulkarnaini et al., 2022). With a coverage of 3% of the earth's surface area (4 000 000 km^2), peatlands store an estimated 550 Gt C (Beaulne et al., 2021). Currently, northern peatlands, characterized by thick

(> 30 to 40 cm) organic sediments, are estimated to contain 400 to 500 Pg C, while tropical peatlands hold approximately 105 Pg C (Abdalla et al., 2016; Treat et al., 2019). Under natural circumstances, in the presence of abundant moisture, peatlands maintain their wet state, thereby effectively preserving the substantial C reserves.

Reclaiming natural peat for various purposes, such as agriculture, will disrupt its hydrological characteristics, which are typically characterized by constant wetness and inundation throughout the year. The conversion of peatlands for agricultural purposes can lead to a reduction in the soil surface because of the accelerated decomposition of peat and the source of greenhouse gases (Widiarso et al., 2020). One of the initiatives aimed at reclaiming peatlands for a variety of purposes involves the implementation of drainage systems. Draining peatlands not only enhances the hydrological conditions for diverse purposes, but it also accelerates the process of decomposition and oxidative conditions in peat, leading to detrimental effects such as subsidence, irreversibility, and the release of greenhouse gases (GHGs) (Abdalla et al., 2016; Berglund et al., 2021; Li et al., 2021; Saharjo and Novita, 2022). The types of land use can impact the rate and movement of GHG emissions, thereby altering the contribution of each GHG in different land use categories (Ishikura et al., 2018). Therefore, the contribution of each GHG may vary among land use types (Wachiye et al., 2020).

Peatland drainage instigates deterioration, which is perceived as one of the factors contributing to the loss of C or the emission of GHGs from peat. The emission of CO_2 from drained peat soils releases when the oxygenated uppermost layer of peat decomposes, whereas methane (CH_4) can be engendered in the deeper, water-saturated stratum by methanogens and potentially oxidized in the oxygenated upper stratum by methane-oxidizing bacteria (Norberg et al., 2021; Klemme et al., 2022). In wetland soils, CH_4 is produced in the anaerobic areas of submerged soils by methanogens. In aerobic areas, CH_4 is transformed into CO_2 by methanotrophs and is discharged into the atmosphere when the equilibrium between production and consumption is positive (Abdalla et al., 2016). Currently, degraded peatlands discharge approximately 2000 Mt CO_2 equivalent (CO_2e) of GHGs through microbial oxidation, accounting for 4% of all anthropogenic emissions, excluding fires (UNEP, 2022). Fires occurring on drained peatlands are particularly grave as they can result in exceedingly substantial emissions of GHGs (UNEP, 2022). Oxidative conditions expedite the rate of organic matter decomposition and liberate a substantial amount of CO_2 (Normand et al., 2021).

Greenhouse gases such as CO_2, CH_4, and nitrous oxide (N_2O) have the potential to create a heat-trapping layer in the atmosphere, leading to the reflection of infrared rays emitted by the earth's surface. The rise in anthropogenic GHG emissions in the atmosphere is contributing to an increase in the earth's surface temperature, a trend that has been observed since the previous century and is projected to continue with an expected rise of 1.0-3.7 °C by the conclusion of the 21st century (Li et al., 2021). The warming impact of CH_4 and N_2O gases (referred to as global warming potential) in the atmosphere is significantly greater than that of CO_2, with respective values of 21 and 296 times (IPCC, 2014). According to the Ministry of the Environment and Forestry (2021) of the Republic of Indonesia, national GHG emissions experienced an increase from 1453 Gg CO_2e in 2012 to 1457 Gg CO_2e in 2016, largely driven by emissions from land use change and forestry (LUCF), including peat fires (43.59%) and energy (36.91%), respectively. Generally, CO_2 emission from natural peat forests is outweighed by its sequestration, resulting in the average growth of natural peatlands ranging from 0.5 to 1.0 Mg C ha^{-1} yr^{-1} (Wigena et al., 2015). The release of CH_4 from peatlands into the atmosphere is contingent upon the equilibrium of CH_4 production, oxidation, and transportation rate (Li et al., 2021). In Central Kalimantan of Indonesia, CH_4 emission from peatlands was measured at 5.71 mg m^{-2} h^{-1}, while from rice fields it was 9.40 mg m^{-2} h^{-1} (Rumbang, 2015; Nurzakiah et al., 2020). Alterations in the water table due to peat drainage exert an influence on the dynamics of GHG fluxes (van Huissteden et al., 2006). Jaenicke et al. (2010) documented that for every 10 cm increase in drainage depth, an average of 9 t CO_2 ha^{-1} yr^{-1} would be released. Specifically, it has been demonstrated that the critical drainage depth in oil palm plantations in Sarawak is 60 cm (Busman et al., 2023), and for agricultural land in Central Kalimantan it is 30 cm (Rumbang, 2015).

The objective of this research was to determine the production potential of greenhouse gases (CO_2 and CH_4) on different water levels from peatland used for agricultural crop cultivation.

MATERIALS AND METHODS

Experimental design

The laboratory experiment was conducted using a factorial randomized block design with three replicates. The first-factor treatment included peat samples from maize (*Zea mays* L.) cultivation (P1), pineapple (*Ananas comosus* L. Merr.) cultivation (P2), and scrubs (P3), while the second-factor treatment involved different water levels: 0 (W0), 10 (W1), 20 (W2), and 30 cm depth (W3). The selection of peat samples from maize, pineapple, and scrub cultivation was based on the historical land use over 3 yr. Farmers typically apply ameliorant materials in peatland for each cropping season, as shown in Table 1. The peat samples were collected from Jabiren peatland, Pulang Pisau Regency, Central Kalimantan, situated along the banks of the Jabiren River, a tributary of the Kahayan River, approximately at the Trans Kalimantan km 55 road from Palangka Raya to Banjarmasin, or at coordinates 2º30'54" S and 114º10'11" E. It is noted that Jabiren peat generally has a depth of around 6 m (Maswar, 2013).

Table 1. Ameliorant materials applied on maize and pineapple in peatland. Chicken manure and dolomite are applied before planting time, while NPK, SP36, and urea are applied 1 mo after planting.

Ameliorant	Maize	Pineapple
Chicken manure, t ha^{-1}	1.25	0.6
Dolomite, t ha^{-1}	1.6	0.8
NPK, kg ha^{-1}	250	150
SP36, kg ha^{-1}	200	125
Urea, kg ha^{-1}	50	50

Parameters observed

Samples of peat were collected from soil columns representing three different peat utilization methods at a 50 cm depth. The peat columns were housed in closed cylindrical PVC pipe chambers, equipped with injection septum, electrode holes, and thermometer holes. These chambers had a diameter of 11 cm and a height of 50 cm. The water level in the columns was maintained and monitored using a plastic hose. The peat samples underwent a 3-mo incubation period, commencing on 23 April 2020. Gas samples for greenhouse gas (GHG) flux analysis (CO_2 and CH_4) were collected biweekly, while pH and redox potential were measured concurrently with air sampling. Redox potential measurements were limited to 30 cm depth due to electrode constraints. The organic C content of the peat in the three cropping uses was determined using the dry ashing method (Hamzah et al., 2019).

Gas samples were obtained using a 10 mL injector at T_0 and after 24 h (T_{24}). These samples were then injected into a gas chromatograph with a thermal conductivity detector (TCD) and a flame ionization detector (FID) to quantify the concentrations of CO_2 and CH_4, respectively. The potential production of CO_2 and CH_4 was calculated using the formula used by Susilawati et al. (2020):

$$E = (C_{24}-C_0) \times Vh/Ws \times mW/mV \times 273.2/(273.2+T) \quad \ldots\ldots\ldots\ldots (1)$$

where E is production of CO_2 or CH_4 (mg g^{-1} soil d^{-1}), C_0 is concentration of CO_2 or CH_4 at 0 h (mg kg^{-1}), C_{24} is concentration of CO_2 or CH_4 at 24 h (mg kg^{-1}), Vh is volume headspace in soil column (mL), Ws is weight of soil sample (g), mW is molecule weight of CO_2 or CH_4 (g), mV is molecule volume of CO_2 or CH_4 (22.4 L at standard temperature and pressure in mol L^{-1}), T is average temperature in soil column (°C).

The measurement of GHG emissions was also indicated through the utilization of the global warming potential (GWP) index, which facilitated the computation of the emissions of specific GHGs by converting them into CO_2 equivalents (Golasa et al., 2021). According to Susilawati et al. (2020) and based on IPCC (2014), the GWP was computed using the equation $[CO_2] \times 1 + [CH_4] \times 25$; where $[CO_2]$ is flux of CO_2 and $[CH_4]$ is flux of CH_4.

Data analysis

Data of flux of CH_4 and CO_2 was processed and statistically analyzed with the ANOVA test using SPSS software (IBM, Armonk, New York, USA) followed by the Duncan multiple range test (DMRT) at the 5% level to find out the significant difference in the mean between treatments.

RESULTS AND DISCUSSION

Content of ash and organic C in peat soil

The use of peatlands determines the diversity of organic C and ash content in peat. The ash content in the peat used to cultivate maize, pineapple, and scrubs ranged from 0.03%-2.49%, 0.44%-4.10%, and 0.07%-2.48%, respectively, with the average shown in Table 2. The organic C content in peat used to cultivate maize, pineapple, and scrubs ranges from 10.91%-16.82%, 11.52%-16.24%, and 10.33%-16.91%, respectively. Peatland typically has a composition of more than 65% organic matter and a thickness exceeding 50 cm (Hairani et al., 2024). As a C store, degraded peat will release C in the form of CH_4 and CO_2. Based on the ash content, the peat in the three land uses is categorized as oligotrophic peat (2%-5%) (Noor et al., 2014), which generally has a low fertility rate, and its formation is influenced by rainwater. The ash content decreases with the depth of the peat. Oligotrophic peat generally consists of thick peat and poor nutrients (Arabia et al., 2020).

Based on bulk density value, the peat in the three cropping uses is classified as fibrous peat, especially in layers > 50 cm. According to Arabia et al. (2020), fibrous peat has a bulk density (BV) < 0.075 g cm^{-3} and total porosity > 90%, hemic if BV is 0.075-0.195 g cm^{-3} and total porosity is 85%-90%, and sapric if BV > 0.195 g cm^{-3} and total porosity < 85%.

Table 2. Content of ash and organic C in peat used for maize, pineapple, and scrub. Values averaged from six subsamples.

Commodities	Organic C	Ash content
	%	%
Maize	12.90 ± 2.26	1.11 ± 1.00
Pineapple	14.06 ± 1.81	1.77 ± 1.23
Scrub	14.11 ± 2.53	1.34 ± 1.05

Greenhouse gases flux

The pattern of CH_4 flux in the soil column differs between peat cropping uses. Figure 1 shows that the pattern of CH_4 flux in maize is relatively the same as in scrubs, with peaks on observations of 21 May, 4 June, and 16 July 2020, while the peak on peat for pineapple occurred on 16 June 2020. In general, the daily CH_4 production from peat cultivated with maize is higher than from peat under pineapples and scrub crops. Daily CH_4 production at a water level of 10 cm is relatively lower than others. The decrease in CH_4 production occurred after more than 2 mo incubation in the three peat cropping uses. However, it increased again on the observation on 16 July 2020. The water level of 10 cm produced CH_4 flux lower relatively than others.

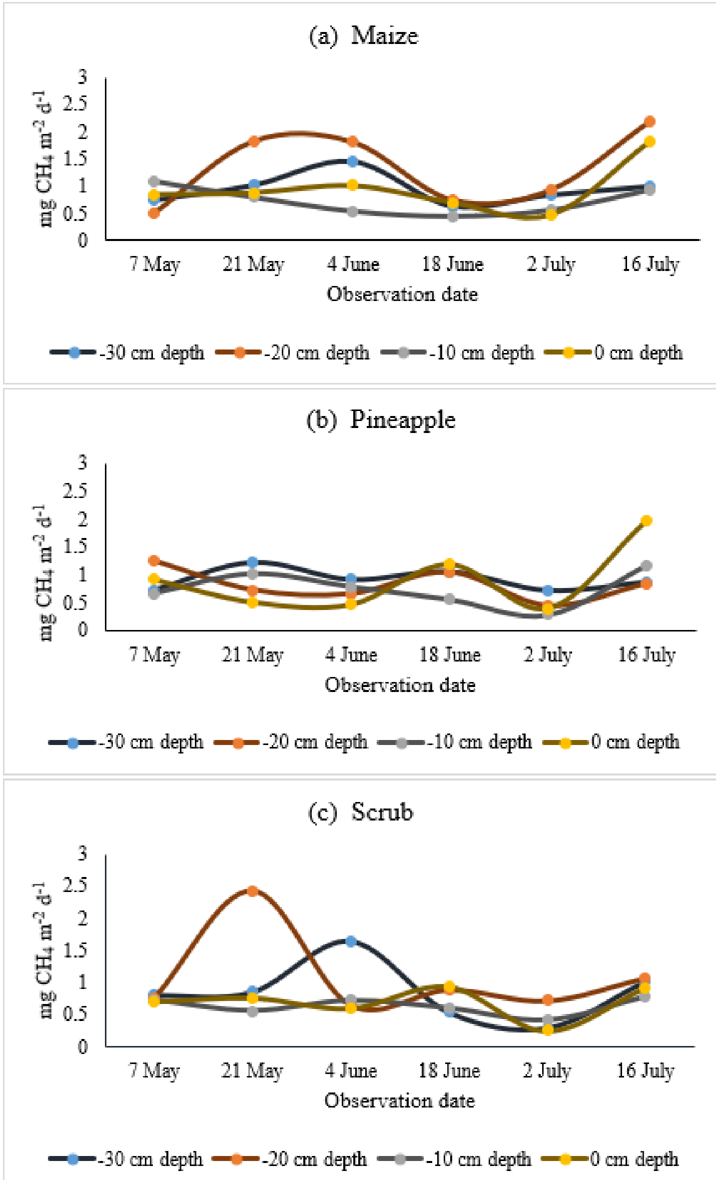

Figure 1. Methane flux in peat from three cropping uses and different water levels, in 2020.

Figure 2 presents the fluctuating pattern of CO_2 fluxes in three-peat cropping uses. The daily CO_2 production from peatlands for scrubs is higher than peatlands for maize and pineapple. The deeper the water level produces, the higher the daily CO_2. The CO_2 peak from peatlands occurred on 4 June and 2 July 2020 (for maize), 7 May and 2 July 2020 (for pineapple), 4 and 18 June 2020 (for scrubs), respectively.

Peat cropping use significantly interacts with the peat water level on the potential for CH_4 production (Table 3). Table 3 shows that CH_4 flux at the water level of 20 cm is generally higher than other water levels in three-peat cropping uses. The CH_4 flux at 30 cm water level does not differ significantly from 10 and 0 cm.

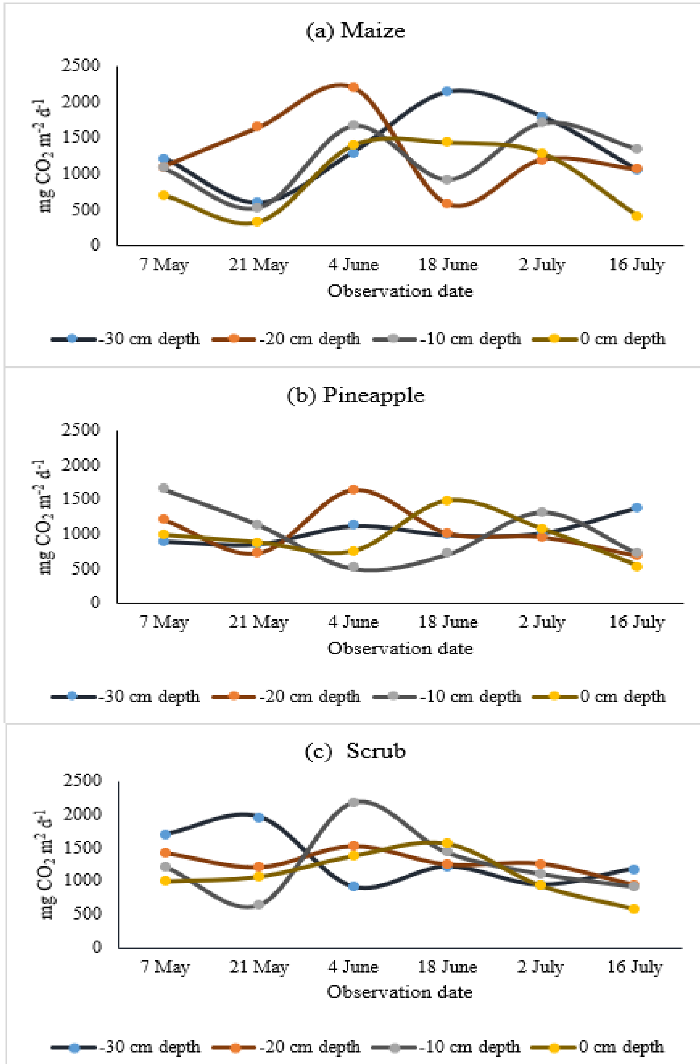

Figure 2. Carbon dioxide flux in peat from three cropping uses and different water levels, in 2020.

Peat cropping use exhibits a significant interaction with the water level in peat, thereby affecting the potential for CO_2 production as evidenced in Table 3. The emission of CO_2 diminishes as the water level in the peat rises; however, it increases when the depth of the water level declines during the process of drainage. Moreover, the reduction of the water level in the peat significantly augments the CO_2 flux in all three peat cropping uses, as shown in Table 3. The act of lowering the water table through drainage entails alterations in the biological, chemical, and physical attributes of the soils, thereby promoting soil aeration, as highlighted by Abdalla et al. (2016). This condition results in an acceleration of CO_2 production and subsequent release. It is important to note that the peat cropping use exhibits a significant interaction with the water level in peat, thereby impacting the potential for global warming, as shown in Table 3. The lowest GWP at a 0 cm peat water level was 944 (pineapple use), 961 (maize use), and 1097 mg CO_2e m^{-2} d^{-1} (scrub use). In maize and scrub uses, GWP is higher than in pineapple use. GWP information from the use of peat at different water table depths is important as a consideration in development for cultivation and conservation that ensures environmental sustainability. Cultivation development should be carried out in integrated and sustainable practices by implementing low external input sustainable agriculture (LEISA) and zero waste principles (Hairani et al., 2024).

Table 3. Greenhouse gas fluxes in three peat cropping uses and different water levels. Means in the same column followed by the same letters do not differ significantly at DMRT ($p \leq 0.05$), GWP: Global warming potential. CO_{2e}: CO_2 equivalents.

Peat cropping uses	Water level depth	CH_4 flux	CO_2 flux	GWP
	cm	mg CH_4 m^{-2} d^{-1}	mg CO_2 m^{-2} d^{-1}	mg $CO_{2}e$ m^{-2} d^{-1}
Maize	30	0.94^{bc}	1343^{a}	1363^{a}
	20	1.34^{a}	1294^{ab}	1322^{ab}
	10	0.72^{cd}	1201^{abcd}	1216^{a-d}
	0	0.96^{bc}	924^{e}	944^{e}
Pineapple	30	0.91^{bcd}	1036^{cde}	1055^{cde}
	20	1.04^{b}	1027^{cde}	1049^{cde}
	10	0.75^{cd}	1003^{de}	1018^{de}
	0	0.90^{bcd}	943^{e}	961^{e}
Scrub	30	0.73^{cd}	1311^{ab}	1327^{ab}
	20	1.09^{ab}	1261^{abc}	1284^{abc}
	10	0.63^{d}	1248^{abcd}	1262^{a-d}
	0	0.71^{cd}	1082^{bcde}	1097^{b-e}
p-value		0.0010	0.0050	0.0048

Redox potential and pH in different cropping uses

Global warming potential (GWP) is affected by the physicochemical conditions of the peat, such as redox potential and soil acidity. As shown in Figure 3, a decrease in the peat water level for crops (maize and pineapple) and scrub increases the GWP. The relationship between peat water level and GWP is significant on peat overgrown with scrubs ($p < 0.05$) as shown by the linear equation Y = -0.0023X + 1.1323 (R^2 = 0.6952) (Figure 3c), whereas the relationship is nonsignificant for peat for maize cultivation (Figure 4a), and for peat for cultivation pineapple (Figure 3b) as shown by the linear equation Y = -0.0021X + 1.3027 (R^2 = 0.243), and Y = -0.0011X + 1.077 (R^2 = 0.3087), respectively, where Y is the GWP and X is the redox potential. The increase in redox potential increases the GWP, meaning that the oxidative peat condition triggers the release of GHGs, especially CO_2. The reductive conditions of peat for cultivating crops and scrub will benefit GHG-producing microbes, primarily CH_4. Plants with different root structures would be associated with contrasting oxygen inputs and resultant GHG emissions (Girkin et al., 2020).

The peat acidity (pH) in peat used for agricultural crop cultivation tends to be lower than peat for scrubs. The average pH values of peat for pineapple, maize, and scrubs were 3.76, 3.73, and 3.53. An increase in the depth of the peat water table generally tends to lower the peat pH or increase the peat acidity. The average pH values of peat treated with depth water levels of 30, 20, 10, and 0 cm were 3.45, 3.56, 3.75, and 3.93. Figure 4 visually portrays a negative correlation between soil pH and GWP in the case of maize, pineapple, and scrubs. The relationship between pH and GWP is significant for peat employed in pineapple cultivation and scrubs ($p < 0.05$), whereas an insignificant relationship is observed for peat utilized in maize cultivation ($p > 0.05$). The research findings of Maftuah et al. (2022) report that an increase in peat pH corresponds to an increase in CO_2 emissions in peat utilized for shallot cultivation. The CO_2 emissions in the pH range of 4.8-6.0 display a strong association with the respiration activity of soil organisms in peatlands designated for shallot cultivation (Maftuah et al., 2022). Acid conditions notably diminishes root biomass (Meng et al., 2019). In peat soil from all cropping uses, an augmentation in peat pH results in a decrease in GWP. Multiple studies have reported that GHG emissions are elevated at low peat pH, as exemplified by a research report authored by Nielsen et al. (2023). Maize and scrubs are plants that display tolerance to acidic soil conditions and can flourish in such environments. Peatland generates organic acids that contribute to the acidification of peat soil. The abundant organic acids undergo decomposition, thereby producing substantial amounts of CO_2 and CH_4 in the peatland. According to Dommain et al. (2014), an increase in pH can lead to a decline in C emissions due to its promotion of the growth of specific types of vegetation, such as *Sphagnum mosses*, which possess a notable capacity for C sequestration. This signifies that the development of technologies capable of increasing the pH of degraded peats represents an endeavor to mitigate GHG emissions. The relationship between pH and GWP in various land use types in the field necessitates a comprehensive examination to ascertain the factors that exert influence upon them.

Maintaining a low pH in peatlands is essential for preserving their C storage capacity and reducing C emissions. It can be achieved through various management practices, such as avoiding drainage, reducing fire incidence, and restoring degraded peatlands.

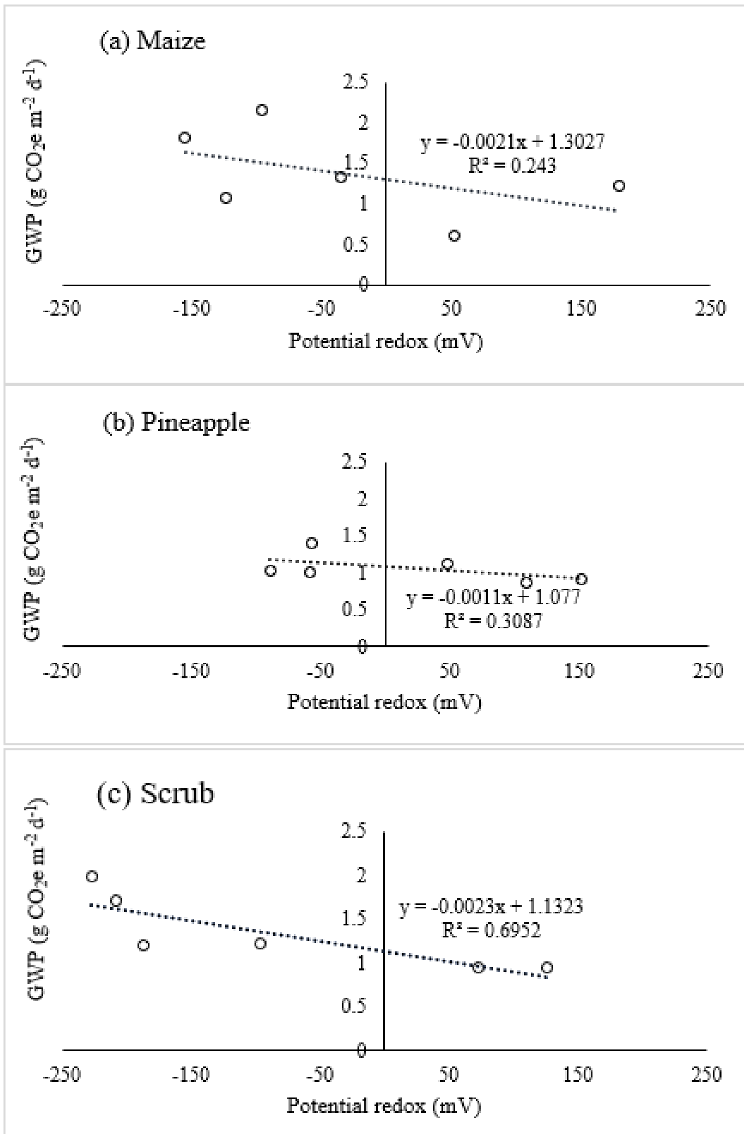

Figure 3. Relationship between redox potential and global warming potential (GWP) in peatland used for plant cultivation.

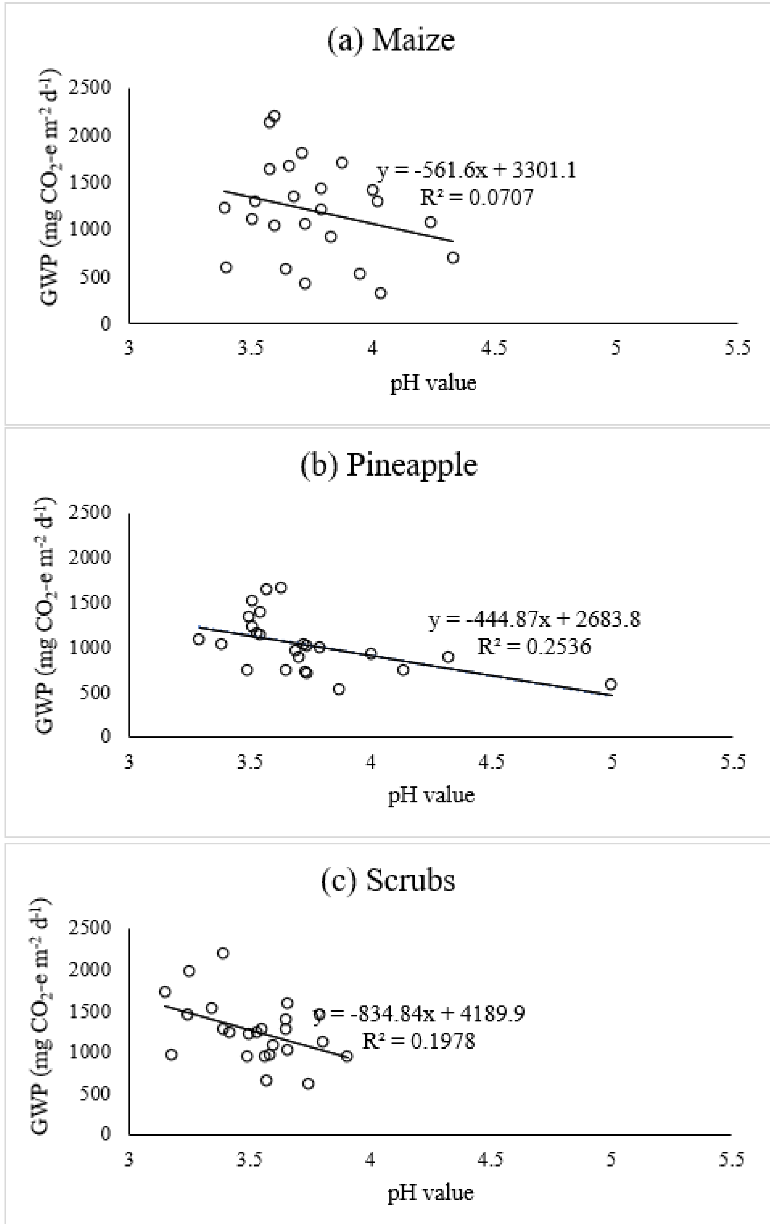

Figure 4. Relationship between pH value and global warming potential (GWP) in three peat cropping uses.

CONCLUSIONS

Peat cropping use and water level interaction significantly affect greenhouse gas flux and global warming potential (GWP). In all three peat cropping uses, the depth of the water table has a notable effect on the increase of CO_2 flux and GWP. When peat is used for pineapple cultivation, it results in the lowest production of CO_2 and GWP compared to its use for maize cultivation and scrubs. The GWP index is influenced by the redox potential and soil acidity. The inverse correlation between redox potential and GWP is particularly noteworthy in peat used for scrubs. The rise in pH value has a significant impact on reducing GWP in peat used for pineapple cultivation and scrubs.

Author contribution

Conceptualization: A.W., E.S.H., M.T.S. Methodology: A.W., E.S.H., M.T.S. Software: A.W., E.S.H., N.A.V., T.A.A. Validation: A.W., M.T.S. Formal analysis: A.W., E.S.H., I.M.S. Investigation: A.W., M.T.S., T.A.A. Resources: A.W., E.S.H. Data curation: A.W., E.S.H. Writing-original draft: A.W., E.S.H., M.T.S., A.N.A., I.M.S. Writing-review & editing: A.W., E.S.H., M.T.S., I.M.S., A.N.A., N.A.V., T.A.A. Visualization: A.W., E.S.H. Supervision: A.W., E.S.H. Project administration: A.W., T.A.A., M.T.S. Funding acquisition: A.W., T.A.A., M.T.S. All authors reviewed the final version and approved the manuscript before submission.

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