Soil characteristics controlling nitrous oxide emissions of tropical peatlands

by Bambang Joko Priatmadi

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Abstract. Emission of nitrous oxide (N_2O) from peatlands contributes very significantly to the world global warming, although the factors controlling N_2O emissions from peatlands are not yet clear. This study aimed to determine peat characteristics controlling N_2O emissions in peatlands. N_2O emissions and several soil characteristics (pH, electrical conductivity, height of water table, water-filled pore space, decomposition degree of peats, bulk density, organic carbon, total nitrogen, and concentrations of ammonium and nitrate) were observed in peatlands with different crops and land-uses: lettuce, spring-onion, albizia, shrubs-peat, and burned-peats. Correlation-regression analyses were employed to quantify peat properties influencing the rates of N_2O emission from peatlands. The results of the study showed that N_2O emissions varied based on the type of crops/land-uses, in which peats used for crop cultivation had higher N_2O emissions than others. The results of the analysis also revealed that N_2O emissions of peat were controlled by variables related to water contents and the contents of NH_4^+ and NO_3^-. In peats with relatively similar NH_4^+ and NO_3^- contents, N_2O emissions were determined by variables related to water contents (height of water table and volumetric water contents). The result of this study shows the need for water and peat fertility management for the mitigation of N_2O emission from peatlands. Thus, managing the availability of nitrogen by using biological fertilizers to reduce the amounts of inorganic nitrogen fertilizers is required to reduce N_2O emissions without decreasing crop yields in peatlands.

Keys-words: denitrification, global-warming, mitigation, nitrification, nitrogen-cycles

1. Introduction

Peatlands are characterized by waterlogged anaerobic conditions that cause the rate of accumulation of organic matter is higher than the rates of organic matter decomposition. The area of peatlands in the world is estimated to be in the range of 185-423 million hectares or 1.2–2.8% of total lands in the surface of earth [1]. An area of 90-170 million hectares of global peatlands are tropical peatlands which are mainly located in the region of South America, South East Asia, and Central Africa [2]. Organic carbon content in global peatlands reaches 528-600 Pg, in which 10-30% of global organic carbon is stored in tropical peatlands [3]. High organic carbon contents cause tropical peatlands potentially become one of the largest emitter greenhouse gases.

Nitrous oxide (N_2O) is an important greenhouse gas due to its global warming potential which is greater than that of CO_2 and CH_4, in which most of the N_2O is produced from chemical reactions in soils mediated by soil microorganisms. High content and mineralization rates of nitrogen lead to peatlands become one of the largest contributors of global N_2O emission. Nitrogen content in peatlands could reach 2.3 Gt N [4], in which some of the nitrogen in peatlands converted to N_2O emission through nitrification and denitrification. N_2O either result in as a by-product in the chemical reaction of ammonium oxidation to nitrate. The reduction of NO_3^- to N_2O and N some of the N in peatlands may also be a source of N_2O emission through nitrification and denitrification conducted by facultative anaerobic bacteria.

Deforestation, logging, drainage and land use changes may result in variations in peatland characteristics that eventually influence the rates of N_2O emissions. The application of pineapple residue ash to tropical peatlands reduces N_2O emission compared to peatlands without ash application [5]. Application of coated nitrogen fertilizer to tropical peatlands decreases N_2O emission rates by 31 and 48% in wet and dry season related to peatland plots applied with conventional nitrogen fertilizer [6]. However, changes in environmental factors including climate variability, increasing nitrogen deposition, land use change, nitrogen fertilizer use, and drainage result in increases in N_2O emission rates [7]. Results of these studies show that the peat characteristics control N_2O emission of tropical peatlands is still not clear. Therefore, this study aimed to quantify the effect of peatland characteristics on the rates of N_2O emission in tropical peatlands experiencing different crops and land-uses.

2. Materials and methods

2.1. Study sites and peat characterization

Tropical peatlands used for this research are administratively located in Landasan Ulin Utara Village, Liang Anggang Sub-district, Banjarbaru Regency City, South Kalimantan Province, Indonesia. The air temperature in the study area was in the range of 21.0–35.4 °C with the highest average maximum air temperature occurring in August (29.4 °C) and the lowest minimum temperature occurring in December (27.5 °C). Annual precipitation in the study area reached to 3,141.5 mm, with the lowest rainfall in the study area occurred in August (57.20 mm) and the highest in January (572.40 mm).

Five different peatlands with different land-use: shrubs-peat, burned-peat, Albizia-peat, spring onion-peat and lettuce peat are situated in similar peat hydrological area and have similar vegetational origin. This peatland has also been drained so that most of the peatland is used as a crop cultivation. Shrubs-peat is reserved to delimit adjacent areas and is not used for crop cultivation. Burned-peat experienced fires in 2015-2017 and is currently still in the revegetation stage. Albizia-peat planted with *Albizia chinensis* (9 years old), and this area has never received fertilization. Cultivated-peats are used for spring onions and lettuce cultivation, in which these cultivated peatlands receive nitrogen and phosphorus fertilization 2-3 times a year.

Measurement of N_2O emissions and observations of peatland characteristics were carried out at five different points for each land-use. Direct measurements for water table, peat pH and electrical conductivity were carried out in the field during peat sampling, in which peat sampling was carried out by taking peat samples at a depth of 0-25 cm. After cleaning from plant residues, peat samples were put into plastic bags for determination of the physical and chemical properties of peat in the laboratory. Determination of peat characteristics in the laboratory consist of: rubbed fiber content and bulk density [8], the contents of NH_4^+ and NO_3^- [9], organic carbon content [10], and total nitrogen [11].

2.2. Measurement of nitrous oxide emission

Measurement of N_2O emission was carried out at the same point as peat sampling to determine the physico-chemical properties of peat. Measurement of N_2O emissions was carried out in the morning using the static chamber method, in which gas was sampled at intervals of 5, 10, 15 and 20 mins. The sampled gas was then transferred to a 10 mL air-tight glass vial for N_2O measurement using Shimadzu GC-14A equipped with an electron capture detector. The N_2O emission rates were calculated using linear relationship between changes in gas concentrations and time interval of gas sampling, areas covered by chamber, volume chamber and corrected for the field measured air temperature and atmospheric pressure.

2.3. Statistical analysis

Data of peatland characteristics and N_2O emission were analyzed using descriptive statistics to obtain a description of characteristics and N_2O emission in tropical peatlands with different land-uses. Correlation and regression analyses between peatlands characteristics and N_2O emission were performed to quantify peat characteristics and control the rates of N_2O emission in the tropical peatlands. The GenStat 12th Edition was employed to perform all statistical analyses.

3. Results and Discussion

3.1. Peat characteristics

Bulk density in tropical peatlands with different land-use was in the range of 0.13–0.40 Mg m^{-3} (Table 1). The lowest BD was observed in shrubs-peat, while burned-peats showed the highest BD. The highest BD in burned-peats is attributed to the fact that fire may cause physical breakdown of big peat particles into smaller peat particles, which eventually results in increasing peat bulk density. Increasing BD with peat exposure to air due to drainage has also been observed on peatlands used for agriculture [12].

Table1. Characteristics of peatlands with different land-uses (average ± standard deviation)

Characteristics	Shrubs-peat	Burned-peat	Albizia	Spring Onion	Lettuce
Bulk density (kg m^{-3})	0.13 ± 0.07	0.40 ± 0.08	0.25 ± 0.03	0.34 ± 0.10	0.35 ± 0.07
Rubbed fibre (%)	45.39 ± 5.10	16.38 ± 4.08	29.81 ± 4.58	20.82 ± 2.16	22.23 ± 6.37
Water table (cm)	-50.58 ± 9.97	-59.70 ± 9.03	-45.01 ± 5.36	-25.98 ± 7.06	-35.52 ± 6.37
WFPS (%)	41.79 ± 6.24	36.45 ± 7.20	43.19 ± 6.83	69.39 ± 7.27	59.58 ± 7.07
EC (mS)	109.99 ± 9.81	120.75 ± 8.53	122.72 ± 8.36	196.57 ± 44.85	197.38 ± 19.25
Peat pH	3.99 ± 0.12	4.43 ± 0.26	4.12 ± 0.27	4.43 ± 0.21	4.46 ± 0.35
NH_4^+ (mg kg^{-1})	11.72 ± 2.49	9.29 ± 4.20	24.91 ± 6.72	37.60 ± 5.49	38.74 ± 5.38
NO_3^- (mg kg^{-1})	12.96 ± 4.12	15.78 ± 4.91	19.98 ± 5.06	26.25 ± 5.60	27.08 ± 5.87
Total N (g kg^{-1})	13.66 ± 3.50	10.77 ± 2.19	12.62 ± 3.81	14.48 ± 3.00	15.84 ± 4.01
Organic C (g kg^{-1})	284.21 ± 28.11	136.18 ± 33.78	218.95 ± 25.98	177.53 ± 21.94	176.65 ± 24.54

Rubbed fiber (RF) content is frequently used to determine the levels of peat decomposition. Burned-peat has the lowest rubbed fiber content (16.3%) (Table 1), which can be classified as sapric peat [8]. Meanwhile, shrubs-peat has the highest RF content (Table 1), which can be classified as fibric peat [8]. Peatlands with spring onion and lettuce cultivation had RF content in the same range (20.8% and 22.2%), indicating that these two peats had the same decomposition rate (hemic peats).

The water table on the five peats with different land-uses varied from 25.9–59.7 cm from the peat surface (Table 1). The deepest water table was observed in burned-peats, while the shallowest water table was observed in lettuce-peatland. Differences in water table and rubbed fiber contents results in these five peatlands having different water-filled pore spaces (WFPS). Peat with low rubbed fiber content has low water holding capacity [13], so that burned-peat with the deepest water table from the peat surface has the lowest WFPS (Table 1). On the other hand, spring onion and lettuce peatlands with a shallow water table from the peat surface and relatively high RF contents had relatively high WFPS (Table 1).

Peatlands cultivated with spring onion or lettuce displayed the highest electrical conductivity (EC), 196-197 mS, while the lowest EC occurred at shrubs-peat (Table 1). The pH of five peatlands was in a relatively narrow range, 3.99-4.46 (Table 1). These pHs were in the pH range of tropical peats reported previously. For example, tropical peatlands with land-uses that vary from uncultivated to rice-cultivated peats and undrained to drained peats have a pH in the range of 3.34 to 5.33 [14, 15]. Tropical-forested peatlands with varying organic carbon content had a pH range of 3.95-4.16 [16].

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3.2. Nitrous oxide emissions

Results of the study showed that shrubs-peat had N_2O fluxes up to 150 g N m^{-2} h^{-1} (13.12 kg N ha^{-1} $year^{-1}$) (Figure 1). Fluxes of N_2O from shrubs-peat in this study are in the range of N_2O emission of uncultivated tropical peatlands, which was in the range of 9.81 kg N ha^{-1} $year^{-1}$ in drained forest [17] to 858 kg N ha^{-1} $year^{-1}$ in unplanted and unfertilized peatlands [18]. Fluxes of N_2O of tropical peatlands cultivated with spring onion and lettuce reached to 496 mg N m^{-2} h^{-1} (43.48 kg N ha^{-1} $year^{-1}$) and 400 mg N m^{-2} h^{-1} (35.07 kg N ha^{-1} $year^{-1}$), respectively (Figure 1). Emission of N_2O presented in this study were comparable to those reported in other studies: in cropland peats: 11–698 kg N kg N ha^{-1} $year^{-1}$ [19], and agricultural peatlands 26 kg N ha^{-1} $year^{-1}$ [20]. The lowest N_2O emission of 115 mg N m^{-2} h^{-1} or 10.06 kg N ha^{-1} $year^{-1}$ was observed in burned-peat (Figure 1). N_2O fluxes of burned-peat obtained in the present study was higher than those reported in the previous study. According Hatano et al. [19], N_2O fluxes from burned-peat are 0.97–1.5 kg N ha^{-1} $year^{-1}$. Higher available substrates (NH_4^+ and NO_3^-) observed in the present study compared with those in the previous study may ascribed to higher N_2O fluxes.

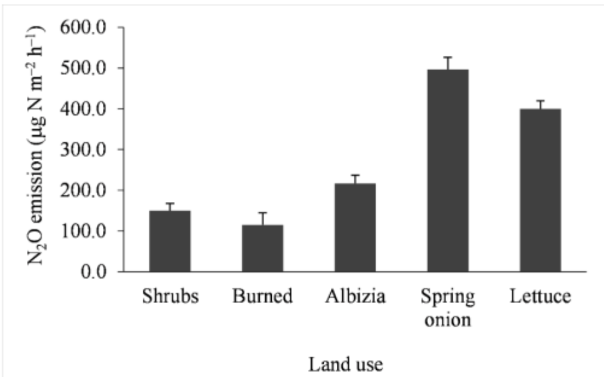

Figure 1. Nitrous emissions of tropical peatlands with different land-uses. Lines above the bars represent the standard deviation of mean (n=5).

3.3. Peatland characteristics control nitrous oxide emissions

Correlation and regression analyses were performed to determine the peat characteristics control for N_2O emission rates of tropical peatlands (Table 2). Water table had a significant correlation (r = 0.81; P <0.01) to N_2O emission (Table 2 and Figure 2A). Changes in water table from -50 cm to -30 cm increase N_2O emission due to increasing water table stimulates denitrification process. Result of this study suggest the importance of water table in controlling the amount of N emit from tropical peatlands through the controlling effect of water table on nitrification and denitrification processes.

The results of the analysis also showed that water-filled pore spaces (r = 0.91; P <0.01) correlated significantly with the emission rates of N_2O (Table 2 and Figure 2B). Several previous studies reported that water content significantly control the amount of N_2O released from the soils. The amount of water in soil pores (water-filled pore space – WFPS) affects the composition and activity of denitrifier and nitrifier in soils, which ultimately influences the amount of N emit from soils [21]. The effect of WFPS on N_2O fluxes is the greatest at 80% WFPS [22]. N_2O fluxes are very responsive to changes in WFPS, in which a change of 0.01 in WFPS led to changes in N_2O fluxes of approximately 0.25 Tg N per year [23].

Concentration of NO_3^- plays an important role in increasing N_2O emission from tropical peatlands through denitrification process. N_2O fluxes is controlled by soil nitrate contents, in which increasing soil nitrate content results in increases in N_2O flux. The avalaibility of NO_3^- in this present study had a significant correlation (r = 0.69; P <0.01) to N_2O emission (Table 2 and Figure 2C). Increasing N_2O

emission due to an increase in NO_3^- availability at 70-96% WFPS indicates that the process of N emission from peat into the atmosphere occurs through the denitrification process. However, WFPS observed on all peatlands in the present study was in the range of 36-69% (Table 1). Significant correlation between NO_3^- availability and N_2O emission in this study indicates that nitrification also contributes to N_2O emissions in tropical peatlands.

Table 2. Correlation between nitrous emissions and characteristics of peatlands

No.	Characteristics of peatland	Coefficient correlation (*r*)
1.	Bulk density	0.27 ns
2.	Rubbed fiber content	-0.31 ns
3.	Height of water table	0.81 **
4.	Water-filled pore space	0.91 **
5.	Redox potential	-0.88 **
6.	Electrical conductivity	0.34 ns
7.	Peat pH	0.38 ns
8.	Concentration of NH_4^+	0.87 **
9.	Concentration of NO_3^-	0.69 **
10.	Total nitrogen	0.37 ns
11.	Organic carbon	-0.20 ns

* Significant at $P < 0.05$
** Significant at $P < 0.01$
ns Not significant

Emission of N_2O ftrom tropical peatlands is also controlled by the availability of ammonium as indicated by positive and significant correlation between N_2O fluxes and the concentrations of NH_4^+ ($r = 0.87$; $P < 0.01$) (Table 2 and Figure 2D). The contents both NH_4^+ and NO_3^- in peatlands used for spring onion and lettuce cultivation were comparable, reaching to 38–39 mg NH_4^+-N kg^{-1} and 14–16 mg NO_3^--N kg^{-1}, respectively (Table 1). Contents of NH_4^+ and NO_3^- in these peatlands were higher than those in shrubs-, burned-, and Albizia-peatlands (Table 1). Urea application to improve the growth and yield of spring onion and lettuce may ascribe to high NH_4^+ and NO_3^- contents. However, N_2O emission was higher in spring onion-peat than that of lettuce-peat (Figure 1). Water table of spring onion-peat was lower than that of lettuce-peats, and this leads to higher WFPS in spring onion-peat, which ultimately results in higher N_2O emission from spring onion peat than that in lettuce peat (Figure 1). Result of this study suggests that on cultivated tropical peatlands containing comparable contents of NH_4^+ and NO_3^-, the emission of N_2O is controlled by water contents of peatlands.

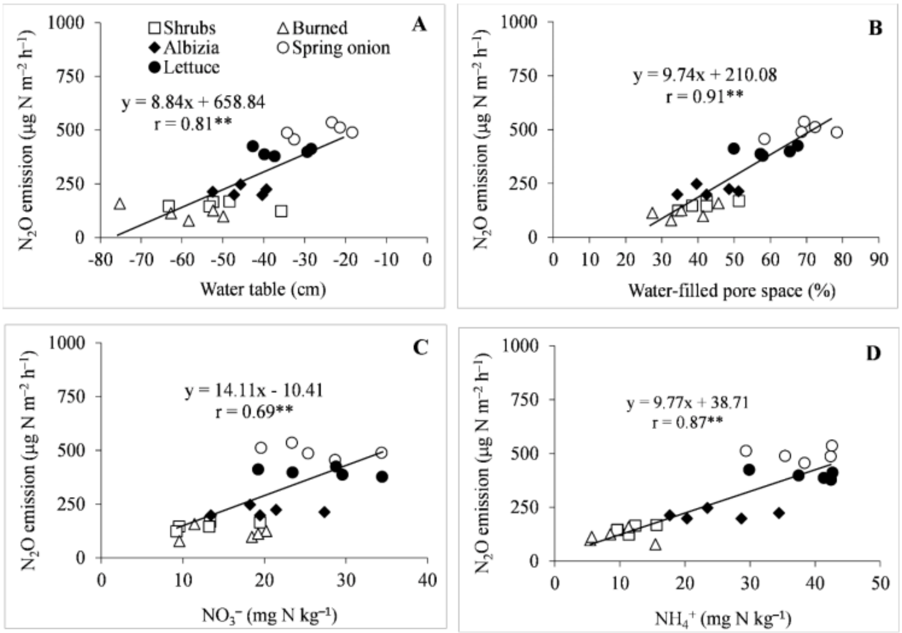

Figure 2. Relationship between nitrous emissions and height of water table (A), water-filled pore space (B), concentration of nitrate (C), ammonium (D) of tropical peatlands.

4. Conclusion

Results of the study showed that tropical peatlands experiencing different land-uses have distinct characteristics. Burned-peat was characterized by high BD, deep water table, and low rubbed-fiber content, low WFPS, and low contents of ammonium and nitrate. Meanwhile, peatlands used for spring onion and lettuce cultivation have shallow water table, high WFPS, and high contents of ammonium and nitrate. Emission of N_2O varied across five tropical peatlands, in which peatlands cultivated by spring onion and lettuce showed the highest N_2O emission, while burned peat showed the lowest N_2O emission. Correlation and regression analyses revealed that the rates of N_2O emission in the tropical peatlands were controlled by water table, WFPS and concentrations of NH_4^+ and NO_3^-. In cultivated peatlands encompassing relatively similar amounts of NH_4^+ and NO_3^-, the rates of N_2O emission were regulated by water table and WFPS of peatlands. Results of this study demonstrate the needs of water and fertilizer managements to reduce N_2O emission without compromising crop yield in topical peatlands.

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