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Variation in Soil Properties Regulate Greenhouse Gas Fluxes and Global Warming Potential in Three Land Use Types on Tropical Peat

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Abstract: This study investigated spatial factors controlling CO₂, CH₄, and N₂O fluxes and compared global warming potential (GWP) among undrained forest (UDF), drained forest (DF), and drained burned land (DBL) on tropical peatland in Central Kalimantan, Indonesia. Sampling was performed once within two weeks in the beginning of dry season. CO₂ flux was significantly promoted by lowering soil moisture and pH. The result suggests that oxidative peat decomposition was enhanced in drier position, and the decomposition acidify the peat soils. CH₄ flux was significantly promoted by a rise in groundwater level, suggesting that methanogenesis was enhanced under anaerobic condition. N₂O flux was promoted by increasing soil nitrate content in DF, suggesting that denitrification was promoted by substrate availability. On the other hand, N₂O flux was promoted by lower soil C:N ratio and higher soil pH in DBL and UDF. CO₂ flux was the highest in DF (241 mg C m⁻² h⁻¹) and was the lowest in DBL (94 mg C m⁻² h⁻¹), whereas CH₄ flux was the highest in DBL (0.91 mg C m⁻² h⁻¹) and was the lowest in DF (0.01 mg C m⁻² h⁻¹), respectively. N₂O flux was not significantly different among land uses. CO₂ flux relatively contributed to 91–100% of GWP. In conclusion, it is necessary to decrease CO₂ flux to mitigate GWP through a rise in groundwater level and soil moisture in the region.

Keywords: greenhouse gas emission; tropical peatland; global warming potential; land use

1. Introduction

Peat soils are generated through the accumulation of undecomposed plant materials from thousands of years ago and play a role of net carbon (C) sink during the Holocene [1,2]. The peat soils are distributed only 3% of the global terrestrial area but occupy around one-third of global soil C stocks [3,4]. In tropical area, peatland is predominantly composed of woody materials rather than mosses, and 88.6–104.7 Pg C are stored in tropical peatland [4,5]. However, forest cover has been lost by peat fire and land reclamation in tropical peatland [6,7], and the tropical peat soils have been decomposed rapidly due to drainage and land use change especially since the 1990s [6,8]. The rapid decomposition of peat influences global C cycles [9,10], which is a globally and regionally urgent issue.

To date, greenhouse gas (GHG) fluxes from tropical peatland have mainly been studied to explain the temporal variations. It is because large temporal variations in GHG fluxes mainly due to clear seasonal change in meteorology: dry and rainy seasons. Researchers in tropical peatland revealed that

carbon dioxide (CO₂) flux is promoted by lowering groundwater level (GWL) [11–15] and by increasing root respiration, which contributes 21–62% to soil respiration [16,17]. Methane (CH₄) flux is promoted by a rise in GWL [18–20]. Because redox potential determines the balance between CO₂ and CH₄ fluxes, microtopography is also important [21,22] as well as seasonal variations in GWL. Furthermore, CO₂ and CH₄ fluxes are influenced by inputs of organic matter through litter fall and root exudates [23] and by quality of organic matter [24,25], which are different among plant species. Nitrous oxide (N₂O) flux is promoted by increasing nitrate content under moderately anaerobic condition via denitrification [26,27] and by increasing nitrification. Aggregates are developed in peat soils as well as mineral soils, and denitrification can occur in micro spots in aggregates [28]. Thus, researchers have measured these environmental factors with a high temporal resolution, obtained the relationship between GHG fluxes and the environmental factors, and calculate GHG emissions by the sum of fitted GHG fluxes [12,22].

Nevertheless, the evaluation of GHG emissions remains high uncertainties in tropical peatland. The environmental factors controlling GHG fluxes vary spatially due to land use [27,29], microtopography of peat surface [30], and location in a peat dome [31]. Thus, the high uncertainties of GHG emissions might be due to large spatial heterogeneity. However, studies on spatial variations and spatial controlling factors of GHG fluxes are still limited in tropical peatland and have not been understood well.

Controlling factors are different for each GHG. CO₂ flux is promoted by drainage [29] whereas the CH₄ flux is enhanced by the development of the anaerobic condition [32,33]. Thus, higher soil water content will decrease CO₂ flux but increase CH₄ flux. Neutralization of soil acidity would also increase CO₂ and CH₄ production potential [34]. On the other hand, N₂O flux is promoted by 60–70% of water-filled pore space (WFPS) [27,35], higher nitrate content [27], and acidified condition [36]. Because the mitigation strategies to reduce each GHG emission are different, it is necessary to quantify how much each GHG contributes to the whole global warming potential (GWP) so that the most important factor is revealed to reduce the whole GWP. However, studies on the contribution of each GHG to GWP are still limited [37].

In Southeast Asian tropical peatland, land use types have drastically changed since 1990s driven by land reclamation [38,39], drainage [40,41], and peat fires [6,42]. These events have led to the patchy distribution of land use types [43]. The land use types have influenced the environmental factors controlling GHG fluxes, and thus GHG fluxes [27,29,32]. Therefore, the contribution of each GHG might be changed in different land use types.

The objectives of this study are (1) to clarify spatial factors controlling GHG fluxes, and (2) to evaluate GWP in different land uses in tropical peatland.

2. Materials and Methods

2.1. Site Description

Study site was located in Kalampangan, near Palangka Raya, Central Kalimantan, Indonesia. Mean annual temperature and precipitation were 26.1°C and 2452 mm yr⁻¹, respectively [44]. Generally, dry season is between July and October in this region. The soil type was a Typic Haplofibrist [45] with typical peat thickness of 3–5 m. Peatland in the area was covered by Kahayan River and Sebangau River. The area was developed by Ex-Mega Rice Project from 1996 to 1999 and has been drained by canals [46]. Because of the canal drainage, a huge area of drained forest was burned in dry seasons almost every year, especially in El Niño-Southern Oscillation (ENSO) years (1997, 2002, 2006, 2009, and 2015) [6], to change into a drained burned forest.

Here, seventeen transect plots (1–17) were established with 500 m intervals from Kahayan River to Sebangau River (Figure 1) to take samples in various peat thickness. The transect line crossed a trunk road between the plot 5 and 6, and a canal between the plot 11 and 12. The road and canal were almost parallel to the rivers. The plots 1–11 were attributed to the drained burned land (DBL), and the plots 12–17 were attributed to the drained forest (DF). Dominant species in the DBL are fern

(*Stenochlaena palustris* (Burm. f.) Bedd. and *Pteris* sp.) and shrub (*Combretocarpus rotundatus* Dancer), and vegetation in the DF is *Shorea balangeran* (Korth.) Burck, *C. rotundatus*, *Xanthophyllum eurhynchum* Miq., etc. [47–49]. Furthermore, samplings were conducted in two more plots (18 and 19) in Sebangau National Park. Sebangau National Park had been suffered by selective logging by 1990s but has not been logged nor drained since 2004. Therefore, plots 18 and 19 were attributed to the undrained forest (UDF). These two plots were out of the transect line, but were selected in this study because there is no longer any undrained forest between Kahayan and Sebangau River, and these two plots were easily accessed due to transportation for Sebangau National Park.

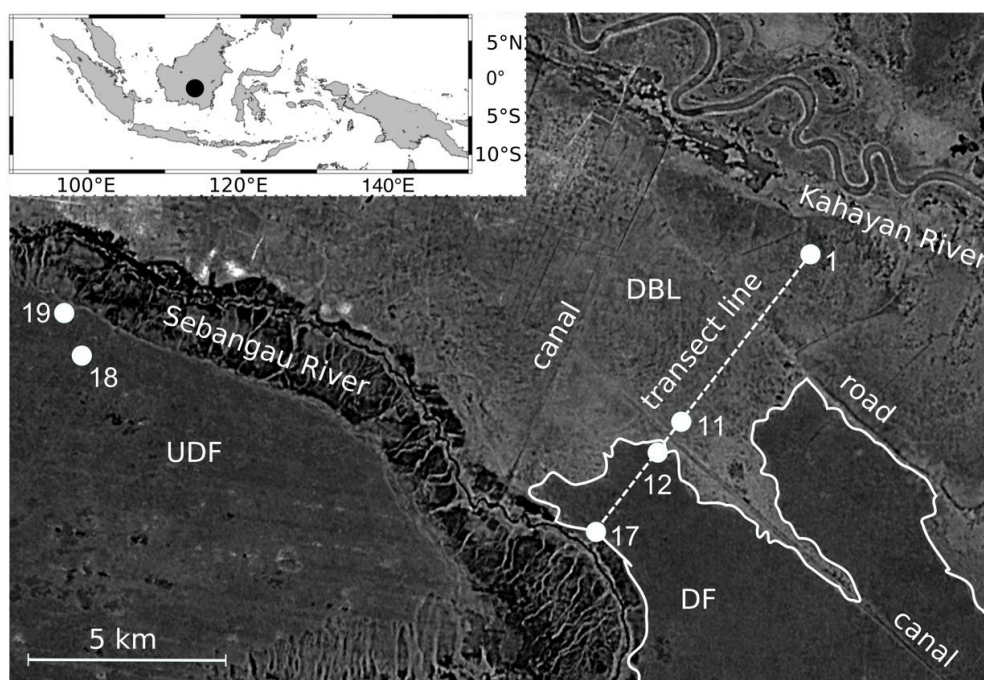


Figure 1. Map of the study site. The study site is located at the black circle of upper left map. Numbers beside the white circles denote plot ID. Plot ID of 1–11 attribute to drained burned land (DBL), 12–17 attribute to drained forest (DF) that was surrounded by the white solid line, and 18–19 attribute to undrained forest (UDF) that was southwest of Sebangau River. Not all plots are shown due to visibility.

2.2. Greenhouse Gas Flux and Environmental Variables

GHG fluxes were measured by a closed chamber method [11] in July 2011, which was the beginning of dry season. Stainless-steel and white-painted chambers with 25 cm height and 18.5–21.0 cm diameter were used. Three chamber collars (inner diameter of 18.2 cm) were installed from depressed (hollows) to medium positions (intermediate between hollows and hummocks) in each plot on the previous date of sampling. Gas samples in the chamber headspace were taken at 0 and 6 min for CO₂ and 0, 20, and 40 min for CH₄ and N₂O after closing chambers. The linearity of increasing gas concentrations over time in the chamber headspace was verified during the chamber closing [50]. Gas samples were stored into Tedlar bags® (GL Sciences Inc., Tokyo, Japan) for CO₂ and into vacuum vial bottles (10 mL) with butyl rubber septum (SV-10, NICHIDENRIKA-GLASS CO., LTD., Kobe, Japan) for CH₄ and N₂O, respectively. CO₂ concentration was analyzed within 10 h after sampling using an infrared CO₂ analyzer (ZFP-9, Fuji Electric Systems, Tokyo, Japan). Concentrations of CH₄ and N₂O were analyzed by gas chromatography (GC-8A and GC-14B, Shimadzu, Kyoto, Japan) with a flame ionization detector (FID) and with an electron capture detector (ECD), respectively. Gas flux (F ; mg C m⁻² h⁻¹ for CO₂ and CH₄, μg N m⁻² h⁻¹ for N₂O, respectively) was calculated by the following equation:

$$F = \rho \times \frac{dc}{dt} \times \frac{V}{S_b} \times \frac{273.15}{273.15 + T_{\text{air}}} \times \alpha \quad (1)$$

where ρ was gas density (1.977 kg m⁻³ for CO₂, 0.717 kg m⁻³ for CH₄ and 1.978 kg m⁻³ for N₂O, respectively), dc/dt was rate of change in gas concentration over time in a chamber headspace during chamber close (10⁻⁶ × m³ m⁻³ h⁻¹ for CO₂ and CH₄, and 10⁻⁹ × m³ m⁻³ h⁻¹ for N₂O), V is the volume of a chamber (m³), S_b is the area of a chamber collar (m²), T_{air} was air temperature (°C), and α was the ratio of molecular weight of C to CO₂ (0.273), C to CH₄ (0.749), and N to N₂O (0.636), respectively. It should be noted that the CO₂ fluxes in this study might be biased because it was calculated by the two time points (0 and 6 min), which could not detect gas leaks, sudden disturbance, etc during the close of the chambers. Nevertheless, the relationship between the multiple-times sampling and the two-points sampling is linear of 1:1 [51], and the bias is less than 20% for the closing of 10 min [50].

GWP (mg CO₂-eq m⁻² h⁻¹) was calculated in each plot by the following equation:

$$\text{GWP} = \frac{F_{\text{CO}_2}}{\alpha_{\text{CO}_2}} + \frac{F_{\text{CH}_4}}{\alpha_{\text{CH}_4}} \times 28 + \frac{F_{\text{N}_2\text{O}}}{\alpha_{\text{N}_2\text{O}}} \times 265 \times 10^{-3} \quad (2)$$

where F_{CO_2} , F_{CH_4} , and $F_{\text{N}_2\text{O}}$ were CO₂, CH₄, and N₂O fluxes, respectively, and α_{CO_2} , α_{CH_4} , and $\alpha_{\text{N}_2\text{O}}$ were α value for CO₂, CH₄, and N₂O described above, respectively. The values of 28 and 265 were relative values of radiative forcing of CH₄ and N₂O to CO₂ over 100-years' time horizon, respectively [52].

Soil temperature (°C) at 4-cm depth and volumetric soil water content (m³ m⁻³; ML2 Theta Probe Delta-Y Devices, Cambridge, UK) were measured in three replications around a chamber collar. Water-filled pore space (WFPS) was calculated by the proportion of volumetric soil water content in soil porosity. To measure groundwater level (GWL, m; positive value represents flooding), a hole was dug at 5–10 m away from the chamber collars when the chamber collars were installed, and GWL in the hole was measured after the sampling of GHG fluxes. Soils in 0–10 cm depth were taken in three replications to make composite samples for soil chemical properties.

Soil samples were air-dried and sieved in 2 mm mesh. Total C and N contents were measured by an elemental combustion analyzer (vario MAX cube CN, Elementar Analysensysteme GmbH, Langensfeld, Germany). Soil samples were extracted by deionized water (1:5 of soil to water), and soil pH (pH meter F-52, Horiba, Kyoto, Japan) and electrical conductivity (EC, mS m⁻¹; CM30V, TOA Electronics Ltd., Tokyo, Japan) were measured, respectively. The water suspension was filtered by 0.2 µm membrane (ADVANTEC M-085, Toyo Roshi Kaisha, Ltd., Tokyo, Japan), and soil NO₃⁻ (mg N kg⁻¹) was measured by an ion chromatography (DIONEX Ion Chromatograph DX-AQ, DIONEX Japan, Osaka, Japan). The soil samples were also extracted by KCl (1:10 of soil to KCl), and NH₄⁺ of the extraction was determined by indophenol-blue method using an ultraviolet-visible (UV-Vis) spectrophotometer (UV mini 1240, Shimadzu, Kyoto, Japan). We hypothesized that the environmental properties above (GWL, soil temperature, soil moisture, and soil chemistry) were the possible factors controlling GHG fluxes.

2.3. Statistical Analysis

To compare the GHG fluxes and soil properties between DF, and DBL, *t*-test was performed. If a variable violates normality by Shapiro test ($p < 0.05$), Wilcoxon test was performed alternatively. Because the sample size of UDF was only two, the data of UDF was not used for statistical comparison. To find out the controlling factors of CO₂ and N₂O fluxes, stepwise (backward) multiple regression analyses were performed based on Akaike Information Criterion (AIC) [53]. The predictors of the full model were listed all in Table 1 except EC because there was a collinearity with soil nitrate. Linear regression was performed for natural log-transformed CH₄ flux using GWL. The transformation of natural logarithm was performed only for CH₄ flux and only for its linear regression. All the statistical analyses were conducted on R software (version 3.5.1) [54].

3. Results

3.1. Environmental Variables

Table 1 shows the environmental variables in DBL, DF, and UDF. GWL was significantly lower in DF than in DBL and UDF ($p < 0.001$). WFPS was also significantly lower in DF ($p < 0.001$). Soil temperature was significantly higher in DBL than in DF and UDF ($p < 0.001$). Total C content was significantly higher in DBL ($p < 0.001$), whereas total N content was significantly higher in DF than in DBL ($p < 0.01$). In consequences, C:N ratio was significantly lower in DF than in DBL ($p < 0.001$). Soil NH_4^+ and NO_3^- content were significantly higher in DF than in DBL ($p < 0.05$ and $p < 0.01$, respectively). Peat thickness, soil pH, EC were not significantly different between DBL and DF.

Table 1. Soil properties in DBL (drained burned land), DF (drained forest), and UDF (undrained forest). Values show mean \pm 1 standard deviation, and the same letters beside the values denote no significant difference between DBL and DF ($p < 0.05$).

Property	DBL ($n = 11$)	DF ($n = 6$)	UDF ($n = 2$)
GWL (m)	$-0.08 \pm 0.07a$	$-0.44 \pm 0.14b$	-0.16 ± 0.07
WFPS ($\text{m}^3 \text{m}^{-3}$)	$0.99 \pm 0.02a$	$0.60 \pm 0.06b$	1.00 ± 0.00
Soil temperature ($^{\circ}\text{C}$)	$29.9 \pm 1.6a$	$26.7 \pm 0.5b$	25.3 ± 0.7
Peat thickness (m)	3.9 ± 0.6	3.4 ± 1.6	2.9 ± 1.8
Total C (g C kg^{-1})	$542 \pm 26a$	$513 \pm 15b$	555 ± 8
Total N (g N kg^{-1})	$17.8 \pm 3.5b$	$22.2 \pm 1.3a$	18.6 ± 0.8
C:N ratio [†]	$32 \pm 11a$	$23 \pm 2b$	30 ± 1
pH (H_2O)	3.8 ± 0.4	3.6 ± 0.1	3.9 ± 0.1
EC (mS m^{-1}) [†]	5.7 ± 4.0	10.7 ± 5.1	1.9 ± 0.1
NH_4^+ (mg N kg^{-1}) [†]	$7.4 \pm 4.4b$	$40.7 \pm 24.7a$	0.7 ± 0.3
NO_3^- (mg N kg^{-1}) [†]	$5.0 \pm 8.5b$	$23.2 \pm 21.3a$	25.7 ± 7.7

[†] Wilcoxon test was applied due to a violation of normality.

3.2. Greenhouse Gas Flux and Global Warming Potential

CO_2 fluxes varied from 8 to 374 $\text{mg C m}^{-2} \text{h}^{-1}$ in all the plots (Figure 2a). CH_4 fluxes varied from -0.04 to 7.69 $\text{mg C m}^{-2} \text{h}^{-1}$ in all the plots (Figure 2b). The maximum CH_4 flux was obtained in the plot 6 where the CO_2 flux was minimum. The CO_2 flux was significantly higher in DF than in DBL ($p < 0.01$, $F_{2,16} = 10.6$; Table 2). In contrast, the CH_4 flux was significantly higher in DBL than in DF ($p < 0.001$; Table 2). The mean CH_4 flux in DBL was 0.23 $\text{mg C m}^{-2} \text{h}^{-1}$ if an outlier of “hot spot” in Plot 6 was excluded. The CH_4 flux in DBL was significantly higher than in DF ($p < 0.01$) even though the outlier was excluded. In plot 6, NH_4^+ content was almost double (14.3 mg N kg^{-1}) compared with the mean in DBL. N_2O fluxes varied from -46.7 to 97.8 $\mu\text{g N m}^{-2} \text{h}^{-1}$ (Figure 2c) and were not significantly different among land uses ($p = 0.42$; Table 2). GWP was significantly higher in DF than in DBL ($p < 0.01$; Table 2). However, GWP in UDF was not significantly different from DBL and DF (Table 2). CO_2 flux was the largest contributor for GWP in all land uses, while CH_4 and N_2O fluxes showed the minor contribution to GWP (Table 2).

Stepwise multiple regression analysis for CO_2 flux showed WFPS and soil pH were significant predictors ($p < 0.001$; Table 3) selected from the environmental variables in Table 1 excluding EC due to collinearity with soil nitrate content. The result shows that CO_2 flux was negatively correlated with WFPS and soil pH (Figure 3a). The CO_2 flux was also significantly correlated with GWL (Figure 3b), but R^2 and AIC were better for the model using WFPS and pH (Table 3). CH_4 flux showed a significantly exponential relationship with GWL ($p < 0.01$; Table 3, Figure 4). Negative CH_4 fluxes were obtained when GWL was below -0.3 m. Stepwise multiple regression analysis for N_2O flux showed soil C:N ratio and pH were significant predictors ($p < 0.05$) for all land uses. However, N_2O flux showed significantly positive correlation with soil nitrate only in DF (Figure 5a, Table 3). Then, stepwise multiple regression analysis was performed again for N_2O flux only in UDF and DBL. The result showed that soil C:N ratio and pH were selected as significant predictors (Figure 5b, Table 3).

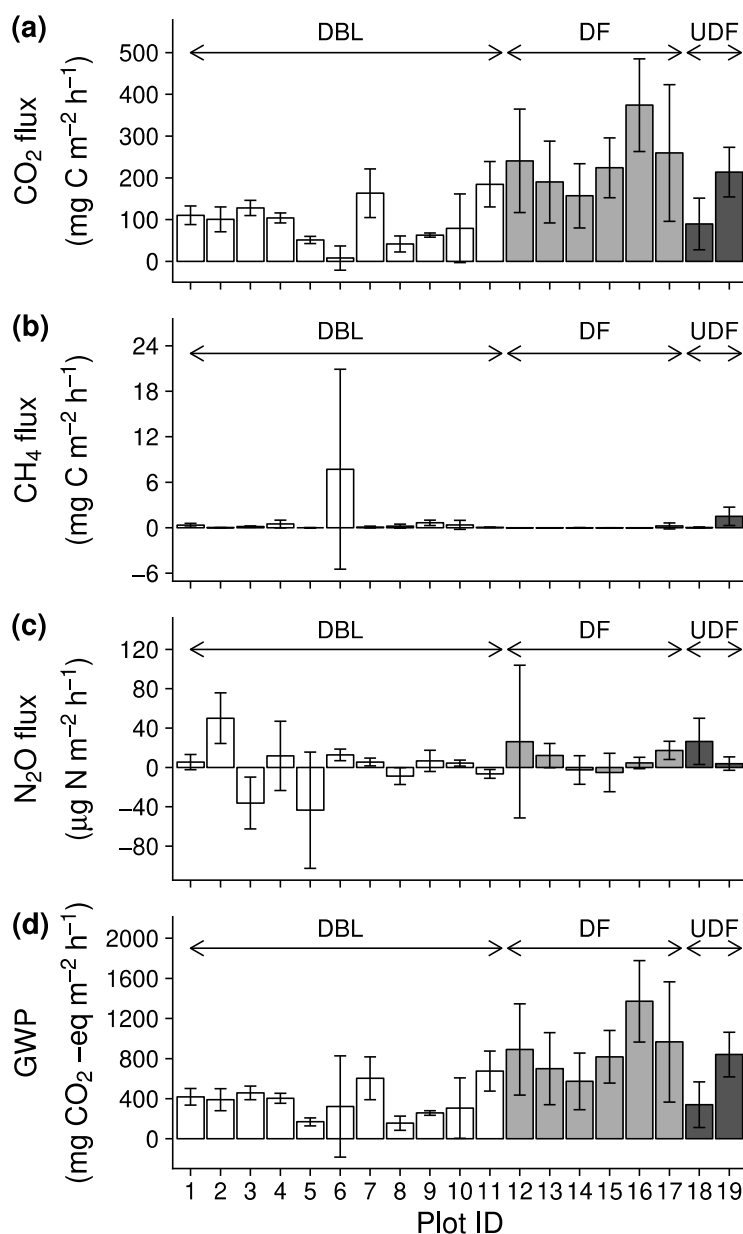


Figure 2. (a) CO₂ flux, (b) CH₄ flux, (c) N₂O flux, and (d) global warming potential (GWP) in each plot of DBL (drained burned land), DF (drained forest), and UDF (undrained forest). Error bars show ±1 SD.

Table 2. GHG (greenhouse gas) fluxes and GWP (global warming potential) in DBL (drained burned land), DF (drained forest), and UDF (undrained forest). GWP was based on radiative forcing over a 100-years’ time horizon: CO₂ = 1, CH₄ = 28, and N₂O = 265. Values represent mean ± 1 SD (% relative contribution to GWP). Same letters denote not significantly different between DBL and DF (*p* < 0.05).

Greenhouse Gas Flux	DBL	DF	UDF
	(<i>n</i> = 11)	(<i>n</i> = 6)	(<i>n</i> = 2)
CO ₂ (mg C m ⁻² h ⁻¹)	94 ± 53 (91)a	241 ± 75 (100)b	152 ± 88 (94)
CH ₄ (mg C m ⁻² h ⁻¹) [†]	0.91 ± 2.26 (9)b	0.01 ± 0.11 (0)a	0.76 ± 1.03 (5)
N ₂ O (µg N m ⁻² h ⁻¹)	0.1 ± 25.0 (0)	8.7 ± 12.1 (0)	15.2 ± 16.0 (1)
GWP (mg CO ₂ -eq m ⁻² h ⁻¹)	378 ± 162a	886 ± 275b	590 ± 354

[†] Wilcoxon test was applied due to a violation of normality.

Table 3. Multiple regression analysis for GHG (greenhouse gas) fluxes. R^2 represents the determination of coefficients, and AIC represents Akaike information criterion (Akaike 1987). Higher R^2 and lower AIC show better model.

Target	Land Use	Equation	p -Value	R^2	AIC
CO ₂ flux	All	CO ₂ = 690 – 303 × WFPS – 75 × pH	<0.001	0.53	216
	All	CO ₂ = 82 – 323 × GWL	<0.01	0.45	218
CH ₄ flux	All	Null model			228
	All	Ln[CH ₄ + 0.07] = –1.26 + 4.16 × GWL	<0.01	0.42	56
	All	Null model			65
N ₂ O flux	All	N ₂ O = –64.0 – 1.37 × C:N + 29.2 × pH	<0.05	0.35	166
	All	Null model			172
	DF	N ₂ O = –2.24 + 0.47 × NO ₃ [–]	<0.05	0.69	45
	DF	Null model			50
	UDF, DBL UDF, DBL	N ₂ O = –63.5 – 1.37 × C:N + 28.8 × pH Null model	<0.05	0.38	119 122

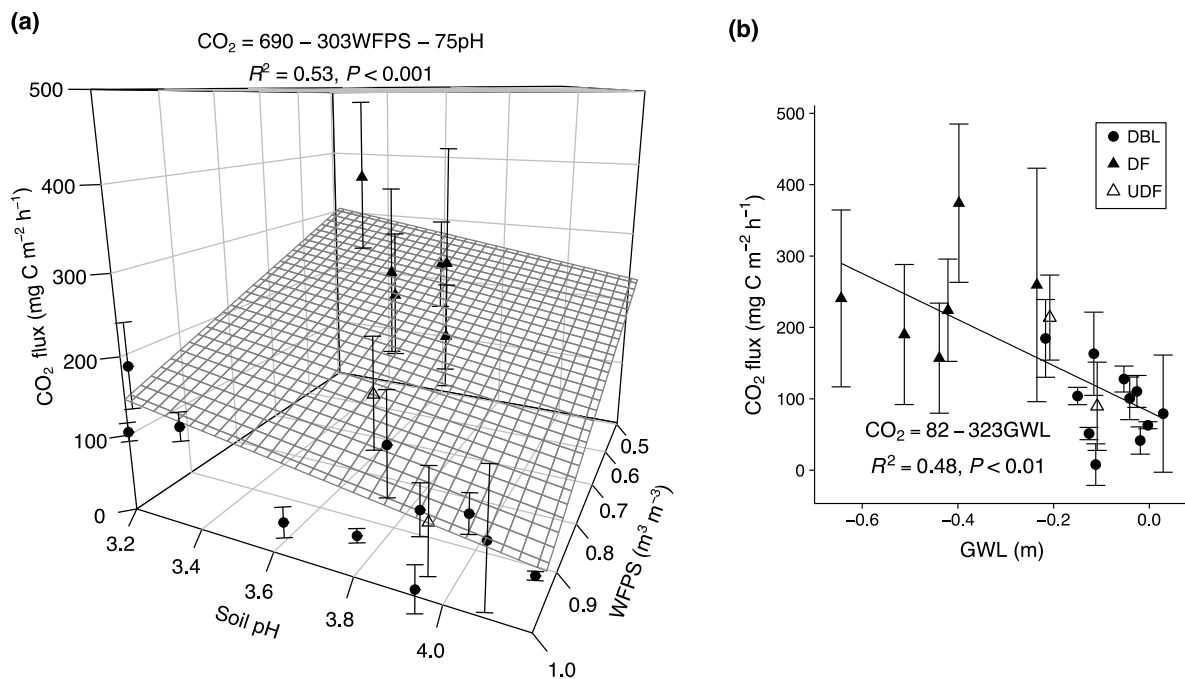


Figure 3. Relationship between CO₂ flux and (a) water-filled pore space (WFPS) and soil pH, and (b) groundwater level (GWL) in DBL (drained burned land), DF (drained forest), and UDF (undrained forest). Error bars show ±1 SD. Meshed surface and line show the result of regression (Table 3).

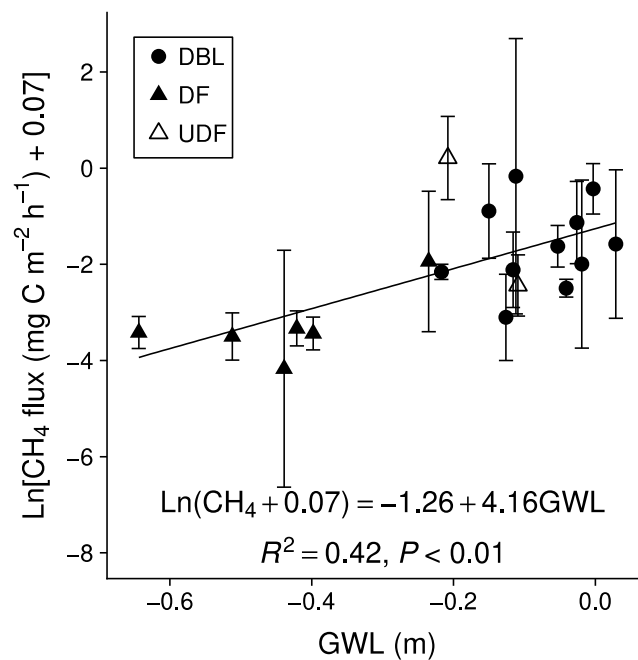


Figure 4. Relationship between log-transformed CH₄ flux and groundwater level (GWL) in DBL (drained burned land), DF (drained forest), and UDF (undrained forest). Error bars show ±1 SD. Line shows the result of regression (Table 3).

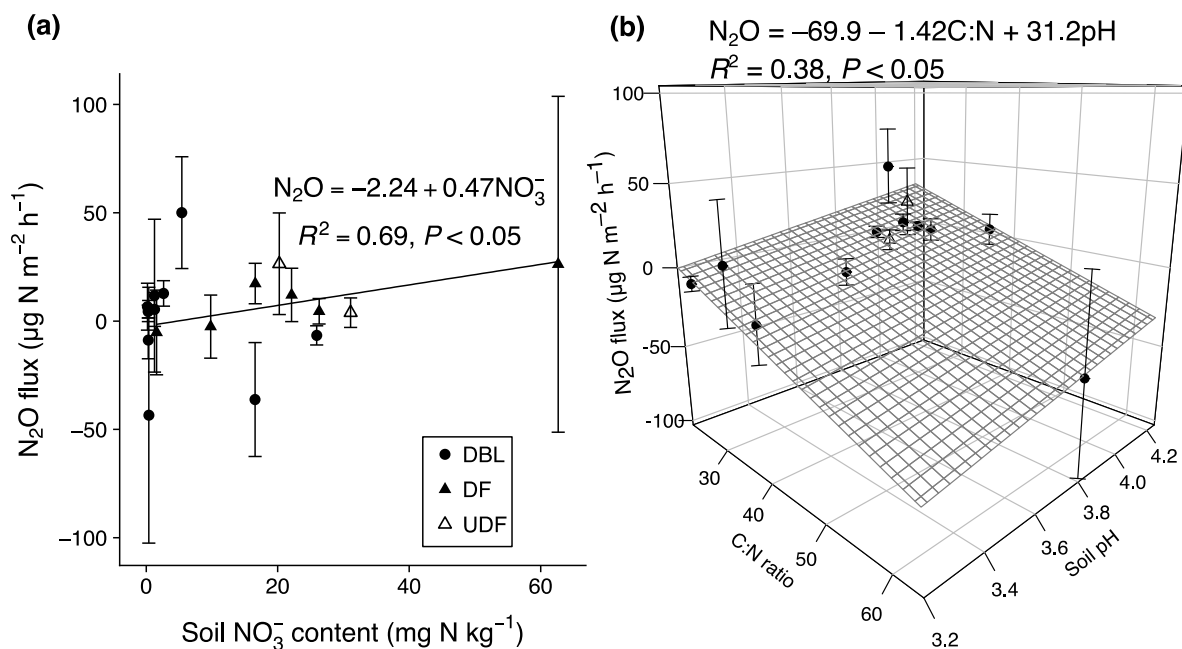


Figure 5. Relationship of N₂O flux with (a) soil nitrate content in all land uses, and (b) soil C:N ratio and pH in undrained forest (UDF) and drained burned land (DBL). Error bars show ±1 SD. The regression line in (a) is obtained from the data in drained forest (DF) only. The meshed surface in (b) show the result of multiple regression using data in UDF and DBL.

4. Discussion

4.1. Factors Controlling Greenhouse Gas Fluxes

CO₂ flux showed the significantly negative relationship with WFPS and GWL (Figure 3a, Table 3). These results suggested that oxidative peat decomposition was promoted by drying peat soils. It is

well known that CO₂ flux is promoted by lowering GWL in tropical peatland [11,13–15,18,55], which strongly support our results. In this study, CO₂ flux also showed a significantly negative relationship with soil pH (Figure 3b, Table 3). This result suggests that promotion of organic matter decomposition acidify the soil. In contrast, the neutralization of soil acidity promotes organic matter decomposition in tropical peat soils [11,56]. It is suggested that the relationship between CO₂ flux and soil pH might be changed in different seasons. On the other hand, CO₂ flux is increased by the rise in soil temperature in tropical peatland [57] as well as in boreal peatland. However, soil temperature was not selected by stepwise multiple regression for CO₂ flux (Table 3) even though soil temperature was significantly different among land uses (Table 1). The soil temperature was 4.6 °C higher in DBL than in UDF on average (Table 1). If we apply Q_{10} value of 1.16–3.0 obtained in this region [40,55], the difference in soil temperature might increase in CO₂ flux by 58–150%. However, the CO₂ flux was the lowest in DBL (Table 2) where the soil temperature was the highest (Table 1). These results suggest that soil moisture was a stronger controlling factor than temperature in this study.

As opposed to CO₂ flux, CH₄ flux was exponentially increased by the rise in GWL (Figure 4, Table 3), suggesting that development of anaerobic condition promoted methanogenesis. Similar relationships between CH₄ flux and GWL was obtained in previous studies in tropical peatland [19,58]. The population of methanotrophs of the peat soil was increased by lowering soil moisture [59], which supports the negative CH₄ fluxes in this study when GWL was below −0.3 m.

It is well known that soil nitrate plays an important role on denitrification as a substrate, and N₂O flux is increased by increasing soil nitrate content [26,51] when WFPS is between 0.6 to 0.8 m³ m^{−3} [27,35]. The mean WFPS was 0.6 m³ m^{−3} in DF (Table 1), and N₂O flux was positively correlated with soil nitrate content in DF (Figure 5a, Table 3). Therefore, it was suggested that enhancement of denitrification would promote the N₂O flux in DF. On the other hand, the soil moisture was almost saturated in DBL and UDF (Table 1). Therefore, complete denitrification might happen and N₂O might be reduced to N₂ in DBL and UDF. Overall denitrification is promoted by neutralization of soil acidity [60]. Also, lower C:N ratio increases denitrification [61,62]. These previous studies agree to our result of multiple regression in DBL and UDF (Figure 5b, Table 3).

These previous studies were obtained from temporal variations of the GHG fluxes, whereas the results in this study was obtained from spatial variations within two weeks. Therefore, these factors controlling GHG fluxes as shown above might be changed in the late dry season and rainy season. For example, soil pH is decreased during dry season due to organic matter decomposition and is increased again when rainy season comes due to dilution by heavy rain [63]. Soil pH influences organic matter decomposition [11,56] and denitrification [64]. Thus, the factors controlling CO₂ and N₂O fluxes might be changed in different seasons.

4.2. Effect of Different Land Use Types on Greenhouse Gas Fluxes

CO₂ flux was significantly lower and CH₄ flux was significantly higher in DBL than in DF (Table 2). In this region, topsoil and subsoil are sometimes lost to a depth of 20–60 cm through a peat fire [65]. DBL area had been suffered peat fires at least in 1997, 2002, 2004, 2006, and 2009 so that the surface elevation was decreased from the adjacent un-burned forest [66]. Thus, the higher GWL in DBL might result from the lower elevation because of the recurring peat fires in DBL. The higher GWL might result in lower CO₂ flux and higher CH₄ flux in DBL than in DF (Table 2). Also, peat fires have changed the dominant vegetation type. The fresh organic matter is supplied in DF and UDF through litter fall and root exudates [23], whereas the supply of organic matter is limited in DBL because it is an open area. Furthermore, changes in vegetation type from forest (UDF and DF) to fern (DBL) might result in decrease of the amount of root. The smaller amount of root will decrease root respiration, which might be another reason of lower CO₂ flux in DBL. Additionally, the change in vegetation type would influence microbial communities because they are correlated to each other [67]. The change in microbial communities might influence the difference of CO₂ and CH₄ fluxes among land uses in this study.

The outlier of “hotspot” of CH₄ flux was found in plot 6 (Figure 2b) and the NH₄⁺ content was double compared with the mean in the DBL. Type I methanotrophs were identified in this region [59], and CH₄ oxidation by the type I methanotrophs is inhibited by NH₄⁺ [68]. Therefore, the “hotspot” of CH₄ flux in the plot 6 might be due to inhibition of CH₄ oxidation. The plot 6 is located near the road and a house where people keep free-range chickens. Thus, the higher NH₄⁺ content might be derived from the human and chicken wastes. Also, the relative elevation of the plot 6 is lowered due to the road, and flooding water collects around plot 6 in the rainy season. Because the flooding periods are longer than in the other plots in DBL, labile organic matter might be accumulated in the plot 6, which leads to enhancement of anaerobic organic matter decomposition. Furthermore, the longer flooding periods inhibit nitrification, and accumulates NH₄⁺, which might be another reason of higher NH₄⁺ content in the plot 6.

On the other hand, CO₂ flux was not clearly different between DF and UDF (Table 2) though GWL was clearly higher in UDF (Table 1). Higher enzyme activities (e.g., β-glucosidase and N-acetylglucosaminidase) were obtained in UDF than in DF especially in 0–3 cm in this region [69]. Therefore, oxidative peat decomposition in UDF might be compensated between repression by higher GWL and promotion by higher enzyme activity. Also, it is possibly the insufficient number of samples to detect the difference of CH₄ flux between UDF (*n* = 2) and DF (*n* = 6) because the spatiotemporal variability of CH₄ flux is very high compared with CO₂ flux [70].

N₂O flux tended to be higher in UDF, following DF and DBL though it was not significant (Table 2). N₂O flux is promoted by increasing nitrate content through denitrification if WFPS is between 0.6 and 0.8 m³ m⁻³ [27,35]. In this study, nitrate content was significantly higher in DF than in DBL, and WFPS was 0.6 m³ m⁻³ in DF (Table 1). Therefore, the higher N₂O flux in DF than in DBL might result from the optimized condition of denitrification.

GWP was significantly higher in DF than in DBL (Table 2). The GWP mainly consisted of CO₂ flux more than 90%, and the CO₂ flux was significantly higher in DF than in DBL (Table 2). Therefore, higher GWP resulted from higher CO₂ flux in DF than in DBL. Although CH₄ flux was significantly higher in DBL than in DF, the CH₄ flux accounted only for 0–9% of GWP (Table 2). Thus, the influence of CH₄ flux was minor for GWP. Similar results were reported in other tropical peatlands that CO₂ was the major contributor for GWP [37,71].

The result of the major contribution of CO₂ to GWP suggests that water management to rise in GWL is essential to mitigate GWP, especially in DF. Moreover, the rise in GWL would decrease the risk of peat fires in tropical peatland. Canal blocking and dam construction might be helpful to rise in GWL [72,73]. In oil palm plantation, land compaction contributes to retain more water in the soil because the compaction decreases in soil macro-porosity so that capillary rise from groundwater is expected [13,74]. If the DBL continues to abandon or will be converted to agricultural field in the near future, the land compaction might be helpful to rise in GWL and soil moisture.

5. Conclusions

Although this study was only carried out in the beginning of dry season, soil chemical properties clearly show the importance to control the GHG fluxes as well as soil moisture and GWL. CO₂ emission mostly contributes to GWP more than 90%. CH₄ flux was promoted by higher GWL. N₂O flux was promoted by increasing soil nitrate content in drained forest, and was promoted by higher soil pH and lower C:N ratio in water-saturated ecosystems (drained burned forest and undrained forest). In conclusion, it is important to reduce CO₂ emission by a rise in soil moisture and GWL to mitigate GWP in this region. It is necessary to rewet degraded peatlands and to hydrologically preserve intact peatlands.

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