Diversity In Characteristics Of Tropical Peatlands Varying In Land Uses Leads To Differences In Methane And Carbon Dioxide Emissions

by Bambang Joko Priatmadi

BIODIVERSITAS
Volume 23, Number 12, December 2022
Pages: 6293-6301

ISSN: 1412-033X
E-ISSN: 2085-4722
DOI: 10.13057/biodiv/d231225

Diversity in characteristics of tropical peatlands varying in land uses leads to differences in methane and carbon dioxide emissions

AKHMAD R. SAIDY[1,2,♥], BAMBANG J. PRIATMADI[1], MELDIA SEPTIANA[1]
[1]Department of Soil, Faculty of Agriculture, Universitas Lambung Mangkurat. Jl Jenderal Achmad Yani Km 36, Simpang Empat, Banjarbaru 70714, South Kalimantan, Indonesia. Tel./fax.: +62-511-4772254, ♥email: asaidy@ulm.ac.id
[2]Doctoral Program of Agricultural Science, Postgraduate Program, Universitas Lambung Mangkurat. Jl. Jenderal Achmad Yani Km 36, Simpang Empat, Banjarbaru 70714, South Kalimantan, Indonesia

Manuscript received: 24 September 2022. Revision accepted: 7 December 2022.

Abstract. *Saidy AR, Priatmadi BJ, Septiana M. 2022. Diversity in characteristics of tropical peatlands varying in land uses leads to differences in methane and carbon dioxide emissions. Biodiversitas 23: 6293-6301.* The use of tropical peatlands for commercial agriculture causes a change in their original function as carbon storage to become sources of methane (CH_4) and carbon dioxide (CO_2) emissions. Therefore, this research aims to quantify the emission of CH_4 and CO_2, and peat characteristics in five tropical peatlands with different land uses, namely shrubs-, burned-, *Albizia*-, spring onion-, and lettuce-peatlands, to determine factors controlling carbon emissions. The results showed that CH_4 emission ranged from 0.21 to 0.58 mg C m^{-2} h^{-1}, with the lowest and the highest obtained in burned- and cultivated-peatlands (spring onion- and lettuce peatlands), respectively. The emission of CO_2 ranged from the lowest in burned peatland (34.10-47.06 mg C m^{-2} h^{-1}) to the highest in shrubs-peatland (136.79-180.87 mg C m^{-2} h^{-1}). This showed that the diversity in CH_4 emissions with different land uses is attributed to variations in the water table, water-filled pore space, ammonium, and nitrate contents. The rates of CO_2 emission were controlled by carbohydrate-, fiber-, organic C-, and lignin-contents. This indicated that land and water managements need to be applied to reduce the emissions of CH_4 and CO_2 in tropical peatlands with different land uses.

Keywords: Carbon emission, carbon mineralization, methanogens, microbial decomposition, peatland conversion

INTRODUCTION

Tropical peatlands are unique and complex ecosystems that have several important environmental functions. Intact tropical peatlands store large amounts of water so that they function for flood prevention (Cobb and Harvey 2019), and serve as wildlife habitats (biodiversity conservation) (Sasidhran et al. 2016). These rich ecosystems are formed in anoxic conditions due to the relatively high water table, which causes a faster accumulation of organic matter than the microbial decomposition process (Takada et al. 2016), even in tropical temperatures, which are favorable for microbial degradation. As large peat deposits have formed beneath rich tropical rainforests, natural tropical peatlands store a large amount of carbon and play a very important role in global climate mitigation (Warren et al. 2017). With an estimated area of 440,000 km^2, the amount of organic C stored in tropical peatlands has been estimated in the range of 40-90 Gt C (Kurnianto et al. 2015).

The area of tropical peatlands in Indonesia is 13,405 million ha, of which 46,294 ha is situated in South Kalimantan Province (Anda et al. 2021). Due to economic pressure, most peatlands in these areas have been utilized for the expansion of commercial agriculture and other forms of economic development. Anthropogenic activities such as drainage, plantation, deforestation, and land conversion result in changes in land uses of tropical peatlands (Dohong et al. 2017; Zulkarnaini et al. 2022). Carbon-rich tropical peatlands in South East Asia in their natural circumstance are swamp forests, but currently, most of them have been converted to commercial agriculture, especially for pulpwood *Acacia* and oil palm plantation (Dommain et al. 2016). Miettinen et al. (2016) reported that the conversion of tropical peatlands to plantations in Peninsular Malaysia, Sumatera, and Borneo in the period of 1990-2015 had reached 1.1 million ha of *Acacia* plantation and 3.1 million ha of oil palm plantation, or a total of 30% of the peatland areas.

Changes in land uses of tropical peatlands result in diversity in peatland characteristics. Generally, agricultural development is always accompanied by the construction of drainage channels, causing a decrease in the water table of tropical peatlands (Ismail et al. 2021). Changes in the water table ultimately cause a shift in the biochemical reactions of peat decomposition, which initially occurred in anoxic conditions to become oxic conditions (Marwanto et al. 2019). Changes in the quality and quantity of biomass inputs from aboveground vegetation also occur when tropical peatlands swamp forests are converted to agricultural land and crop plantations. The study conducted by Cooper et al. (2019) showed that the conversion of peatlands to oil palm plantations results in a decrease in litter input rates, followed by a decrease in the amount of easily decomposable organic C and an increase in the relative abundance of recalcitrant organic C. The results of these studies show that changes in a number of peatland characteristics lead to changes in the initial function of peatlands as carbon stores in the terrestrial ecosystem.

Differences in the characteristics of tropical peatlands due to changes in the land uses lead to changes in fluxes of

CH_4 and CO_2. Research conducted by Hadi et al. (2005) showed that the emissions of CH_4 and CO_2 were strongly affected by land-use and hydrological zone. Emission of CH_4 is generally higher in natural peat swamp forests than that in oil palm plantations due to lowering groundwater in oil palm plantations (Wong et al. 2020). Kiew et al. (2020) reported that the high CO_2 emission from oil palm plantations in tropical peatlands is controlled by a large amount of plant debris left in the plantation. Arai et al. (2014) found that changes in land uses result in changes in CO_2 fluxes of tropical peatlands through changes in microbial activities. The results of those studies imply that different factors play an important role in controlling the rate of CH_4 and CO_2 emissions in tropical peatlands varying in land uses. Information on the environmental factors controlling CH_4 and CO_2 emissions is very crucial in determining peatland management to mitigate greenhouse gas emissions in tropical peatlands. Therefore, this research aims to quantify peat characteristics influencing the rate of CH_4 and CO_2 emission in tropical peatlands with different land uses. The hypothesis is that different peatland characteristics due to varying land use of tropical peatlands lead to a different rate of CO_2 and CH_4 emissions.

MATERIALS AND METHODS

Study area

This research was conducted on peatlands that are administratively situated in the Desa Landasan Ulin Utara, Liang Anggang Sub-district, Banjarbaru City, South Kalimantan, Indonesia (Figure 1). The peatlands used are part of the Peat Hydrological Area of Banjarbaru, which is located between the Martapura and the Maluka Rivers. The average air temperature ranged from 27.5 to 29.3°C, where the highest value of 35.4°C occurred in March (Statistics of Banjarbaru Municipality, 2022). Meanwhile, the lowest average temperature was observed in April with a value of 23.9°C and the humidity was within the range of 73.6-82.2%. The annual rainfall reached 3141.5 mm, where the highest value was observed in January (572.4 mm) and the lowest 57.2 mm occurred in August.

The physico-chemical characteristics, CH_4, and CO_2 emissions of tropical peatlands were observed in five different land use, namely spring onion-, lettuce-, *Albizia*-, shrubs-, and burned peatlands. Peatlands in this area are formed from similar aboveground vegetation and from similar hydrological areas. These differences in land use in tropical peatlands have occurred for at least five years ago. The peatlands in these areas were mostly drained in 2014 for agricultural cultivation and leaving no peatlands in a natural condition (undisturbed peatlands). The spring onion- and lettuce peatlands have been used for agriculture for 5 years, in which nitrogen and phosphorus fertilizers were applied 2-3 times every year.

Generally, farmers performed canal blocking on cultivated peatlands in 2018 to keep the peat surface moist for plant growth. *Albizia chinensis* (height of 8-12 m) was the dominant plant found on *Albizia*-peatland, with the underground grasses grown. *Albizia*-peatland only received nitrogen and phosphorus fertilization once at the time of planting. Although shrubs-peatland had also been drained, the land was not used for crop cultivation and functioned as a boundary between areas used for cultivation. Grasses, ferns, and *Melaleuca leucadendron* with a height of 4-6 m were the dominant vegetation on shrubs-peatland. The burned peatland experienced fires in 2015 and 2019 and is currently still in the revegetation stage.

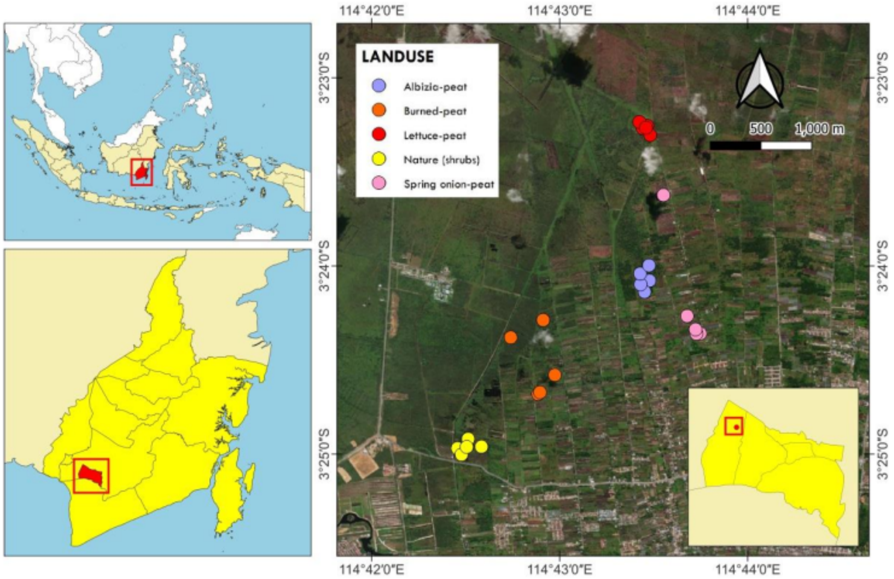

Figure 1. Study areas of peatlands with five different land uses (spring onion-, lettuce-, *Albizia*-, shrubs-, and burned peatlands)

Measurement of methane and carbon dioxide emissions

Measurement of CH_4 and CO_2 emissions were carried out in the morning (before 11.00 am) in the second week of June 2022 (dry season), in which gas emission measurements were carried out at five different sampling points for each land-use of tropical peatlands. Sampling points were selected purposively to obtain peat and gas samples from lands with the same age of plants or crops for each land use. Gas sampling was carried out using a static chamber (10 x 15 x 25 cm) method with the interval time of gas collection 5, 10, 15 and 20 minutes after the closure of the chamber. The gas was sampled through the septum in the middle of the chamber using a 10 mL syringe, then the sampled gas was transferred to a 10 mL air-tight vial glass for CH_4 and CO_2 measurements using Shimadzu GC-14A equipped with flame ionization and thermal conductivity detectors, respectively. The gas fluxes were quantified using linear regression between changes in gas concentrations and time interval of gas sampling, areas covered by the chamber, and chamber volume and corrected for the field-measured air temperature and atmospheric pressure (Sackett et al. 2015).

Sampling and characterization of peatlands

Peat sampling was carried out using a peat auger at a depth of 0-25 cm at each measurement point of CH_4 and CO_2 emissions. A water level data logger (Hobo U20L-02) placed near the bottom of perforated PVC pipe (ca. 1.7 m from peat surface) was employed for measuring and recording the water table in each land-use of peatlands. After cleaning of plant debris, collected peat samples were placed in plastic bags for peat characterization in the laboratory, i.e. fiber content, bulk density, and water-filled pore space (WFPS) (Parent and Caron 1993), peat pH and electrical conductivity (Bešter-Rogač and Habe 2006; McLean 1982), total nitrogen (Bremer and Mulvaney 1982), the concentrations of NH_4^+ and NO_3^- (Bundy and Meisinger 1994), and organic C contents (Nelson and Sommers 1996). Carbohydrate (hot-water soluble C) was extracted from the peats using warm water (60°C), and the concentration of organic C in the extract was quantified using the anthrone-sulfuric acid method (Grandy et al. 2000). Lignin contents of the peat was quantified using the method described by Chesson (1981).

Data analysis

One-way analysis of variance was performed to quantify the effect of different land uses on the changes in peat characteristics, CH_4 and CO_2 emissions of tropical peatlands. Prior to the analysis of variance, the Shapiro-Wilk and Bartlett tests were carried out to ensure that the data had a normal distribution and homogeneous variance, respectively. If the test results showed that the data has a non-normal distribution and a non-homogeneous variance, then a data transformation will be performed. When the results of the analysis of variance showed a significant effect, a mean comparison was performed using the least significant difference (LSD) test at $P < 0.05$ to differentiate the effect among the treatments. The relationship between all peatland characteristics and CH_4 and CO_2 emissions was quantified using correlation and simple linear regression analyses. All statistical analyses were performed using the GenStat 12th Edition.

RESULTS AND DISCUSSION

Diversity in peatland characteristics

The results showed that tropical peatlands with different land uses have different characteristics, with the exception of total N contents. The organic carbon (C) content in shrubs-peatland of 284 g C kg^{-1} was higher than other peatlands, which were 177-219 g C kg^{-1} (Table 1). Organic C contents vary based on different land uses resulting from different plant litter inputs due to contrasting aboveground vegetation, management practices, and long-term differences in the rate of peat decomposition (Cooper et al. 2019; Girkin et al. 2019; Hoyos-Santillan et al. 2019; Upton et al. 2018). The lowest organic C was observed in burned peatland, which only reached 136 g C kg^{-1}. These results are in line with the previous report, which significantly decreased organic C content in peatlands experiencing fire (Silviana et al. 2021; Wasis et al. 2019).

Changes in land use also cause variations in carbohydrate and lignin contents in tropical peatlands. The carbohydrate content of uncultivated peatland (shrubs-peat) was 104 mg kg^{-1}, decreased by 51-71% in cultivated tropical peatlands (Table 1). The lowest carbohydrate content was observed in burned peatland, which only reached 12 mg kg^{-1} (Table 1). In contrast to carbohydrates, lignin content increased from 41 mg kg^{-1} in uncultivated peatlands to 74-88 mg kg^{-1} in cultivated peatlands (Table 1). The decrease in carbohydrates and increase in lignin contents with changes in land use from uncultivated peatlands to cultivated peatlands are in agreement with the concept of changes in the chemical structure of organic C contained in peatlands with agricultural activities. Several agricultural activities in peatlands, such as drainage, fertilizing and liming, enhance the decomposition process of organic C contained in the peats, which in turn causes a decrease in organic C with structures that are easily decomposed, such as carbohydrates and results in the accumulation of organic C that is resistant to biodegradation such as lignin (Saidy et al. 2018; Saidy et al. 2020).

Research conducted by Sinclair et al. (2020) showed that drainage, deforestation, and peat fires led to an increase in the bulk density (BD) of peatlands. This is consistent with the results of this study which showed that burned peatland and cultivated-peatlands (spring onion and lettuce) had higher BD (0.34-0.40 kg m^{-3}) than relatively uncultivated peatlands (shrubs-peatland) (0.13 kg m^{-3}) (Table 1). The high BD in burned peatland is attributed to the smaller peat particles due to the physical breakdown of big peat particles by fire (Wijedasa 2016). Meanwhile, the high BD in spring union- and lettuce-peatlands is related to continuous peat oxidation due to plant cultivation in peatlands which leads to the peat particles becoming smaller. This is in accordance with the observations by Anshari et al. (2010) who showed that increasing the number of peat particles with a smaller size because of drainage increased the process of peat oxidation in agricultural peatlands.

Table 1. Characteristics of peatlands with different land uses (average ± standard error). The similar letter after a standard error in each row indicates a similar effect of the treatments based on the least significant difference (LSD) test at $P < 0.05$

Characteristics	**Spring onion**	**Lettuce**	**Shrubs-peat**	**Burned-peat**	***Albizia***
Organic C (g kg^{-1})	177.53 ± 9.81b	176.65 ± 10.97 b	284.21 ± 12.57 d	136.18 ± 15.11 a	218.95 ± 11.62 c
Carbohydrate (mg kg^{-1})	30.48 ± 2.66 b	32.67 ± 1.79 b	103.60 ± 5.80 d	12.35 ± 1.46 a	50.66 ± 2.66 c
Lignin (mg kg^{-1})	88.08 ± 5.29 d	74.59 ± 5.41 bc	40.86 ± 2.78 a	64.93 ± 3.73 b	79.80 ± 3.93 cd
Total N (g kg^{-1})	14.48 ± 1.34 a	15.84 ± 1.79 a	13.66 ± 1.56 a	10.77 ± 0.98 a	12.62 ± 1.71 a
NH_4^+ (mg kg^{-1})	37.60 ± 2.46 c	38.74 ± 2.41 c	11.72 ± 1.11 a	9.29 ± 1.88 a	24.91 ± 3.01 b
NO_3^- (mg kg^{-1})	26.25 ± 2.56 cd	27.08 ± 2.62 d	12.96 ± 1.84 a	15.78 ± 2.20 ab	19.98 ± 2.26 bc
EC (mS)	196.57 ± 20.06 b	197.38 ± 8.61 b	109.99 ± 5.28 a	120.75 ± 5.16 a	122.72 ± 5.08 a
Peat pH	4.43 ± 0.09 bc	4.46 ± 0.16 c	3.99 ± 0.05 a	4.43 ± 0.12 bc	4.12 ± 0.12 ab
Water table (cm)	-25.98 ± 3.16 a	-35.52 ± 2.85 ab	-50.58 ± 4.46 cd	-59.70 ± 4.49 d	-45.01 ± 2.40 bc
WFPS (%)	69.39 ± 3.25 c	59.58 ± 3.16 b	41.79 ± 2.79 a	36.45 ± 3.22 a	43.19 ± 3.06 a
Bulk density (kg m^{-3})	0.34 ± 0.10 bc	0.35 ± 0.03 c	0.13 ± 0.02 a	0.40 ± 0.03 c	0.25 ± 0.01 b
Fiber content (%)	20.82 ± 0.96 a	22.23 ± 2.69 a	45.39 ± 2.28 c	16.38 ± 1.83 a	29.81 ± 2.05 b

Different BD of tropical peatlands with differing land uses also related to variances in the fiber contents of the peats. Fiber content is one of the indicators used to determine the degree of peat decomposition (Keller and Madvedeff 2016). The fiber contents of these five tropical peatlands varied from 16 to 45% (Table 1). Burned peatland had the lowest fiber content value, i.e., 16% (Table 1), indicating that burned peatland is the most decomposed peat (sapric). Meanwhile, the highest fiber content (45%) was observed in shrub-peatland (Table 1), indicating that this peat is the least decomposed peat (fibric). *Albizia*-, spring onion-, and lettuce-peatlands have fiber contents of 20-29% (Table 1), which is classified as moderately decomposed peat (hemic). It was evident that increasing the degree of peat decomposition (fibric peat to sapric peat) leads to increasing BD of peats. The result of this study is in line with several studies that reported that increasing fiber contents is followed by a decrease in BD (Kurnain et al. 2006; Rocha Campos et al. 2011).

Differences in land use also lead to variations in the water table and water-filled pore space (WFPS) of tropical peatlands. The deepest water table was observed at shrub-peatland (59 cm from the peat surface), while the shallowest water table was observed at spring-onion peatland (26 cm from the peat surface) (Table 1). Meanwhile, the water table of lettuce-, *Albizia*-, and shrub-peatlands varied from 36 to 51 cm of peat surface. Water table depth difference led to differences in water-filled pore space (WFPS), in which WFPS of those tropical peatlands varied from 36% of burned peatland to 69% of spring onion-peatland (Table 1). The relatively shallow water table and high WFPS of spring onion-peat are related to canal blocking which is carried out on drainage channels to maintain relatively low peat conditions for the growth of spring onions.

Methane and carbon dioxide emissions

Methane emissions of tropical peatlands varied based on differences in land uses. The lowest CH_4 emission was observed in shrubs- and burned peatlands (0.21-0.25 mg C m^{-2} h^{-1} or 1.83-1.25 g C m^{-2} $year^{-1}$), while spring onion- and lettuce-peatlands showed the highest rate of CH_4 emissions (0.54-0.58 mg C m^2 h^{-1} or 4.72-5.12 g C m^2 $year^{-1}$) (Figure 2A). The rate of CH_4 emissions obtained in this study is within the range of CH_4 emissions reported in previous studies. For example, Deshmukh et al. (2020) reported annual methane exchanges over the natural forest were 9.1 g C m^{-2} $year^{-1}$ and 4.7 g C m^{-2} $year^{-1}$ of peatlands used for *Acacia* plantation. Methane emission of 8.46 g C m^{-2} $year^{-1}$ was observed for undrained peats swamp forest, 4.17 g C m^{-2} $year^{-1}$ for a relatively disturbing secondary peat swamp forest, and 2.19 g C m^{-2} $year^{-1}$ for oil palm plantation (Wong et al. 2020).

The emission of CH_4 of cultivated peatlands (spring onion- and lettuce-peatlands) was higher than that of uncultivated peatlands (shrubs-peatlands) (Figure 2.A). The results of this study were not consistent with the results of previous studies, which showed that methane emission from cultivated peatlands is generally lower than those of uncultivated peatlands (Deshmukh et al. 2020; Wong et al. 2020). The higher methane emission of cultivated peatlands than in uncultivated peatlands in this study is related to the shallower water table in the cultivated peatlands than in the uncultivated peatlands due to canal blocking to keep the surface of the cultivated peatlands relatively moist for crop growth. Higher CH_4 emission from natural forest peatlands was observed in the study of Deshmukh et al. (2020) is also related to a shallower groundwater level (20-28 cm from the ground surface) in the natural forest than in the *Acacia* plantation plot, which reached to 69-75 cm from the ground surface. The results of this study indicate that the water table level controls the rate of CH_4 emission in tropical peatlands.

In contrast to CH_4 emission, CO_2 emission from uncultivated tropical peatlands (shrubs-peatland) was higher than those of peatlands with other land uses (Figure 2.B). The emission of CO_2 of shrubs-peat reached 149 mg C m^{-2} h^{-1} (1305 g C m^{-2} $year^{-1}$), while burned peatland showed the lowest CO_2 emission (42 mg C m^{-2} h^{-1} or 368 g C m^{-2} $year^{-1}$) (Figure 2.B). Cultivated peatlands (*Albizia*-, spring onion-, and lettuce peatlands) had CO_2 emissions of 69-108 mg C m^{-2} h^{-1} (609-945 g C m^{-2} $year^{-1}$). Emissions of CO_2 observed in this study are in the range of CO_2 emission of tropical peatlands reported in previous studies. Hirano et al. (2014) reported that CO_2 emission of burned tropical peatlands observed through field measurement is in the range of 362-382 g C m^{-2} $year^{-1}$. Emissions of CO_2 in tropical peatlands before and after land clearing for agriculture are 77-143 mg C m^{-2} h^{-1} or 674-1253 g C m^{-2} $year^{-1}$ (Saidy et al. 2020). Based on the monthly observation in the field, Wakhid et al. (2017) found that CO_2 emission from peat decomposition in a tropical peatland reached 1408 g C m^{-2} yr^{-1}. The daily mean CO_2 efflux values were 1060 g C m^{-2} yr^{-1} and 602 g C m^{-2} yr^{-1} in close-to-tree (<2.5 m) and far-from-tree (>3.0 m) plots, respectively (Ishikura et al. 2018).

Relationship between peat characteristics and CH_4 and CO_2 emissions

Simple regression analysis was conducted to quantify the relationship between peat characteristics and CH_4 and CO_2 emissions. Results of the study showed that several peatland characteristics, i.e., water table, water-filled pore space (WFPS), and concentrations of ammonium and nitrate, have a significant relationship with CH_4 emission (Figure 3). On the other hand, other peatland characteristics (bulk density, rubbed fiber, EC, peat pH, total N, organic C, carbohydrate and lignin) did not have a significant relationship with CH_4 emission ($P > 0.05$). The emission of CH_4 has a significant relationship with the water table of tropical peatlands ($P < 0.001$) and water-filled pore space ($P < 0.001$). It is well known that water-filled pore space is influenced by the water table, in which the closer water table to the peat surface increases the water-filled pore spaces of peats. The relationship between the water table and CH_4 emission was shown by the lower CH_4 emission of burned-peats with the water table was 60 cm from the peat surface, and increasing CH_4 emission of cultivated peatlands (spring onion- and lettuce-peats) with the water table was 26-36 cm form peat surface (Figure 3.A). A positive relationship between CH_4 emission and water table observed in this study is in agreement with Ishikura et al. (2019) found that CH_4 emission was higher in the tropical peatlands with water table relatively close to the peat surface than in tropical peatlands with water table relatively far to peat surface.

The results obtained in this study are consistent with several previous studies which showed that the water table controls the amount of CH_4 emission of tropical peatlands. A study conducted in Indonesian tropical peatlands showed that changes in land use from the swamp and drained forest to cassava or coconut cultivation areas result in a lower water table and lead to decreasing CH_4 emission, while the change to lowland paddy results in increasing the water table which eventually leads to increasing CH_4 emission (Inubushi et al. 2005). Luta et al. (2021) found that CH_4 emission from lysimeters under simulated low- and high-water table fluctuation of tropical peatland is controlled by water-table. Wong et al. (2020) reported a positive exponential relationship between CH_4 emission and groundwater level, and rewetting tropical peatlands results in increasing CH_4 emissions (Kumar et al. 2020).

Results of this study also revealed that CH_4 emission was a significant relationship with the contents of NH_4^+ ($P < 0.001$) and contents of NO_3^- ($P < 0.001$) (Figures 3.C and 2.D). Burned peatland with low NH_4^+ dan NO_3^- contents also had low CH_4 emissions, while cultivated peatlands (spring onion- and lettuce-peatlands) with high rates of CH_4 emission had high NH_4^+ and NO_3^- (Figures 3.C and 2D). These increasing CH_4 emissions are ascribed to the increasing population of *Methanocellaceae*, a group of methanogenic microorganisms that produce methane, with increasing NH_4^+ and NO_3^-, which eventually promotes CH_4 emissions (Xiao et al. 2017). A study conducted by Chen et al. (2020) showed that the application of ammonium compounds of 100 kg N ha^{-1} $year^{-1}$ to wetland ecosystems stimulates CH_4 emission. Lau et al. (2022) observed a negligible CH_4 emission in non-fertilized plots of tropical peatlands but found a significant increase in CH_4 emission in tropical peatlands applied with nitrogen fertilizer, particularly in the form of ammonium. The result of this study is also in agreement with several other studies that reported CH_4 emission in peatlands increases with increasing nitrogen contents of the peatlands through nitrogen fertilizer application (Boon et al. 2014; Hoyos-Santillan et al. 2019). This study shows the important role of the availability of nitrogen (NH_4^+ and NO_3^-) in promoting CH_4 emission in tropical peatlands.

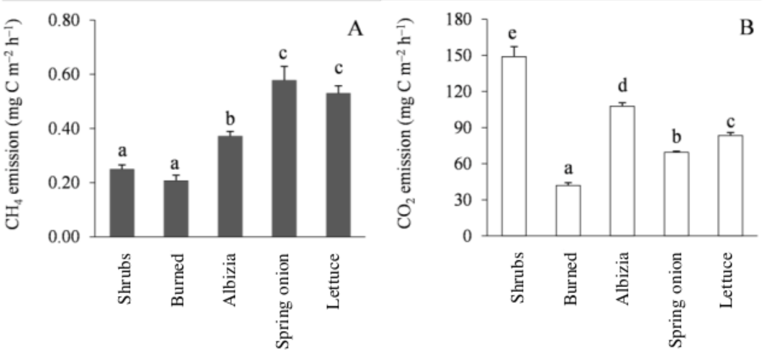

Figure 2. Methane (A) and carbon dioxide (B) emissions of tropical peatlands with different land use/cover. The line above the bars is the standard error (n=5). Similar letters above the lines indicate no significant effect of the treatments based on the least significance difference (LSD) test at *$P < 0.05$*

Results of simple regression analysis revealed that carbon dioxide (CO_2) emission had a relationship with carbohydrate content ($P < 0.001$), fiber content ($P < 0.001$), organic C content ($P < 0.001$), and lignin content ($P < 0.015$) (Figure 4). Other peatland characteristics (bulk density, water table, WFPS, EC, peat pH, NH_4^+, NO_3^- and total N) did not have a significant relationship with CO_2 emission ($P > 0.05$). Carbohydrate is known as an organic C compound with a simple chemical structure so that it is relatively easy to be decomposed by soil microorganisms to produce CO_2 (Cepáková and Frouz 2015). The lowest carbohydrate content in burned peatland produced the lowest CO_2 emission, while high CO_2 emission was produced from a high content of carbohydrates on shrubs-peatland (Figure 4.A). Several previous studies have also shown that peatlands with low carbohydrate content exhibit low CO_2 emission, while high CO_2 emission is generally observed in peatlands with high carbohydrate content (Grover and Baldock 2013; Saidy et al. 2018).

In contrast to carbohydrate contents, increasing lignin contents of tropical peatland with changes in land uses resulted in decreasing CO_2 emissions (Figure 4.B). Shrubs-peatland with low lignin content has high CO_2 emissions, while cultivated peatlands (spring onion- and lettuce peats), despite having high amounts of lignin, have low CO_2 emissions. The inverse relationship between CO_2 emission and peat lignin contents is ascribed to the fact that lignin is an amorphous heteropolymer compound consisting of three phenylpropane units with different bonds, so that specific enzyme are required for the biodegradation of lignin (Feofilova and Mysyakina 2016). Not all microorganisms are able to produce enzymes for lignin decomposition (Asina et al. 2016), so lignin is considered a resistant compound for biodegradation. Peatlands with high lignin content have a low rate of CO_2 emission (Könönen et al. 2016). Saidy et al. (2018) developed a model of greenhouse gas emissions of tropical peatlands and used peat lignin content as a parameter to predict the amounts of CO_2 produced in tropical peatlands, in which increasing peat lignin content suppresses the rate of CO_2 emissions. Results of these studies indicate that lignin content controls the rate of CO_2 emissions of tropical peatlands.

The study also showed that the fiber content of tropical peatlands varied based on the changes in land uses (Table 1), which eventually led to differences in the organic C contents of peatlands. It was evident that burned peatland with low fiber content exhibited low organic C, while shrubs-peatland with high fiber content had high organic C (Table 1).

Variation in organic C content with changes in fiber contents may ascribe to the significant relationship ($P < 0.001$) between fiber contents and CO_2 emission of tropical peatlands (Figure 4.C). Shrubs-peatland with high fiber content experiences high CO_2 emission, and low CO_2 emission was observed on burned-peat experiencing low fiber content.

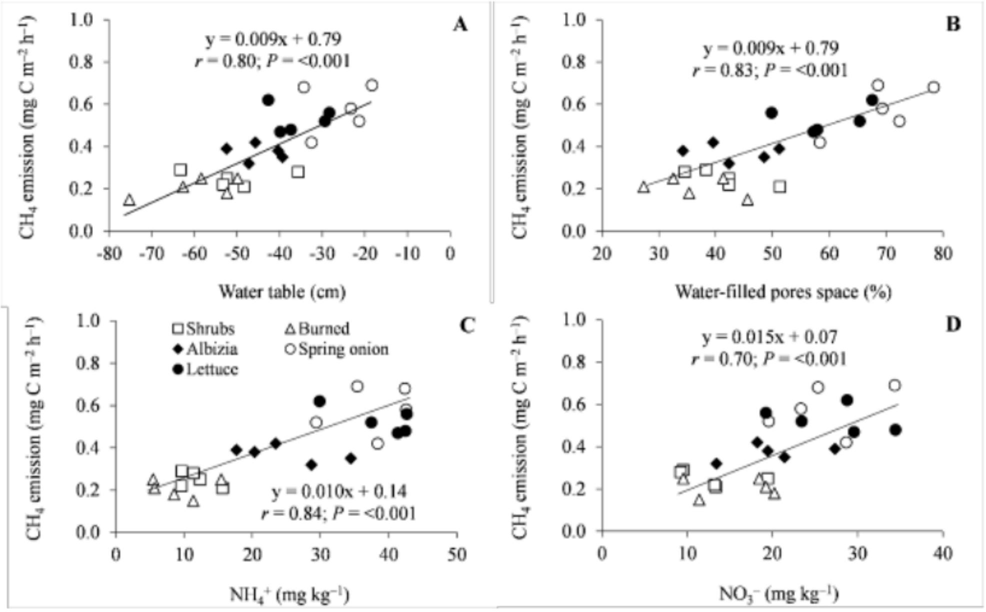

Figure 3. Relationship between water table (A), water-filled pores space (B), concentration of ammonium (C), and concentration of nitrate (D) and methane emission of tropical peatlands with different land uses

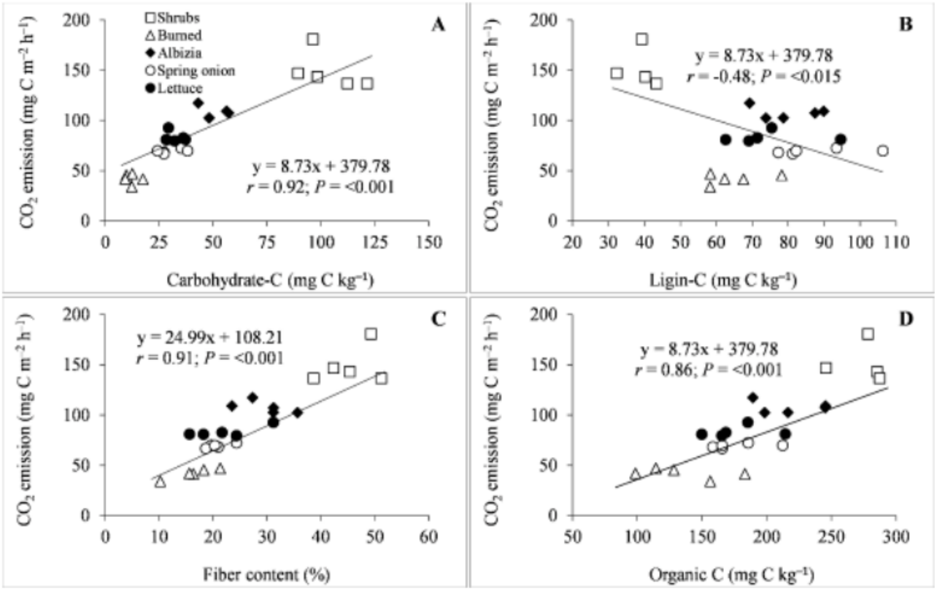

Figure 4. Relationship between carbohydrate (A), lignin (B), fiber contents (C), and organic C contents (D), and carbon dioxide emission of tropical peatlands with different land uses

It is well established that the rate of peat decomposition that contributes to CO_2 emission in peatlands is controlled by the amount of organic C contained in the peats (Cooper et al. 2019; Swails et al. 2018). Control of organic carbon on CO_2 production is also shown by Girkin et al. (2020), which reported the amounts of different organic C inputs from different plant communities on the peat surface to determine the CO_2 production of tropical peatlands. Results of these previous studies support findings obtained in this study that CO_2 emissions in peatlands differing land uses correlated positively significantly with organic C content (P <0.001). Burned peats with low organic C had low CO_2 emissions, while high CO_2 emissions were observed in shrubs-peats with high organic C content (Figure 4.D). The results of this study indicate that the amount of organic C containing in the peat plays a crucial role in determining the rate of CO_2 emission in tropical peatlands.

Results of this study revealed that tropical peatlands with different land use: shrubs-, burned-, cultivated- (*Albizia*, spring onion, and lettuce) peatlands experience diversity in CH_4 and CO_2 emissions. Shrubs- and burned peatlands produce the lowest CH_4 emission, while the highest rate of CH_4 emission was observed in spring onion- and lettuce-peatlands. Simple regression analyses revealed that diversity in CH_4 emissions of tropical peatlands is attributed to differences in the water table, water-filled pore spaces, ammonium contents, and nitrate contents among these peatlands. In contrast to CH_4 emissions, CO_2 emissions of uncultivated tropical peatlands (shrub peats) are higher than those of cultivated tropical peatlands, with the exception of burned peatland. Emission of CO_2 in tropical peatlands experiencing different land use has a relationship with carbohydrate-, fiber-, organic C-, and lignin contents. Results of this study demonstrate that diversity in CH_4 and CO_2 emissions of tropical peatlands experiencing different land uses are controlled by variables related to the water table of peatlands and the quality and quantity of organic C contained in the peatlands, respectively. Therefore, the management of land and water is very crucial to carry out for mitigation of CH_4 and CO_2 emissions in tropical peatlands used for agricultural activities.

ACKNOWLEDGEMENTS

The authors acknowledged the Ministry of Education, Culture, Research and Technology for funding this study through Fundamental Research Grant 2022 (Research Grant # 113/E5/PG.02.00.PT/2022).

REFERENCES

Anda M, Ritung S, Suryani E, Sukarman, Hikmat M, Yatno E, Mulyani A, Subandiono RE, Suratman, Husnain. 2021. Revisiting tropical peatlands in Indonesia: Semi-detailed mapping, extent and depth distribution assessment. Geoderma 402: 115235. DOI: 10.1016/j.geoderma.2021.115235.

Anshari GZ, Afifudin M, Nuriman M, Gusmayanti E, Arianie L, Susana R, Nusantara RW, Sugardjito J, Rafiastanto A. 2010. Drainage and land use impacts on changes in selected peat properties and peat degradation in West Kalimantan Province, Indonesia. Biogeosciences 7: 3403-3419. DOI: 10.5194/bg-7-3403-2010.

Arai H, Hadi A, Darung U, Limin SH, Takahashi H, Hatano R, Inubushi K. 2014. Land use change affects microbial biomass and fluxes of carbon dioxide and nitrous oxide in tropical peatlands. Soil Sci Plant Nutr 60: 423-434. DOI: 10.1080/00380768.2014.903576.

Asina F, Brzonova I, Voeller K, Kozliak E, Kubátová A, Yao B, Ji Y. 2016. Biodegradation of lignin by fungi, bacteria and laccases. Bioresour Technol 220: 414-424. DOI: 10.1016/j.biortech.2016.08.016.

Bešter-Rogač M, Habe D. 2006. Modern advances in electrical conductivity measurements of solutions. Acta Chimica Slovenica 53 (3).

Boon A, Robinson JS, Chadwick DR, Cardenas LM. 2014. Effect of cattle urine addition on the surface emissions and subsurface concentrations of greenhouse gases in a UK peat grassland. Agric Ecosyst Environ 186: 23-32. DOI: 10.1016/j.agee.2014.01.008.

Bremer JM, Mulvaney CS. 1982. Nitrogen-total. In: Page AL, Keeney DR (eds). Methods of Soil Analysis Part 2: Chemical and Biological Methods. Soil Science Society of America Inc., Madison WI.

Bundy LG, Meisinger JJ. 1994. Nitrogen availability indices. In: Weaver RW, Angle JS, Bottomley PS (eds). Methods of Soil Analysis, Part 2: Chemical and Biological Methods. Soil Science Society of America, Madison WI.

Cepáková Š, Frouz J. 2015. Changes in chemical composition of litter during decomposition: a review of published ^{13}C NMR spectra. J Soil Sci Plant Nutr 15: 805-815. DOI: 10.4067/S0718-95162015005000055.

Chen M, Chang L, Zhang J, Guo F, Vymazal J, He Q, Chen Y. 2020. Global nitrogen input on wetland ecosystem: The driving mechanism of soil labile carbon and nitrogen on greenhouse gas emissions. Environ Sci Ecotechnol 4: 100063. DOI: 10.1016/j.ese.2020.100063.

Chesson A. 1981. Effects of sodium hydroxide on cereal straws in relation to the enhanced degradation of structural polysaccharides by rumen microorganisms. J Sci Food Agric 32: 745-758. DOI: 10.1002/jsfa.2740320802.

Cobb AR, Harvey CF. 2019. Scalar simulation and parameterization of water table dynamics in tropical peatlands. Water Resour Res 55: 9351-9377. DOI: 10.1029/2019WR025411.

Cooper HV, Vane CH, Evers S, Aplin P, Girkin NT, Sjögersten S. 2019. From peat swamp forest to oil palm plantations: The stability of tropical peatland carbon. Geoderma 342: 109-117. DOI: 10.1016/j.geoderma.2019.02.021.

Deshmukh CS, Julius D, Evans CD, Nardi, Susanto AP, Page SE, Gauci V, Laurén A, Sabiham S, Agus F, Asyhari A, Kurnianto S, Suardiwerianto Y, Desai AR. 2020. Impact of forest plantation on methane emissions from tropical peatland. Global Change Biol 26: 2477-2495. DOI: 10.1111/gcb.15019.

Dohong A, Aziz AA, Dargusch P. 2017. A review of the drivers of tropical peatland degradation in South-East Asia. Land Use Policy 69: 349-360. DOI: 10.1016/j.landusepol.2017.09.035.

Dommain R, Dittrich I, Giesen W, Joosten H, Rais DS, Silvius M, Wibisono ITC. 2016. Ecosystem services, degradation and restoration of peat swamps in the Southeast Asian tropics. In: Bonn A, Allott T, Evans M, Joosten H, Stoneman R (eds). Peatland Restoration and Ecosystem Services: Science, Policy and Practice. Cambridge University Press, Cambridge. DOI: 10.1017/CBO9781139177788.015.

Feofilova EP, Mysyakina IS. 2016. Lignin: Chemical structure, biodegradation, and practical application (a review). Appl Biochem Microbiol 52: 573-581. DOI: 10.1134/S0003683816060053.

Girkin NT, Dhandapani S, Evers S, Ostle N, Turner BL, Sjögersten S. 2020. Interactions between labile carbon, temperature and land use regulate carbon dioxide and methane production in tropical peat. Biogeochemistry 147: 87-97. DOI: 10.1007/s10533-019-00632-y.

Girkin NT, Vane CH, Cooper HV, Moss-Hayes V, Craigon J, Turner BL, Ostle N, Sjögersten S. 2019. Spatial variability of organic matter properties determines methane fluxes in a tropical forested peatland. Biogeochemistry 142: 231-245. DOI: 10.1007/s10533-018-0531-1.

Grandy AS, Erich MS, Porter GA. 2000. Suitability of the anthrone-sulfuric acid reagent for determining water soluble carbohydrates in soil water extracts. Soil Biol Biochem 32: 725-727. DOI: 10.1016/S0038-0717(99)00203-5.

Grover SPP, Baldock JA. 2013. The link between peat hydrology and decomposition: Beyond von Post. J Hydrol 479: 130-138. DOI: 10.1016/j.jhydrol.2012.11.049.

Hadi A, Inubushi K, Furukawa Y, Purnomo E, Rasmadi M, Tsuruta H. 2005. Greenhouse gas emissions from tropical peatlands of Kalimantan,Indonesia. Nutr Cycl Agroecosyst 71: 73-80. DOI: 10.1007/s10705-004-0380-2.

Hirano T, Kusin K, Limin S, Osaki M. 2014. Carbon dioxide emissions through oxidative peat decomposition on a burnt tropical peatland. Global Change Biol 20: 555-565. DOI: 10.1111/gcb.12296.

Hoyos-Santillan J, Lomax BH, Large D, Turner BL, Lopez OR, Boom A, Sepulveda-Jauregui A, Sjögersten S. 2019. Evaluation of vegetation communities, water table, and peat composition as drivers of greenhouse gas emissions in lowland tropical peatlands. Sci Total Environ 688: 1193-1204. DOI: 10.1016/j.scitotenv.2019.06.366.

Inubushi K, Otake S, Furukawa Y, Shibasaki N, Ali M, Itang AM, Tsuruta H. 2005. Factors influencing methane emission from peat soils: Comparison of tropical and temperate wetlands. Nutr Cycl Agroecosyst 71: 93-99. DOI: 10.1007/s10705-004-5283-8.

Ishikura K, Hirano T, Okimoto Y, Hirata R, Kiew F, Melling L, Aeries EB, Lo KS, Musin KK, Waili JW, Wong GX, Ishii Y. 2018. Soil carbon dioxide emissions due to oxidative peat decomposition in an oil palm plantation on tropical peat. Agric Ecosyst Environ 254: 202-212. DOI: 10.1016/j.agee.2017.11.025.

Ishikura K, Hirata R, Hirano T, Okimoto Y, Wong GX, Melling L, Aeries EB, Kiew F, San Lo K, Musin KK. 2019. Carbon dioxide and methane emissions from peat soil in an undrained tropical peat swamp forest. Ecosystems 22: 1852-1868. DOI: 10.1007/s10021-019-00376-8.

Ismail I, Haghighi AT, Marttila H, Kurniawan U, Karyanto O, Kløve B. 2021. Water table variations on different land use units in a drained tropical peatland island of Indonesia. Hydrol Res 52: 1372-1388. DOI: 10.2166/nh.2021.062.

Keller JK, Madvedeff CA. 2016. Soil Organic Matter. In: Vepraskas MJ, Craft CB (eds). Wetland Soils: Genesis, Hydrology, Landscapes, and Classification. 2nd Edition.CRC Press, Boca Raton.

Kiew F, Hirata R, Hirano T, Xhuan WG, Aries EB, Kemudang K, Wenceslaus J, San LK, Melling L. 2020. Carbon dioxide balance of an oil palm plantation established on tropical peat. Agric For Meteorol 295: 108189. DOI: 10.1016/j.agrformet.2020.108189.

Könönen M, Jauhiainen J, Laiho R, Spetz P, Kusin K, Limin S, Vasander H. 2016. Land use increases the recalcitrance of tropical peat. Wetl Ecol Manag 24: 717-731. DOI: 10.1007/s11273-016-9498-7.

Kumar P, Adelodun AA, Khan MF, Krisnawati H, Garcia-Menendez F. 2020. Towards an improved understanding of greenhouse gas emissions and fluxes in tropical peatlands of Southeast Asia. Sustain Cities Soc 53: 101881. DOI: 10.1016/j.scs.2019.101881.

Kurnain A, Notohadikusumo T, Radjagukguk B. 2006. Impact of development and cultivation on hydro-physical properties of tropical peat soils. Tropics 15: 383-389. DOI: 10.3759/tropics.15.383.

Kurnianto S, Warren M, Talbot J, Kauffman B, Murdiyarso D, Frolking S. 2015. Carbon accumulation of tropical peatlands over millennia: a modeling approach. Glob Change Biol 21: 431-444. DOI: 10.1111/gcb.12672.

Lau SYL, Midot F, Dom SP, Lo ML, Chin M-Y, Jee MS, Yap ML, Chaddy A, Melling L. 2022. Application of ammonium sulfate affects greenhouse gases and microbial diversity of an oil palm plantation on tropical peat. Arch Agron Soil Sci 1-14. DOI: 10.1080/03650340.2021.2022650.

Luta W, Ahmed OH, Omar L, Heng RK, Choo LN, Jalloh MB, Musah AA, Abdu A. 2021. Water table fluctuation and methane emission in pineapples (*Ananas comosus* (L.) Merr.) cultivated on a tropical peatland. Agronomy 11 (8): 1448. DOI: 10.3390/agronomy11081448.

Marwanto S, Sabiham S, Funakawa S. 2019. Importance of CO_2 production in subsoil layers of drained tropical peatland under mature oil palm plantation. Soil Tillage Res 186: 206-213. DOI: 10.1016/j.still.2018.10.021.

McLean EO. 1982. Soil pH and lime requirement. In: Page AL, Keeney DR (eds). Methods of Soil Analysis Part 2: Chemical and Biological Properties. Soil Science Society of America, Madison WI.

Miettinen J, Shi C, Liew SC. 2016. Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 with changes since 1990. Glob Ecol Conserv 6: 67-78. DOI: 10.1016/j.gecco.2016.02.004.

Nelson DW, Sommers LE. 1996. Total carbon, organic carbon and organic matter. In: Sparks DL (ed). Methods of Soil Analysis Part 3: Chemical Methods. Soil Science Society of America-American Society of Agronomy Inc., Madison WI.

Parent LE, Caron J. 1993. Physical Properties of Organic Soils. In: Carter MR (ed). Soil Sampling and Methods of Analysis. Lewis Publishers, Boca Raton.

Rocha Campos JRd, Silva AC, Fernandes JSC, Ferreira MM, Silva DV. 2011. Water retention in a peatland with organic matter in different decomposition stages. Revista Brasileira de Ciência do Solo 35: 1217-1227. DOI: 10.1590/S0100-06832011000400015.

Sackett TE, Basiliko N, Noyce GL, Winsborough C, Schurman J, Ikeda C, Thomas SC. 2015. Soil and greenhouse gas responses to biochar additions in a temperate hardwood forest. GCB Bioenergy 7: 1062-1074. DOI: 10.1111/gcbb.12211.

Saidy AR, Mariana ZT, Adji FA, Nusantara RW, Fitria I, Syahrinuddin. 2018. Carbon mineralization dynamics of tropical peats in relation to peat characteristics. Biodiversitas 19: 1413-1421. DOI: 10.13057/biodiv/d190430.

Saidy AR, Razie F, Aidawati N, Hidayat T. 2020. Increases in greenhouse gases following the use of peatlands for agricultural areas. IOP Conf Ser Earth Environ Sci 499: 012021. DOI: 10.1088/1755-1315/499/1/012021.

Sasidhran S, Adila N, Hamdan MS, Samantha LD, Aziz N, Kamarudin N, Puan CL, Turner E, Azhar B. 2016. Habitat occupancy patterns and activity rate of native mammals in tropical fragmented peat swamp reserves in Peninsular Malaysia. For Ecol Manag 363: 140-148. DOI: 10.1016/j.foreco.2015.12.037.

Silviana SH, Saharjo BH, Sutikno S. 2021. Distribution of carbon stocks in drainage areas on peatlands of Sungai Tohor Village, Meranti Islands District, Indonesia. Biodiversitas 22 (11): 5106-5114. DOI: 10.13057/biodiv/d221149.

Sinclair AL, Graham LLB, Putra EI, Saharjo BH, Applegate G, Grover SP, Cochrane MA. 2020. Effects of distance from canal and degradation history on peat bulk density in a degraded tropical peatland. Sci Total Environ 699: 134199. DOI: 10.1016/j.scitotenv.2019.134199.

Statistics of Banjarbaru Municipality. 2022. Banjarbaru Municipality in Figures. Statistics of Banjarbaru Municipality, Banjarbaru. [Indonesian]

Swails E, Jaye D, Verchot L, Hergoualc'h K, Schirrmann M, Borchard N, Wahyuni N, Lawrence D. 2018. Will CO_2 emissions from drained tropical peatlands decline over time? Links between soil organic matter quality, nutrients, and C mineralization rates. Ecosystems 21: 868-885. DOI: 10.1007/s10021-017-0190-4.

Takada M, Shimada S, Takahashi H. 2016. Tropical Peat Formation. In: Osaki M, Tsuji N (eds). Tropical Peatland Ecosystems. Springer Japan, Tokyo. DOI: 10.1007/978-4-431-55681-7_8.

Upton A, Vane CH, Girkin N, Turner BL, Sjögersten S. 2018. Does litter input determine carbon storage and peat organic chemistry in tropical peatlands? Geoderma 326: 76-87. DOI: 10.1016/j.geoderma.2018.03.030.

Wakhid N, Hirano T, Okimoto Y, Nurzakiah S, Nursyamsi D. 2017. Soil carbon dioxide emissions from a rubber plantation on tropical peat. Sci Total Environ 581: 857-865. DOI: 10.1016/j.scitotenv.2017.01.035.

Warren M, Frolking S, Dai Z, Kurnianto S. 2017. Impacts of land use, restoration, and climate change on tropical peat carbon stocks in the twenty-first century: implications for climate mitigation. Mitigation Adapt Strategies Global Change 22 (7): 1041-1061. DOI: 10.1007/s11027-016-9712-1.

Wasis B, Saharjo BH, Putra EI. 2019. Impacts of peat fire on soil flora and fauna, soil properties and environmental damage in Riau Province, Indonesia. Biodiversitas 20 (6): 1770-1775. DOI: 10.13057/biodiv/d200639.

Wijedasa LS. 2016. Peat soil bulk density important for estimation of peatland fire emissions. Glob Change Biol 22: 2959-2959. DOI: 10.1111/gcb.13364.

Wong GX, Hirata R, Hirano T, Kiew F, Aeries EB, Musin KK, Waili JW, Lo KS, Melling L. 2020. How do land use practices affect methane emissions from tropical peat ecosystems? Agric For Meteorol 282-283: 107869. DOI: 10.1016/j.agrformet.2019.107869.

Xiao L, Xie B, Liu J, Zhang H, Han G, Wang O, Liu F. 2017. Stimulation of long-term ammonium nitrogen deposition on methanogenesis by Methanocellaceae in a coastal wetland. Sci Total Environ 595: 337-343. DOI: 10.1016/j.scitotenv.2017.03.279.

Zulkarnaini, Sujianto, Wawan. 2022. Short Communication: Sustainability of ecological dimension in peatland management in The Giam Siak Kecil Bukit Batu Landscape, Riau, Indonesia. Biodiversitas 23 (4): 1822-1827. DOI: 10.13057/biodiv/d230414.

Diversity In Characteristics Of Tropical Peatlands Varying In Land Uses Leads To Differences In Methane And Carbon Dioxide Emissions

ORIGINALITY REPORT

6%	4%	6%	%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	Akhmad R. Saidy, Fakhrur Razie, Noor Aidawati, Taufik Hidayat. "Increases in Greenhouse Gases Following the Use of Peatlands for Agricultural Areas", IOP Conference Series: Earth and Environmental Science, 2020 Publication	2%
2	jonuns.com Internet Source	1%
3	www.peatlandcongress2021.com Internet Source	1%
4	eprints.nottingham.ac.uk Internet Source	1%
5	Hironori Arai, Abdul Hadi, Untung Darung, Suwido H. Limin, Hidenori Takahashi, Ryusuke Hatano, Kazuyuki Inubushi. "Land use change affects microbial biomass and fluxes of carbon dioxide and nitrous oxide in tropical	1%

peatlands", Soil Science and Plant Nutrition, 2014
Publication

6	lppm.unram.ac.id Internet Source	1 %

Exclude quotes	On	Exclude matches	< 1%
Exclude bibliography	On		