Nitrous oxide emission from conservation forest of Kampar Peninsula peatland ecosystem

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Abstract. *Nitrous oxide (N2O) is a long-lived greenhouse gas with a warming potential of 300 times higher than CO_2. Conserving of intact peat swamp forest can hold the natural physical and chemical properties of the soil, such that the N_2O emission occurs naturally. To quantify N_2O emission from peatland ecosystems, data availability is highly needed. The objectives of this study were to quantify the emission of N_2O and determine the main factors controlling N_2O emission from peatland conservation forests. This research was conducted from January to December 2020 in the Kampar Peninsula, Pelalawan Regency, Riau Province. We employed the static metallic manual ground chamber to collect gas samples and analyzed them using gas chromatograph equipped with electron capture detector. This study found that N_2O emission at peatland conservation forest was 0.23 ± 0.19 kg-N/ha/year. Substantial changes in soil and environmental factors such as water table, soil temperature, soil moisture, water-filled pore space, NH_4-N, and NO_3-N significantly affect the exchange and magnitude of N_2O between peatlands and the atmosphere.*

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INTRODUCTION

In terms of climate change study, the peat ecosystem has a significant role in various biogeochemical cycles of greenhouse gases. Both temperate and tropical peatlands play a major role in gas exchange with the atmosphere, as they are the mainstream greenhouse gases (Nunes *et al*., 2020). The most dominant greenhouse gas emissions in peatlands are carbon dioxide (CO_2), followed by methane (CH_4) and nitrous oxides (N_2O) emissions. N_2O is a long-lived greenhouse gas with a greenhouse gas potential of 300 times higher than CO_2 (IPCC, 2014; Sakabe *et al*., 2018). Tropical forests are still considered a major source of N_2O emissions to the atmosphere (Werner *et al*., 2007). The increase in N_2O in the atmosphere due to human activities affects the global climate, human health, and the function of ecosystems that are very sensitive to climate change (Fowler *et al*., 2013).

Many researchers consider that climate change has become the greatest challenge for humanity. Several natural and artificial activities are responsible for global warming, affecting the environment and humans. The current climate change has become a worldwide concern because it does have not only an impact on the environment but also human life (Fowler *et al*., 2013). Therefore, it is very important to find solutions to reduce

climate change (Nunes *et al*., 2020). Increased CO_2, CH_4, N_2O, and water vapor (H_2O) in the air contribute to global warming (Khare *et al*., 2020). The accumulation of greenhouse gases that form a thin layer in the atmosphere makes the air temperature hotter on the earth's surface. The Kampar Peninsula peat ecosystem covers about 722.929 ha and peat thickness ranging between 5 to 10 m (Arvelyna *et al*., 2019), making it one of the largest peat carbon reservoirs in Southeast Asia (Karyanto *et al*., 2015). Tropical peatlands store large amounts of carbon formed over a long time under water-saturated conditions. The nature of Indonesian peatlands varies significantly in terms of physical, chemical, and biological properties and environmental conditions. These varying conditions of peat properties indicate that peatlands can be used for agricultural development and some that need to be maintained to preserve the environment (Masganti, 2013).

The study on N_2O gas emissions in various ecosystems has not been done much compared to CO_2 and CH_4 gas emissions. Melling *et al*. (2007) explained that the highest N_2O emissions occurred in sago plantations with a production rate of 3.3 kg-N/ha/year, followed by oil palm plantations at 1.2 kg-N/ha/year and mixed peat swamp forest at 0.7 kg-N/ha/year. Conversion of peat swamp forest can cause major changes in the environment and the physical and chemical properties of the soil that will affect the N_2O cycle (Melling *et al*., 2007). Peatland management into agricultural land can cause high N_2O gas emissions, while forest areas still maintained have lower emissions (Takakai *et al*., 2006). Melling *et al*. (2007) stated that N_2O emissions from peatlands are strongly influenced by environmental factors: groundwater level.

Studies of N_2O emissions in tropical peatlands especially in Kampar Peninsula is remain overlooked despite of the lowest contribution to the GHG balance. Therefore, it is important to quantify the contribution of N_2O emissions from conservation forests. This research is part of a large study conducted in Kampar Peninsula related to greenhouse gas emissions (CO_2, CH_4 and N_2O) from different land-use types: conservation forest, acacia plantations, shrubs, and burnt land with measurements from the ground and above canopy. The measurement of greenhouse gas emissions from the ground is carried out using automatic and conventional chamber, while the measurement of emissions above the canopy uses a tower (Eddy covariance tower). We expect that N_2O emission at the natural condition will be insignificant due to less of nitrogen input as the main raw material to break down the chemical cycle into the nitrous oxide. This study aims to determine the N_2O gas emission factor from peatland conservation forests and determine the main drivers that influence the N_2O gas emissions.

METHOD

Study Area and Period

This research was conducted from January to December 2020 on the peatlands of the Kampar Peninsula, Pelalawan Regency, Riau Province. The Kampar Peninsula is one of the peat hydrological units (i.e. KHG) with the code KHG.14.05-08.01. The sampling location has been done atthe Riau Ecosystem Restoration (RER) with the area more than 100.000 hectares (Figure 1a) which is managed to protect biodiversity. Determination of sampling location was using purposive sampling method and the sampling locations were divided into three, namely conservation forest 1 (CF1), conservation forest 2 (CF2) (Figure 1b), and conservation forest 3 (CF3) with a distance between observation locations of 700 to 1 000 meters. The observation site is set within a 2 km radius of the greenhouse gas (GHG) emission measurement tower above the canopy, the framework for a larger GHG emission research project covering CO_2, CH_4 and N_2O gases. At each location, six hoods are installed with a distance between them of about 10 to 30 m. The hoods are installed in high and low areas to represent the peat surface's micro-topographic conditions in conservation forests. At each conservation forest observation location, a piezometer was installed to manually measure the ground water level at the time of gas sampling.
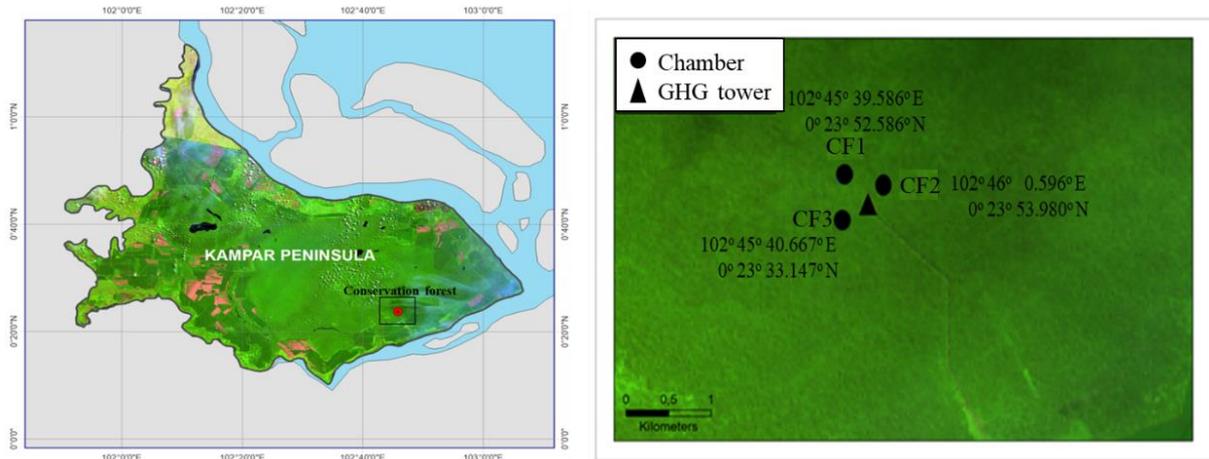
Figure 1 Study area: (a) Kampar Peninsula, Pelalawan Regency, Riau Province, KHG.14.05-08.01; and (b) three observation points in conservation forests (CF1, CF2, and CF3) and GHG tower

N₂O Gas Sampling and Analysis

Samples of N_2O gas emissions were collected using a conventional closed hood technique with a base dimension of 30 cm x 15 cm and a height of 15 cm made of stainless steel with a thickness of 2 mm. Technically, the hood is equipped with a hole covered with a rubber stopper as a place for gas sampling (Figure 2). At each containment point, a collar (frame) was first placed, which was immersed in the ground about one month before the first gas extraction (until the physical disturbance to the soil due to the immersion of the collar was removed) and left and protected from disturbance (physical) during the study. The collar is made of the same material and has the exact dimensions as the lid but is equipped with a canal/trench at the top with 2 cm x 1.5 cm (Figure 2). The canal/trench in this collar serves to accommodate the water given just before the hood is placed so that there is no gas leak during sampling. Gas sampling was carried out in January, April, and from June to December carried out monthly, in this case ignoring daily variations. Gas samples were taken in the time range from 10.00 to 15.00 PM.

Gas sampling was carried out using a 50 ml syringe, then put into a 20 ml sample bottle that had been vacuumed using a NaCl solution with a concentration of 80%, aiming to avoid air contamination in the sample bottle. The time interval for gas sampling is every 15 minutes after the hood is installed, namely at 0, 15, 30, and 45 minutes. All samples that have been taken are put into a cooler box to avoid direct sunlight contact, then analyzed in the laboratory in no more than 24 hours.
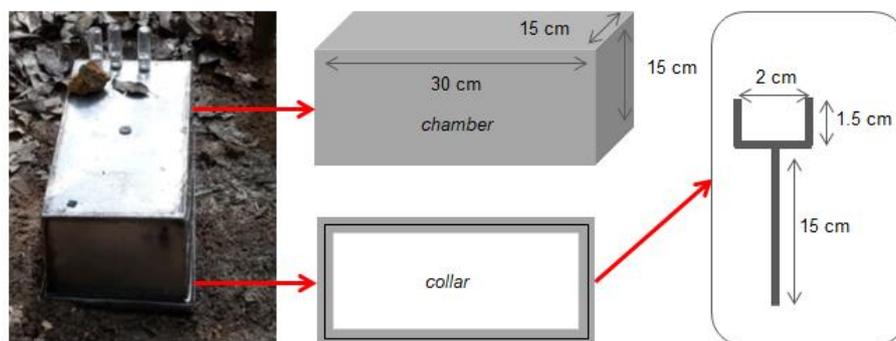
Figure 2 N₂O gas extraction equipment using a hood and collar design (frame)

Supporting Parameter Measurement

Supporting parameters measured in this study are environmental parameters and parameters of soil physical and chemical properties. Environmental parameters include groundwater level, rainfall, soil moisture, and soil temperature. Measurement of groundwater level is carried out in two ways, namely automatic and manual. The daily ground water level is automatically measured using a solinst levelogger (model 3 001) with a recording frequency of every 30 minutes to represent the entire location of conservation forests. Measurement of water level manually was carried out on piezometers at each conservation forest at the time of sampling N_2O gas. Daily rainfall is measured automatically with a rain gauge bucket (part of the equipment of the GHG tower) with a recording frequency of every 30 minutes. Soil moisture and soil temperature were measured at a depth of 15 cm using a steven hydra probe when returning the N_2O gas sample.

The measured soil chemical parameters included pH, C-organic, N-total, NH_4^-N, NO_3^-N, P-available, and K-available. The physical parameters measured were fiber volume, bulk density, porosity, and water-filled pore space (WFPS). Soil samples were taken using a peat sampler with a volume of 0.5 L, for the physical parameters of the soil samples were taken at a depth of 0-50 cm and 50-100 cm, while the chemical parameters of the soil samples were taken at a depth of 0-15 cm, 15-30 cm, and 30-50 cm. Soil samples for physical and chemical parameters were taken at four points in each N2O gas extraction hood; then soil samples were composited per depth to represent the gas sampling point. Wet peat samples were packaged using styrofoam boxes for analysis at the Soil Laboratory, IPB University.

N_2O Gas Emission Analysis and Calculation

Gas samples were analyzed using Gas Chromatography (GC) (SRI-8610C) following the procedure of Chen *et al*. (2010). The gas sample is inserted into the GC using a 3 ml syringe; then, the GC will read the peak gas N_2O on a simple peak application. The simple peak application will read the area from the peak of the GC reading graph, the site is recorded and tabulated for later use in calculating emissions. The N_2O gas in the GC is read with an Electron Capture Detector (ECD) for a maximum of 6 minutes. Two injections were performed as replicates for each sample, and calibration was performed every 20 sample injections (10 samples). The standard gas calibration uses pure N2 gas with a concentration of 330±10 ppb. This calibration aims to neutralize the column detector in the GC after sample injection. Calculation of N_2O gas emissions using the equation according to the IAEA (1992).

$$F= \frac{dc}{dt} \; x \; \frac{Vch}{Ach} \; x \; \frac{mW}{mV} \; x \; \frac{273.2}{273.2+T}$$

The Data from the analysis of emission calculations were used in regression analysis, statistical and descriptive analysis. Multi-variable linear regression analysis was employed to understand the relationship of N_2O gas emissions to the environmental parameters. The Wilcoxon test was used to understand the spatial variation of N_2O gas emissions. All statistical tests in this study used a confidence interval of *p<0.05*.

RESULT AND DISCUSSION

Characteristics of Study Location

Kampar Peninsula is a tropical peat forest area which has an area of about 722.929 ha. This ombrotrophic peat area, which is characterized by high acidity and nutrient-poor, was formed about 8 000 years ago (Deshmukh *et al*., 2020). Kampar Peninsula is the largest peat hydrological unit (KHG) in Riau Province which is located between two main rivers, the Siak River and the Kampar River. Kampar Peninsula has a tropical climate, and based on data from the Meteorology, Climatology and Geophysics Agency from 1997 to 2017,

the average monthly air temperature ranges from 29 to 30 °C, with average annual rainfall over the last five years (from 2014 to 2018) is 1 800 mm (Deshmukh *et al.*, 2020).

According to Miettinen *et al.* (2016) Kampar Peninsula peat forest has land cover characteristics that are dominated by natural forest, industrial plantation forest, and community agricultural areas. Natural forest and acacia plantation forest dominate the land cover in this area up to 80%. Natural forest is also referred to as natural peat swamp forest (Miettinen *et al.*, 2016). The range of tree height in this research location is between 28-35 m, tree density at DBH>5 cm reaches 1 300 trees per hectare (Deshmukh *et al.*, 2020). The average peat thickness in the conservation forest area was 9±1 m, the degree of acidity (pH) of the peat surface was around 3.6 ± 0.1, and the groundwater level during the study period in the conservation forest fluctuated seasonally depending on rainfall (Figure 3). Rainfall in 2020 at the study site was 1923 mm with an average ground water level of -0.32±0.18 m (Figure 3).
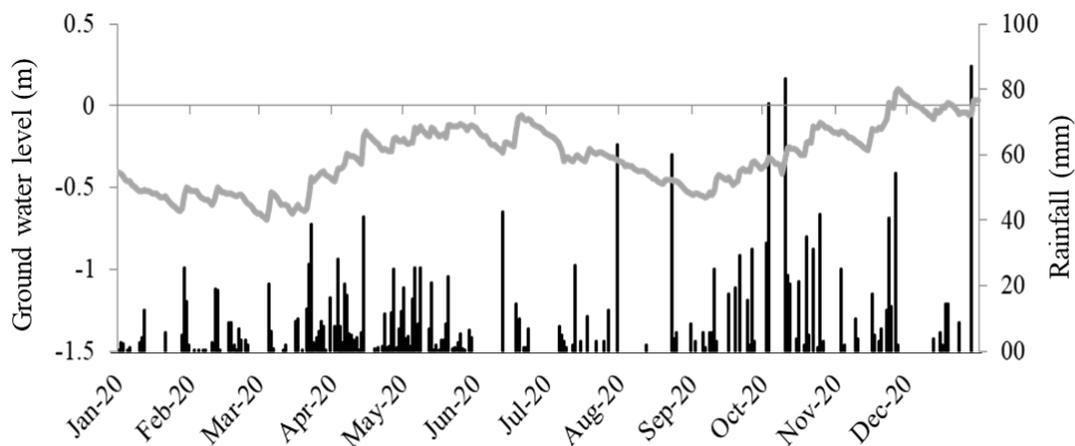
Figure 3 Daily rainfall and ground water level for January-December 2020 at the study site, Kampar Peninsula

The standard deviation of each conservation forest in the N_2O emissions, soil temperature, and soil moisture parameters represents temporal variation, while the other parameters represent variations in depth (Table 1). Between conservation forest locations (CF1, CF2 and CF3) illustrates the spatial variation. The ground water level (GWL) measured manually during gas sampling did not differ between conservation forest locations, with an average value ranging from -0.44 to -0.48 m. Soil temperature in CF1 was significantly higher than in CF2 and CF3. Meanwhile, soil moisture in CF1 and CF2 was considerably higher than in CF3. There are significant differences in fiber volume between conservation forest sites, but the average values ranging from 40 to 60% indicate that the peat maturity level is generally hemic. There was no significant difference in the density value of each peat sampling location with a value of 0.09 g/cm^{-3}. Porosity also does not show a substantial difference between conservation forest locations with a value close to 94%. Meanwhile, the water-filled pore space showed a significant difference in CF3 to CF1 and CF2, with values ranging from 35 to 46%.

The reaction (pH) of peat soil in each location has an average value of less than 4, indicating an acidic environmental condition. There is no significant difference in this trait between conservation forest locations. Meanwhile, other soil chemical properties showed significant differences between conservation forest locations, indicating a significant spatial difference in each area. The average C-organic content was in the range of 47.5 to 52.4% indicating that the peat soil sample was composed of 81.9 to 90.3% organic matter. Conservation forest ecosystems have an average total N content in the range of 1.21 to 1.89%, which indicates very high nitrogen stores by weight. However, the average C/N ratio ranges from 27.7 to 39.2, which is very high, meaning that peat material will still decompose if environmental conditions allow. While decomposition of peat material accompanied by the process of N nutrient immobilization is more dominant than the

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mineralization process. There is a very significant spatial difference in the concentration of NO_3^-N at each location, with a value between 0.13 to 0.24%. The concentration of NH_4-N also had a significantly different value at each location, with values ranging from 668 to 971 ppm. Significant spatial differences were also found in the P-available and K-available parameters.

Table 1 N_2O emissions, environmental parameters, parameters of soil physical and chemical properties of peat in the conservation forest of the Kampar Peninsula

Parameter	Unit	CF1	CF2	CF3
N_2O emissions	mg/m^2/day	0.29±0.21[c]	-0.03±0.13[a]	0.04±0.66[b]
GWL	M	-0.45±0.18[a]	-0.44±0.24[a]	-0.48±0.22[a]
Soil temperature	ºC	28.32±0.92[b]	27.87±1.02[a]	27.6±1.12[a]
Soil moisture	% (v/v)	43±25[b]	40±2[b]	33±2[a]
Soil physical properties:				
Fiber volume	% (v/v)	60.00[c]	40.00[a]	50.00[b]
Bulk density	g/cm^3	0.09 [a]	0.09 [a]	0.09 [a]
Porosity	% (v/v)	93.83 [a]	93.51 [a]	93.81 [a]
WFPS	% (v/v)	46 [b]	43 [b]	35 [a]
Soil chemical properties:				
pH	-	3.24±0.04[a]	3.26±0.1[a]	3.12±0.12[a]
C-organic	% (w/w)	52.36±2.7[c]	50.61±2.04[b]	47.48±2.37[a]
N-total	% (w/w)	1.89±0.05[c]	1.75±0.47[b]	1.21±0.31[a]
C/N Ratio	-	27.70 [a]	28.87 [a]	39.24 [b]
NO_3-N	% (w/w)	0.24±0.11[c]	0.18±0.12[b]	0.13±0.06[a]
NH_4-N	ppm	971.47±802.12[c]	667.87±280.9[a]	738.20±157.14[b]
P available	ppm	49.17±35.96[c]	45.73±13.13[b]	36.50±40.1[a]
K available	ppm	275.97±82.44[c]	182±44.3[b]	128.37±117.43[a]

Notes: Different letters following the numbers in the same row indicate significant differences between locations ($p<0.05$). GWL= ground water level; WFPS= water-filled pore space; CF1= conservation forest 1; CF2= conservation forest 2; CF3= conservation forest 3

N_2O Gas Emissions

Spatially, N_2O gas emissions were significantly different between CF1, CF2, and CF3, with values of 0.29±0.21, -0.03±0.13, and 0.04±0.66 mg/m^2/day, respectively (Table 1). The average value of N_2O gas emissions in conservation forests is 0.10±0.08 mg/ m^2/day or equivalent to 0.23±0.19 kg-N/ha/year. From the measurement results (Figure 4), temporally, about 90% of N_2O emissions in conservation forests are positive (source), while the rest are negative (sink). Negative N_2O values were observed in April 2020, which is a wet month condition when sampling N_2O gas. Monthly N_2O gas emission in conservation forests ranges from -0.03 to 0.21 mg/m2/day. The highest variability of N_2O emissions in conservation forests occurred in November 2020, which was the wet month at sampling. There is a significant seasonal pattern as well as high deviation variations throughout the study period. The high variation in deviation is caused by the large spatial variation of emissions at CF1, CF2, CF3 locations and the combination of environmental and soil factors. The microtopographic condition of the hood placement is thought to have contributed to the high variability, although it was not part of this study.

The highest monthly N_2O emissions occurred in November, while the lowest occurred in April 2020 and the highest monthly rainfall occurred in October, and the lowest occurred in June. A significant difference ($p<0.05$) was found in the monthly seasonal variation of N_2O emissions in conservation forests. In the driest month (August) conservation forests contributed N_2O emissions of 0.08 mg/m^2/day with 36 mm of rainfall.

The wettest month (October) N_2O emission is 0.07 mg/m^2/day with 337 mm of rainfall. Furthermore, during the wet month period (January, March to June, September to December), N_2O emissions that occur range from -0.03 to 0.22 mg/m^2/day or an average of 0.10 mg/m2/day with an average rainfall monthly reach 220 mm. The humid season in this study occurred in February and July. In July, the emission of N_2O was 0.14 mg/m2/day with an average rainfall of 83 mm. Based on data on N_2O emissions and monthly rainfall, it can be seen that there is no fixed pattern of relationship between the two. This is because the N_2O emission process combines the nitrification process of NH_4^+ to NO_3^- which requires aerobic or drier conditions, and the denitrification process of NO_3^- to N_2O which requires anaerobic or wetter conditions.
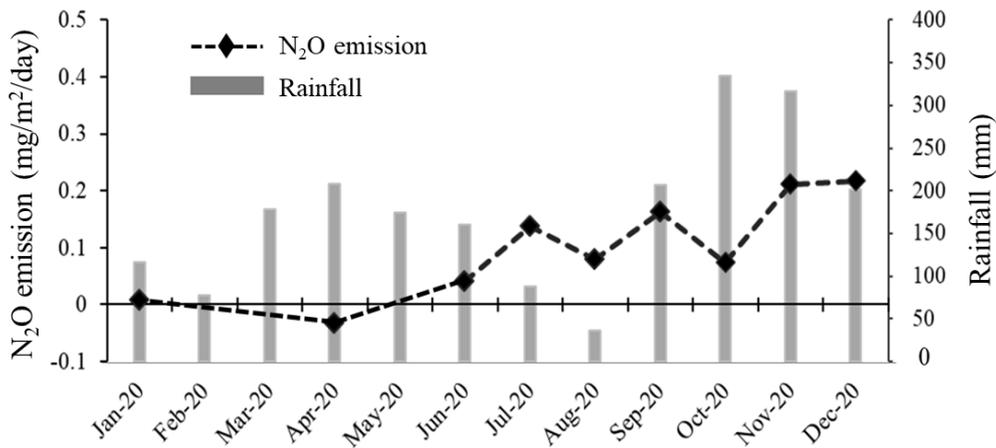
Figure 4 Temporal variation of N_2O gas emission and monthly rainfall in January-December 2020 in conservation forest, Kampar Peninsula

Conservation forests' annual N_2O gas emission value is 0.10 mg/m^2/day or equivalent to 0.23 kg-N/ha/year. This emission value is still smaller than the results of studies in conservation forests or natural forests conducted by Melling et al. (2007), where N_2O emissions in natural forests reached 0.70 kg-N/ha/year, Hassler et al. (2017) with an N_2O emission value of 6.2 kg-N/ha/year, and Hergoualc'h and Verchout, (2020) with an emission value of 1.72 kg-N/ha/year. The value of N_2O emissions in this study is also still within the emission range from tropical secondary forests, as stated by Erickson et al. (2001) and Davidson et al. (2001), whose values were 0.09 and 9.0 kg-N/ha/year, respectively. Many researchers found that N_2O emissions from peat swamp forests have a greater value than from mineral soils. This is directly because the peat swamp forest material is organic or has high levels of C-organic and N-total. In addition, peat swamp forests contain high dissolved organic compounds that play an important role in the nitrification and denitrification processes (Erickson et al., 2001; Davidson et al., 2001).

Although there is no fixed relationship pattern between N_2O emissions and monthly rainfall, there is a significant seasonal variation in N_2O gas emissions in conservation forests, where N_2O gas emissions increase in the wet season compared to the dry season. The results of this study are generally consistent with previous studies regarding increased N_2O gas emissions in tropical rain forests and agricultural sites during periods of high rainfall (Breuer et al., 2000; Melillo et al., 2001; Garcia-Montiel et al., 2003; Kusa et al., 2006). Seasonal variations in N_2O gas emissions are also associated with seasonal changes in groundwater tables caused by changes in rainfall and soil mineral N content (Melling et al., 2007). Inorganic nitrogen (mainly NH_{4+} and NO_3^-) can occur in the thin water film of soil microsites near oxidative sites. During the rainy season and when the soil layer has the right conditions, soil microbes can efficiently utilize this inorganic N and produce N_2O gas (Garcia-Montiel et al., 2003; Davidson et al., 2016). All the results of these studies confirm the importance of measuring N_2O gas emissions during the rainy season, especially in ecosystems dominated by aerobic conditions, to improve the results of studies on the production of total N_2O emissions from peat swamp ecosystems.

Relationship of Environmental Parameters to N_2O Emissions

N_2O gas emissions cannot be separated from the influence of soil parameters, environment, and land changes that have been widely studied (Takakai *et al*., 2006; Melling *et al*., 2007; Hadi *et al*., 2010; Melling *et al*., 2010; Hatano *et al*., 2016; Oktarita *et al*., 2017; Hergoualc'h and Verchout, 2020). Inubushi *et al*. (2003) revealed that rainfall significantly affects N2O gas emissions. However, land change is the main factor that causes changes in N_2O gas emission behavior both temporally and spatially. Keeping natural peatland forests by maintaining biodiversity and keeping them wet can help reduce N_2O gas emissions from their natural ecosystems. Takakai *et al*. (2006) expressed different things, which states that changes in soil moisture are very important parameters controlling seasonal changes in N_2O gas emissions. N_2O emissions are also strongly influenced by water-filled pore space (WFPS) by 60 to 70% and an increase in soil NO_3^-N concentrations (Takakai *et al*., 2006). This is consistent with the results of this study, where the analysis of a single variable on WFPS and NO_3^-N concentrations can explain the variability of N_2O emissions, respectively, of 53% and 82% (Table 2).

Table 2 Equation model of N_2O emissions on environmental parameters

Data	Model + Variable	r^2	*p-value*	AIC	*N*
Monthly average per location	N_2O= 0.152573 + GWL* (-0.4569) + ST* (0.0071) + SM* (-0.19456)	0.52	0.103	-17.505	12

Notes: The environmental, physical, and chemical parameters of the soil used in the model are determined based on the performance of the individual parameter models with indicators of r2 value, p-value and AIC (Akaike Information Criterion); *= significant at p<0.05; GWL= ground water level; ST= soil temperature; SM= soil moisture; WFPS= water-filled pore space

Furthermore, Melling *et al*. (2007) explained related factors controlling N_2O gas emissions in peat ecosystems, especially natural forests, namely groundwater level, NH_4^-N concentration at 25-50 cm, and soil surface temperature. Melling *et al*. (2007) explained that peat surface temperature, groundwater level, and C/N ratio significantly affect N_2O gas emissions. This study is consistent with these results, where the groundwater level, soil surface temperature, and soil moisture explain 52% of N_2O emissions. Generally, several experiments conducted by Hadi *et al*. (2010) and Oktarita *et al*. (2017) explained that N_2O gas emissions increased with N fertilizer. In this study, the concentrations of NH_4-N and NO_3-N became the parameters with the highest R^2 values, namely 95% and 82%, which were in line with the results of the study (Wu and Mu, 2019), which stated that the pH along with nitrate (NO_3^-) and ammonium (NH_4^+) in the soil was the most dominant factor controlling N_2O gas emissions.

In general, the groundwater level is one of the factors most often expressed as controlling N_2O gas emissions in peat ecosystems. This is because the high-water table can cause anaerobic conditions in peat soil which are important for the denitrification process and the thickness of the aerobic layer that determines the volume of soil for the nitrification process (Melling *et al*., 2007). Both processes must coincide to produce N_2O gas emissions. A pH value below 4 indicates an ecosystem in acidic conditions or low base saturation, reducing nitrification activity (Šimek and Cooper, 2002; Strauss *et al*., 2002). The inhibition of the nitrification process causes the accumulation of NH_4-N in the soil which also causes a decrease in N_2O production. The high concentration of NH_4-N is also possible as a result of the low population and nitrifier activity. But on the other hand, the accumulation of NH_4^-N can increase the efficiency of nitrogen utilization in an ecosystem, both absorbed by plants and utilized by bacteria. It explained how the concentration of NH_4^-N significantly affects N_2O emissions in this study (Hadi *et al*., 2010; Oktarita *et al*., 2017; Wu and Mu, 2019).

CONCLUSION

Annual N_2O gas emission in conservation forest is 0.23 ± 0.19 kg-N/ha/year. The high spatial-temporal variation causes a high value of uncertainty in the calculation of annual emissions. Improving sampling frequency through spatial and temporal can help to overcome the uncertainty of N_2O emission quantification in the future. N_2O gas emissions vary seasonally, where N_2O emissions are lower in the dry season and increase in the wet season period. The regression test results on N_2O gas emissions and environmental parameters explain that N_2O emissions are dominantly controlled by groundwater level, soil surface temperature, and soil moisture. Keeping peat forests in their natural state can help reduce N_2O emissions in their natural state, along with the fact that conversion of peatlands leads to increased N_2O gas emissions in peat ecosystems.

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