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To cite this article: Lulie Melling , Ryusuke Hatano & Kah Joo Goh (2007) Nitrous oxide emissions from three ecosystems in tropical peatland of Sarawak, Malaysia, Soil Science and Plant Nutrition, 53:6, 792-805, DOI: [10.1111/j.1747-0765.2007.00196.x](https://doi.org/10.1111/j.1747-0765.2007.00196.x)

To link to this article: <https://doi.org/10.1111/j.1747-0765.2007.00196.x>



Published online: 17 Dec 2010.



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ORIGINAL ARTICLE

Nitrous oxide emissions from three ecosystems in tropical peatland of Sarawak, Malaysia

Lulie MELLING^{1,2}, Ryusuke HATANO¹ and Kah Joo GOH³¹Soil Science Laboratory, Graduate School of Agriculture, Hokkaido University, Sapporo 060-8589, Japan; ²Department of Agriculture, Jalan Badruddin, 93400, Kuching, Sarawak, and ³Advanced Agriecological Research Sdn Bhd, Selangor, Malaysia**Abstract**

Nitrous oxide (N₂O) emissions were measured monthly over 1 year in three ecosystems on tropical peatland of Sarawak, Malaysia, using a closed-chamber technique. The three ecosystems investigated were mixed peat swamp forest, sago (*Metroxylon sagu*) and oil palm (*Elaeis guineensis*) plantations. The highest annual N₂O emissions were observed in the sago ecosystem with a production rate of 3.3 kg N ha⁻¹ year⁻¹, followed by the oil palm ecosystem at 1.2 kg N ha⁻¹ year⁻¹ and the forest ecosystem at 0.7 kg N ha⁻¹ year⁻¹. The N₂O emissions ranged from -3.4 to 19.7 µg N m⁻² h⁻¹ for the forest ecosystem, from 1.0 to 176.3 µg N m⁻² h⁻¹ for the sago ecosystem and from 0.9 to 58.4 µg N m⁻² h⁻¹ for the oil palm ecosystem. Multiple regression analysis showed that N₂O production in each ecosystem was regulated by different variables. The key factors influencing N₂O emissions in the forest ecosystem were the water table and the NH₄⁺ concentration at 25–50 cm, soil temperature at 5 cm and nitrate concentration at 0–25 cm in the sago ecosystem, and water-filled pore space, soil temperature at 5 cm and NH₄⁺ concentrations at 0–25 cm in the oil palm ecosystem. R² values for the above regression equations were 0.57, 0.63 and 0.48 for forest, sago and oil palm, respectively. The results suggest that the conversion of tropical peat swamp forest to agricultural crops, which causes substantial changes to the environment and soil properties, will significantly affect the exchange of N₂O between the tropical peatland and the atmosphere. Thus, the estimation of net N₂O production from tropical peatland for the global N₂O budget should take into consideration ecosystem type.

Key words: metroxylon sagu, mixed peat swamp forest, N₂O, oil palm, soil gas.

INTRODUCTION

Nitrous oxide (N₂O) is one of the most important radiatively active trace gases in the atmosphere. The atmospheric concentration of N₂O has increased by 46 p.p.b. (17%) since 1750 and continues to increase (Houghton *et al.* 2001). N₂O is very stable in the atmosphere with a lifetime of approximately 114 years (Intergovernmental Panel on Climate Change 2001). Although inert in the troposphere, N₂O is indirectly involved in the destruction of the stratospheric ozone layer, which effectively controls UV-B radiation, and contributes to global warming (Cicerone 1987; Solomon 1999). The global warming potential (GWP) of N₂O is

296-fold that of carbon dioxide (CO₂) in a 100-year time horizon (Intergovernmental Panel on Climate Change 2001).

Soil is considered to be one of the major sources of N₂O to the atmosphere and contributes approximately 60% of the global atmospheric source of N₂O (Ehhalt *et al.* 2001). N₂O emissions from soils are biologically produced by the microbiological processes of nitrification (conversion of NH₄⁺ to NO₃⁻) and denitrification (NO₃⁻ to N₂O or N₂) (Davidson 1991; Firestone and Davidson 1989). These processes are controlled by several factors, including water-filled pore space (WFPS) (Aulakh *et al.* 1984; Davidson 1991; Dobbie *et al.* 1999; Ruser *et al.* 2001), temperature (Keeney *et al.* 1979) and mineral nitrogen (NH₄⁺ and NO₃⁻) concentration (Bremner 1997; Firestone and Davidson 1989; Ryden and Lund 1980). The spatial and temporal variation of N₂O emissions is very high because of complex interactions between the factors listed above, which individually may not always be strongly correlated with N₂O fluxes. Thus, quantification

Correspondence: L. MELLING, Department of Agriculture, Jalan Badruddin, 93400, Kuching, Sarawak, Malaysia. Email: lulie_melling@yahoo.com

Received 4 July 2007.

Accepted for publication 23 July 2007.

of terrestrial trace gas fluxes for different ecosystems is now an important scientific priority that is needed for parameterizing and validating biogeochemical models (Grant and Pattey 1999, 2003; Kiese *et al.* 2005; Liu *et al.* 1999; Parton *et al.* 2001; Potter *et al.* 1996, 2001). However, most of the published data on N_2O fluxes refer to boreal and temperate ecosystems (Dobbie and Smith 2001; Maljanen *et al.* 2003; Martikainen *et al.* 1993; Regina *et al.* 2004), whereas limited data are available for tropical environments in particular for tropical peatland (Furukawa *et al.* 2005; Hadi *et al.* 2000; Inubushi *et al.* 2003; Kiese *et al.* 2003; Takakai *et al.* 2002).

Tropical rainforest soils are believed to be the largest natural source of N_2O of all the biomes (Bouwman *et al.* 1995; Matson and Vitousek 1990). It is also assumed that tropical peatland is one of the major sources of N_2O emissions contributing to the global atmospheric N_2O budget (Watson *et al.* 1992). Tropical dry forests or tropical seasonal savannas are poor sources of N_2O emissions; mainly because of low N availability or very low soil moisture content. There is now an on-going extensive conversion of tropical peatland forest to sago and oil palm plantations in Malaysia and Indonesia with approximately 350,000 ha being cultivated in Sarawak alone. Cultivation of sago and oil palm on tropical peatland changes the environment (Melling *et al.* 2005). These changes may affect nitrogen mineralization, which is the main source of NO_3^- , mechanisms of N_2O emission and reduction of soil N_2O gas. The magnitude of N_2O emissions from such ecosystems on tropical peatland is still unreported. Therefore, information on the magnitude of N_2O emissions from these major agro-ecosystems and the major factors controlling them are very much needed to determine their roles in the global budget of N_2O .

This study was conducted to acquire a unique 1-year dataset on N_2O emissions from the forest, sago and oil palm ecosystems on tropical peatland and also to characterize the variations in N_2O emissions and relate them to the environmental parameters that influence the magnitude of N_2O exchange between the soil and the atmosphere.

MATERIALS AND METHODS

Site description

N_2O emissions of tropical peatland in three different ecosystems, mixed peat swamp forest, sago (*Metroxylon sagu*) plantation and oil palm (*Elaeis guineensis*) plantation, in the Mukah Division of Sarawak, Malaysia, were investigated (Fig. 1). The peat was an ombrotrophic peat receiving water solely from precipitation and was characteristically nutrient poor (oligotrophic). In general, atmospheric deposition was its only source of mineral

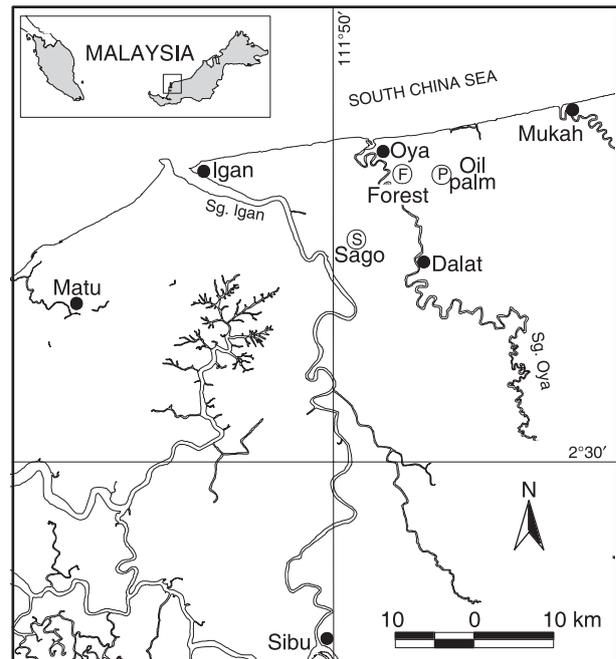


Figure 1 Location of the experimental forest, sago and oil palm sites in the Mukah Division of Sarawak, Malaysia.

nutrients before cultivation. Under the United States Department of Agriculture (USDA) soil classification system, the peat soil is classified as Typic Tropofibrst (Soil Survey Staff 1992). Some of the environmental characteristics of the three different ecosystems are given in Table 1.

The peat soils were all very deep with peat depth ranging from 480 to 650 cm. The von Post's humification value (Parent and Caron 1993) showed that the forest ecosystem was the least decomposed with a humification value of H3–H2. As a result of cultural practices of sago and oil palm cultivation on the tropical peatland, the degree of decomposition of the peat had increased and the oil palm ecosystem was the most decomposed with a humification value of H5–H3. In the oil palm ecosystem, an input of $51.5 \text{ kg N ha}^{-1}$ in the form of urea was applied in each application in November 2002 and May 2003. There was no fertilizer application in the sago plantation or the forest ecosystem. Further descriptions of both site and environmental characteristics were given by Melling *et al.* (2005).

Measurements of environmental variables and N_2O emissions were made at monthly intervals from August 2002 to July 2003.

Determination of N_2O fluxes

N_2O flux was determined using a closed-chamber method (Crill 1991). At each site, three open-bottom

Table 1 Environmental characteristics of the forest, sago and oil palm ecosystems

Ecosystem	Forest 2°49'N 111°51'E	Sago 2°45'N 111°50'E	Oil Palm 2°49'N 111°56'E
Site code	F	S	P
Peat thickness (cm)	480	650	555
Humification value [†] (0–100 cm soil depth)	H3–H2	H4–H2	H5–H3
Bulk density (g cm ⁻³)	0.15 ± 0.00	0.16 ± 0.01	0.20 ± 0.01
Mean monthly air temperature (°C)	27.4 ± 0.2	33.0 ± 0.4	30.9 ± 0.4
Mean monthly soil temperature at 5 cm (°C)	25.9 ± 0.1	28.2 ± 0.2	28.0 ± 0.2
Annual rainfall (mm)	2163	2928	2471 [‡]
Mean monthly water table depth (cm)	45.3 ± 3.3	27.4 ± 2.6	60.2 ± 2.7
Mean monthly water-filled pore space (%) (0–5 cm soil depth)	57.6 ± 2.0	78.1 ± 1.9	60.4 ± 2.0
Mean monthly relative humidity (%)	89.3 ± 1.1	64.7 ± 1.3	71.1 ± 1.5

[†]Humification value was classified according to Von Post (Parent and Caron 1993). Degree of decomposition is divided into 10 levels from H1 (very fibric) to H10 (very humic).

[‡]Rainfall value excludes the month of June 2003 because the rain gauge was stolen.

Figures show the mean ± standard error.

stainless steel cylinders with an internal diameter of 20 cm and a height of 25 cm were placed directly on the soil approximately 30 min before flux measurements (Norman *et al.* 1997) to establish an equilibrium state. The cylinders were pushed into the ground by cutting the soil using a very sharp knife along the edge of the cylinder to a depth of 3 cm from the surface to avoid gas leakage through the bottom of the cylinder by lateral diffusion (Melling *et al.* 2005). Every site was equipped with plank walks to minimize the disturbance by walking.

Sampling was conducted within 2 h, usually between 11.00–13.00 hours each day. Sampling was done during the first or second week of each month so that consecutive samplings were spaced 4–5 weeks apart. Headspace samples of 20 mL were extracted from the chamber at 0, 10, 20 and 40 min using a polypropylene syringe with a three-way stopcock. The extracted gas was transferred to a 10-mL vacuum vial using a double-ended hypodermic needle.

Air temperatures and relative humidity were measured with a digital thermometer and digital relative humidity meter, respectively. Soil temperatures at 5 and 10 cm below the soil surface were measured with another portable digital thermometer. The temperatures and N₂O fluxes were measured at the same time. The mean of the initial and final air temperature was used in gas flux calculations.

N₂O concentration in the soil profile

Soil gas was sampled using a stainless steel pipe with an internal diameter of 7 mm equipped with a silicon tube and a three-way stopcock inserted to a depth of 5, 10, 20, 40 and 80 cm. The pipes were pushed into the peat soil with a steel rod inserted in the pipe to prevent physical damage or obstruction during placement.

Triplicate measurements were made for each depth. After the pipes were set up, 50 mL of air was siphoned out from each pipe. The pipes were then closed using the three-way stopcock. The pipes were kept in place overnight to allow the gas concentrations in the pipes to equilibrate with the soil air. Thus, the pipes were installed a day before N₂O flux sampling. From each pipe, 50 mL of the soil gas was extracted using a polypropylene syringe and transferred into a 10-mL vacuum vial using a double-ended hypodermic needle.

In cases where the water table reached above 80 cm, dissolved N₂O concentrations were determined using a modified version of the methods of Sawamoto *et al.* (2002). Using a 60-mL syringe, 30-mL water samples were extracted from the pipes. Then 30 mL of air was immediately drawn into the syringe in the field. The syringe was shaken vigorously for 3 min and a 20-mL headspace sample was then transferred to a 10-mL vacuum vial bottle. Extraction of N₂O using this method was 50% efficient.

N₂O concentration analysis

N₂O concentration was determined using a gas chromatograph equipped with a microelectron capture detector (HP 6890N; Hewlett Packard, Palo Alto, CA, USA) maintained at 350°C, using a 2-m long Porapak Q column (80/100 mesh) maintained at 50°C with N₂ carrier gas flowing at 40 mL min⁻¹. N₂O fluxes were calculated from the linear increase or decrease in the gas concentration in the chamber with time using a linear regression (Christensen *et al.* 1995). The annual fluxes were calculated from the monthly flux averages as follow:

$$\text{Cumulative gas flux} = \sum_{i=1}^{n-1} R_i \times D_i$$

where R_i is the mean gas flux ($\text{g m}^{-2} \text{day}^{-1}$) of the two sampling times, D_i is the number of days in the sampling interval, and n is the number of sampling times. In this study, negative fluxes indicated the uptake of atmospheric N_2O , whereas positive fluxes indicated net production from the peat soil.

Environmental variables

Perforated polyvinyl chloride pipes (6 cm diameter) for water table measurements were inserted close to the chambers. The depth of the ground water table was recorded when the N_2O flux was measured. Monthly precipitation was also recorded in each ecosystem with a rain gauge (706.9 cm^2). Undisturbed core samples (5 cm depth) from inside the chambers were taken back to the laboratory for measurement of volume using a soil volume analyzer (Model DIK-1110; Daiki Rika Kogyo, Saitama, Japan). The cores were then oven dried at 105°C for 48 h and reweighed to determine their bulk density and moisture content. Soil moisture contents of the peat were expressed as a percentage of the total pore space that was filled with water (percentage water-filled pore space [%WFPS]).

Soil sampling and analysis

In each ecosystem, soil samples at 0–25 cm and 25–50 cm were taken from each chamber site with a peat auger sampler after the flux measurements. Composite soil samples from each ecosystem were sampled monthly from October 2002 to July 2003. The soil samples were air-dried and analyzed for pH, cation exchange capacity (CEC), base saturation (BS), NO_3^- , NH_4^+ , C/N ratio, total C, total N, loss-on-ignition (LOI) and pyrophosphate solubility index (PSI). Soil pH was determined using a suspension of 10 mL soil in 25 mL H_2O . CEC was determined by leaching with neutral 1 mol L^{-1} ammonium acetate based on MS678 Part IV:1980 and determined using Perkin Elmer-Inductively Coupled Plasma (ICP) (AES Optima 3000, Massachusetts, USA). Percentage base saturation is a measure of the proportion of basic cations occupying the exchange sites of a soil. The organic matter content was determined as LOI at 400°C (Karam 1993). Total N was analyzed with a Nitrogen Analyzer (LECO FP528, Michigan, USA). The C content of the soil was analyzed with a Multiphase Carbon Determinator (LECO RE412, Michigan, USA). The PSI was determined using pyrophosphate solution extraction and then measured with a spectrophotometer at 550 nm (Day *et al.* 1979). Hanafi *et al.* (2007) showed that PSI values provided an indication of soluble C in peat soils.

Soil water NH_4^+ and NO_3^- were extracted using a 1:5 soil : water solution (van Reeuwijk 2002) and analyzed with an ion chromatograph (Metrohm 761 Herisau, Switzerland). For NH_4^+ separation, a Metrosep C2-250 cation column and a Metrosep C2 guard column, with

4 mmol L^{-1} tartaric acid and 0.75 mmol L^{-1} dipicolonic acid (flow rate: 1 mL min^{-1}) as eluent, was used. NO_3^- was separated using a Metrosep A SUPP 5 250 anion column equipped with a Metrosep A SUPP 5 guard column. The eluent (flow rate: 0.7 mL min^{-1}) was a mixture of 1 mmol L^{-1} NaHCO_3 and 3.2 mmol L^{-1} Na_2CO_3 solution.

Statistical analysis

Repeated measure analysis was used to compare N_2O flux. Ecosystems were treated as a nested factor and time as a random, crossover factor. The three sampling sites were regarded as subjects within each ecosystem because the samples of N_2O in each month were made at the same sites (Kleinbaum *et al.* 1998). This statistical analysis was carried out using GenStat (GenStat 2002). Multiple regression analysis was used to establish the relationship between environmental factors and N_2O emission. Only non-correlated independent variables were used in the regression to avoid the problem of multicollinearity. The multiple regression analysis was carried out using the statistical package SAS (SAS Institute 1989).

RESULTS

Peat soil characteristics

The chemical characteristics of the soil samples at 0–25 cm and 25–50 cm in each ecosystem are presented in Table 2. Soil pH was less than 4, indicating acidic conditions resulting from a large amount of exchangeable hydrogen ions. The peat soil had a very high LOI of approximately 99%, signifying that the peat was made up of almost 100% organic material. The forest ecosystem had the highest PSI, whereas similar values were obtained for the sago and oil palm ecosystems. The oil palm ecosystem, which requires drainage and compaction for its cultivation on peat, had the highest bulk density. Organic C contents in the three ecosystems were between 45 and 48% and N contents between 1.8 and 2.0%, resulting in a C:N ratio exceeding 22:1. The uncultivated forest ecosystem had the highest C:N ratio of 27:1.

Seasonal variation in NH_4^+ and NO_3^-

Inorganic N pools were dominated by NO_3^- -N in all three ecosystems (Table 2), except at the lower depth (25–50 cm) in the sago ecosystem (Fig. 2). Taking both soil depths, the mean soil NH_4^+ -N pool in the sago ecosystem was smaller compared with the forest and oil palm ecosystems. The soil NO_3^- -N was highest in the oil palm ecosystem (0–25 cm), which received regular annual inputs of 103 kg N ha^{-1} in the form of urea in November 2002 and May 2003. There was no fertilizer application for the sago plantation, but both the sago and oil palm ecosystems showed a similar marked seasonality in NO_3^- -N pools with relatively large pools

Table 2 Chemical properties of the peat soil at 0–25 cm and 25–50 cm soil depth

Ecosystem	Forest		Sago		Oil palm	
	0–25	25–50	0–25	25–50	0–25	25–50
Soil depth (cm)						
Soil pH (1:2.5)	3.6 ± 0.0	3.5 ± 0.0	3.6 ± 0.0	3.5 ± 0.0	3.4 ± 0.0	3.4 ± 0.0
Loss of ignition (%)	98.7	99.2	98.8	99.1	99.1	99.2
Pyrophosphate solubility index	69.6 ± 5.1	56.6 ± 2.5	30.1 ± 2.7	34.2 ± 3.1	30.0 ± 2.1	41.2 ± 3.6
C:N ratio	27.2 ± 1.0	34.3 ± 2.0	22.6 ± 0.8	27.6 ± 1.6	23.4 ± 1.1	28.9 ± 1.2
NH ₄ -N (mg kg ⁻¹)	54.9 ± 12.3	14.0 ± 5.4	37.5 ± 6.9	22.4 ± 4.4	58.2 ± 12.9	17.1 ± 5.4
NO ₃ -N (mg kg ⁻¹)	78.8 ± 33.5	18.5 ± 5.3	102.2 ± 57.2	19.6 ± 5.5	198.4 ± 101.4	102.6 ± 60.0
Cation exchange capacity (cmolc kg ⁻¹)	47.2 ± 2.1	47.7 ± 3.5	42.3 ± 2.0	45.5 ± 3.5	44.5 ± 3.1	47.2 ± 5.8
Base saturation (%)	22.9 ± 1.7	19.2 ± 1.9	30.1 ± 2.6	22.9 ± 3.7	32.3 ± 4.5	25.6 ± 4.0

Figures show the mean ± standard error ($n = 10$).

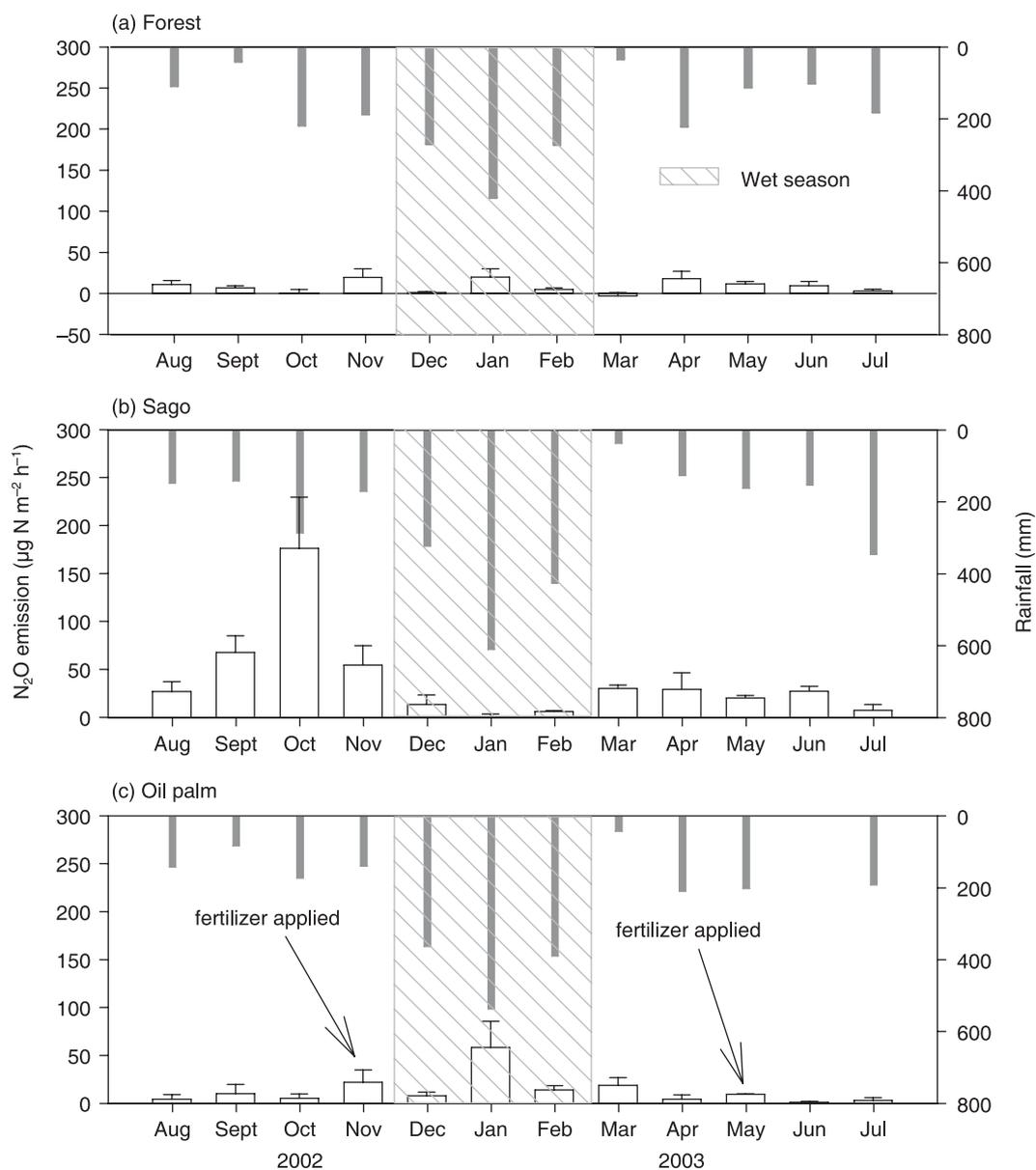


Figure 2 Monthly N₂O emission and rainfall in the (a) forest, (b) sago and (c) oil palm ecosystems. Data represent mean ± standard error ($n = 3$). Symbols without error bars have errors smaller than the symbols.

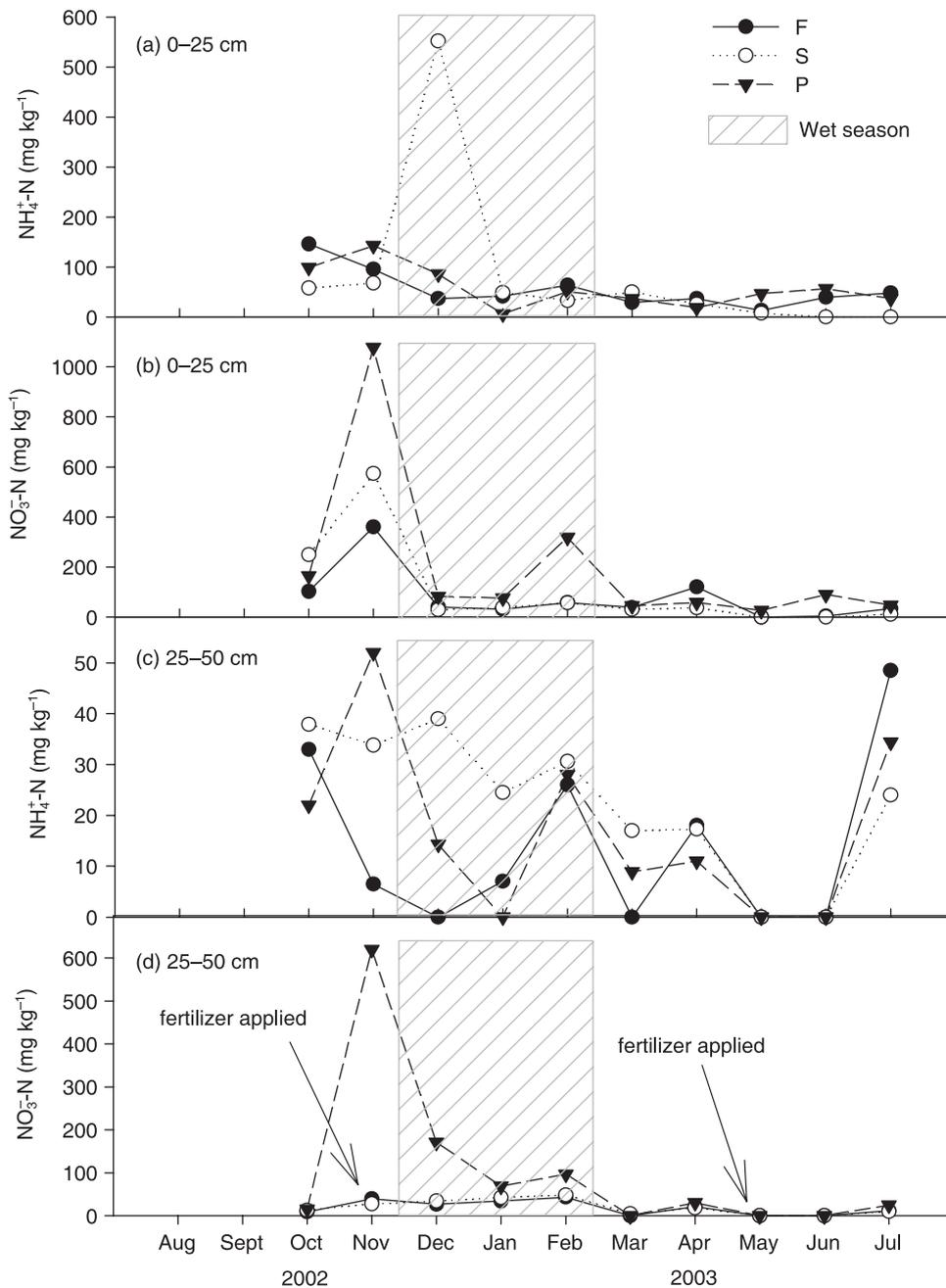


Figure 3 Monthly soil (a) NH_4^+ at 0–25 cm, (b) NO_3^- at 0–25 cm, (c) NH_4^+ at 25–50 cm and (d) NO_3^- at 25–50 cm in the forest (F), sago (S) and oil palm (P) ecosystems.

in the dry season and relatively small pools in the wet season. The highest concentrations of NH_4^+ and NO_3^- in the soils of both ecosystems were found at the beginning of the wet season.

Monthly N_2O fluxes

Monthly N_2O fluxes in the forest ecosystem ranged from -3.4 to $19.7 \mu\text{g N m}^{-2} \text{h}^{-1}$ (Fig. 2a). In the sago and

oil palm ecosystems, the N_2O fluxes ranged from 1.0 to $176.3 \mu\text{g N m}^{-2} \text{h}^{-1}$ and 0.9 to $58.4 \mu\text{g N m}^{-2} \text{h}^{-1}$, respectively. Temporal variations were large for both the sago and oil palm ecosystems, but relatively constant for the forest ecosystem. Monthly N_2O fluxes for both the sago and oil palm ecosystems showed a strong seasonal pattern (Fig. 2b,c). The highest N_2O emissions were recorded during the wet season in January 2003 for

Table 3 Soil N₂O-N emission and cumulative flux for forest, sago and oil palm ecosystems

Ecosystem	N ₂ O emission ($\mu\text{g N m}^{-2} \text{ h}^{-1}$)	Cumulative ($\text{kg N ha}^{-1} \text{ year}^{-1}$)	N ₂ O emission ($\mu\text{g N m}^{-2} \text{ h}^{-1}$ wet season)	% of emission (wet season)
Forest	8.4	0.7	8.4	25.3
Sago	38.3	3.3	6.8	4.5
Oil palm	13.5	1.2	26.7	50.6

The probability (*P*) value for the ecosystem was 0.10. The standard error of differences of means of N₂O emission for the ecosystem was 14.3. The wet season occurred from December 2002 to February 2003 (i.e. three months).

both the forest ecosystem and the oil palm ecosystem. However, in the sago ecosystem, the highest N₂O emission was recorded towards the end of the dry season in October 2002, just before the commencement of the rainy season in December 2002.

Repeated measure analysis showed significant differences for the interaction between ecosystem and time (Table 3). On an annual basis, all the ecosystems were sources of N₂O. N₂O emission was highest in the sago ecosystem with a production rate of 3.3 kg N ha⁻¹ year⁻¹, followed by the oil palm ecosystem at 1.2 kg N ha⁻¹ year⁻¹ and the forest ecosystem at 0.7 kg N ha⁻¹ year⁻¹. Approximately half of the N₂O production in the oil palm ecosystem occurred during the wet season. In each ecosystem or across ecosystems, most of the environmental variables had no significant relationship with N₂O emissions (Table 4). The exception was soil temperature at a depth of 5 cm, which showed a positive correlation with N₂O emission in the sago ecosystem.

The multiple regression analysis is summarized in Table 5. The results showed that the water table and NH₄⁺ concentration at 25–50 cm depth were best correlated with N₂O emission in the forest ecosystem. The equation explained approximately 57% of the total monthly variation in N₂O emission. Different environmental and soil properties were related to N₂O emissions in the sago and oil palm ecosystems. We found that soil temperature at 5 cm and nitrate concentration at 0–25 cm explained approximately 63% of the variation in N₂O emission in the sago ecosystem, whereas WFPS, soil temperature at 5 cm and NH₄⁺ concentrations at 0–25 cm were identified as the key factors explaining 48% of the variation in N₂O emissions in the oil palm ecosystem.

N₂O concentrations at different soil depths

The increases in N₂O concentrations with soil depth from 5 to 40 cm in the three ecosystems were most pronounced in the oil palm ecosystem, but in all cases they decreased at 80 cm depth (Fig. 4). In the oil palm ecosystem, the N₂O concentration was highest at the 40 cm layer because the water table fluctuated mainly between 40 and 60 cm. At 80 cm the condition was highly

Table 4 Correlations of single-factor correlation analysis on each environmental factor regulating N₂O emission in each ecosystem

Variable	Ecosystem			
	All ecosystems	Forest	Sago	Oil palm
Tempf	0.37 (0.025) <i>n</i> = 36	-0.39 (0.209) <i>n</i> = 12	0.60 (0.040) <i>n</i> = 12	-0.46 (0.135) <i>n</i> = 12
WFPS	0.28 (0.104) <i>n</i> = 36	-0.25 (0.428) <i>n</i> = 12	-0.01 (0.976) <i>n</i> = 12	0.03 (0.922) <i>n</i> = 12
WT	0.30 (0.077) <i>n</i> = 36	0.36 (0.253) <i>n</i> = 12	-0.01 (0.979) <i>n</i> = 12	0.53 (0.076) <i>n</i> = 12
NO ₃ ⁻ -o	0.23 (0.218) <i>n</i> = 30	0.44 (0.204) <i>n</i> = 10	0.49 (0.155) <i>n</i> = 10	0.14 (0.693) <i>n</i> = 10
NO ₃ ⁻ -s	0.0011 (0.995) <i>n</i> = 30	0.42 (0.226) <i>n</i> = 10	-0.24 (0.507) <i>n</i> = 10	0.20 (0.575) <i>n</i> = 10
NH ₄ ⁺ -o	-0.04 (0.851) <i>n</i> = 30	-0.11 (0.765) <i>n</i> = 10	0.37 (0.287) <i>n</i> = 10	-0.25 (0.486) <i>n</i> = 10
NH ₄ ⁺ -s	0.19 (0.327) <i>n</i> = 30	-0.22 (0.534) <i>n</i> = 10	0.35 (0.325) <i>n</i> = 10	-0.15 (0.688) <i>n</i> = 10

Numbers in parentheses indicate the probability values. Tempf, soil temperature at 5 cm (°C); WFPS, water-filled pore space (%); WT, water table (cm); NO₃⁻-o, soil nitrate at 0–25 cm (mg N kg⁻¹); NO₃⁻-s, soil nitrate at 25–50 cm (mg N kg⁻¹); NH₄⁺-o, soil ammonium at 0–25 cm (mg N kg⁻¹); NH₄⁺-s, soil ammonium at 25–50 cm (mg N kg⁻¹).

anaerobic for N₂O production, whereas at 20 cm it was an aerobic layer most of the time. Thus, the highest N₂O concentration was found at 40 cm depth. Seasonal changes in N₂O emissions followed a similar pattern with changes in the soil N₂O concentrations (Figs 2,4). The highest mean soil N₂O concentrations were observed during the wet season in January 2003 for both the forest and oil palm ecosystems, whereas in the sago ecosystem the highest mean soil N₂O concentration was recorded towards the end of the dry season in October 2002.

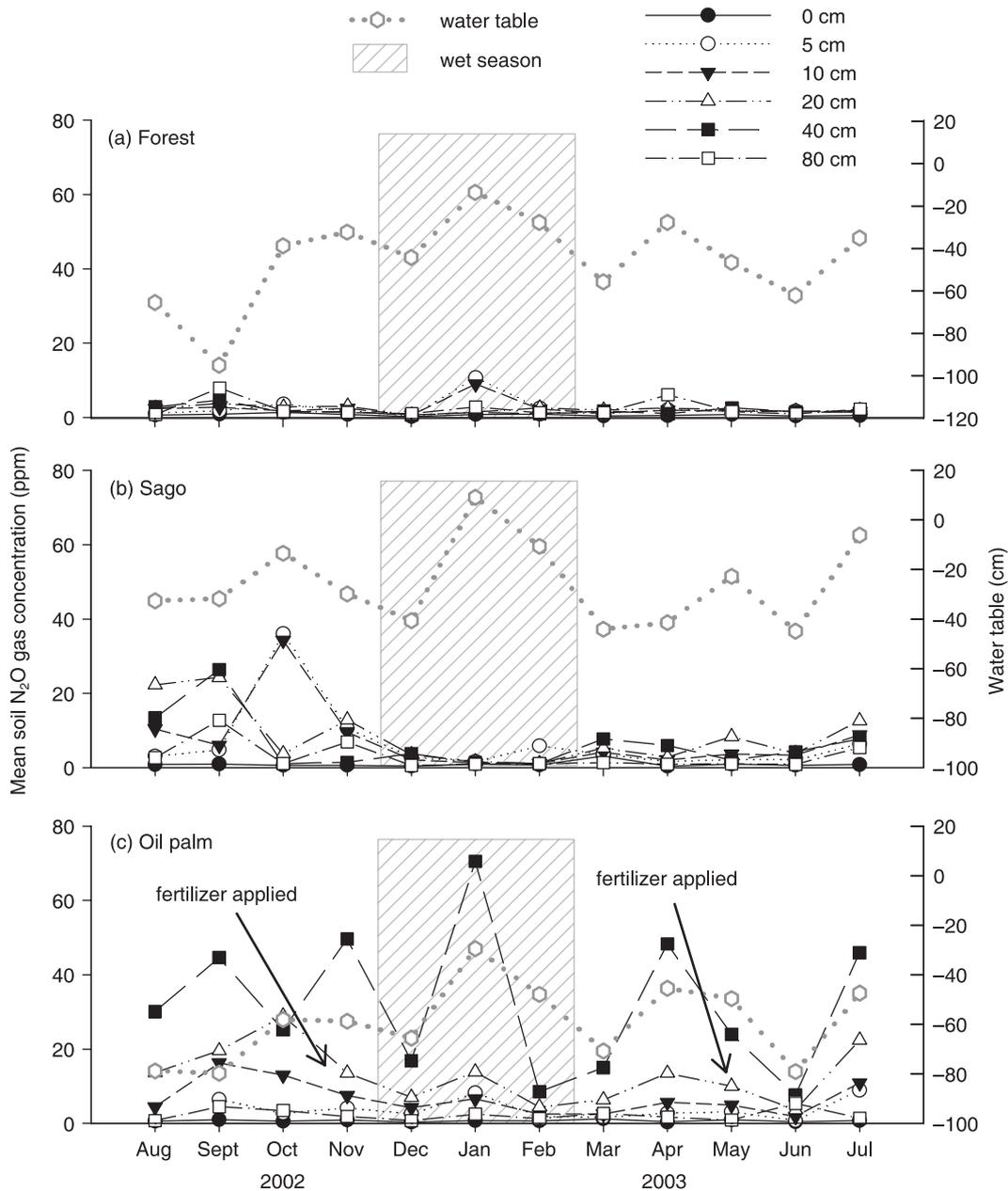


Figure 4 Monthly mean soil N_2O concentration and water table of (a) forest, (b) sago and (c) oil palm ecosystems for each soil depth.

DISCUSSION

Seasonal variation in N_2O emission

On an annual basis, all the ecosystems were sources of N_2O . The N_2O emission was highest in the sago ecosystem with a production rate of $3.3 \text{ kg N ha}^{-1} \text{ year}^{-1}$, followed by the oil palm ecosystem at $1.2 \text{ kg N ha}^{-1} \text{ year}^{-1}$ and the forest ecosystem at $0.7 \text{ kg N ha}^{-1} \text{ year}^{-1}$. The annual N_2O production from the forest ecosystem was within the range of tropical secondary forest (Davidson *et al.* 2001;

Erickson *et al.* 2001), whereas that from the sago ecosystem was in the upper range of N_2O losses from tropical rainforest (Breuer *et al.* 2000). Some researchers have found higher N_2O emissions from peat soils compared with mineral soils (Duxbury and Bouldin 1982; Nyakanen *et al.* 1995; Velthof and Oenema 1995; Velthof *et al.* 1996) because of their higher organic matter content, which constitutes an important soluble organic C substrate for nitrification and denitrification. However, in our study, the annual losses of N_2O from the three

ecosystems ($0.7\text{--}3.3 \text{ kg N ha}^{-1}$) were much lower than those from peat soils reported by Terry *et al.* (1981), Duxbury and Bouldin (1982) and Velthof and Oenema (1995).

Seasonal variability of N_2O emissions in the forest and oil palm ecosystems were similar with significantly higher mean N_2O emissions during the wet season (Table 3) compared with the dry season, despite their generally aerobic soil conditions in the upper horizons. The results are in general agreement with previous reports concerning increased N_2O emissions from soils of tropical rain forest and agricultural systems during periods of high rainfall (e.g. Breuer *et al.* 2000; Garcia-Mendez *et al.* 1991; Garcia-Montiel *et al.* 2001, 2003; Keller and Reiners 1994; Kiese and Butterbach-Bahl 2002; Kiese *et al.* 2003; Kusa *et al.* 2006; Melillo *et al.* 2001; Verchot *et al.* 1999).

Seasonal variations in N_2O emissions in both the sago and oil palm ecosystems are most likely associated with seasonal changes in the water table and soil mineral N. This may be because of low microbial activity during the dry season resulting in an accumulation of inorganic N (Shields *et al.* 1974). The inorganic N may occur in thin water films of microsites near oxidizing sites. With the onset of the rainy season, the soil microbes can quickly use these N pools and produce pulses of N_2O emissions after rainfall events. This process has been studied in tropical dry forests of Central America (Davidson *et al.* 1991, 1993; Garcia-Mendez *et al.* 1991) and several temperate ecosystems in North America (Davidson 1992).

Seasonal variability in N_2O emission is very important, especially in plantation fields on tropical peatland in which higher rainfall will induce a higher soil moisture condition that is probably conducive to N_2O emission during the dry season in the sago ecosystem and during the wet season in the oil palm ecosystem (Fig. 2). This confirms the importance of recording N_2O fluxes during the rainy season for ecosystems that are dominated by aerobic conditions, for better assessment of the total N_2O production from tropical peatland.

N_2O concentration at different soil depths

The higher N_2O emissions in all three ecosystems are also mirrored by the higher soil N_2O concentrations. These data show that N_2O production differs with soil depth and among ecosystems because of different depths of the water table. For the forest ecosystem, the soil N_2O gas concentration at 5 cm soil depth was the highest with up to 10.7 p.p.m. and lowest close to the surface with 0.8 p.p.m. N_2O . High N_2O soil gas concentration at 5 cm in the forest ecosystem in January 2003 may be because of a high water table resulting in enhanced denitrification and, therefore, higher N_2O concentration. Similarly for the sago ecosystem in October 2002 the

soil N_2O gas concentration was 36.0 p.p.m. N_2O at 5 cm soil depth and 34.3 p.p.m. N_2O at 10 cm when water table was high.

The soil gas concentration in the oil palm ecosystem was the highest with up to 70.5 p.p.m. N_2O at 40 cm soil depth and lowest at 80 cm with 2.5 p.p.m. N_2O . The high N_2O concentration at 40 cm soil depth resulted from the maintenance of the water table between 40 and 60 cm at most times (Fig. 4c). Above the water table, the soil was mainly aerobic, resulting in nitrification. The higher soil gas concentration deeper down the soil profile in the oil palm ecosystem compared with the forest ecosystem may be because of the effect of soil compaction, whereby the anaerobic sites would increase resulting in a decrease in gas diffusion. The other reasons for the differences between the two ecosystems could be because of the higher soil NO_3^- and lower C:N ratio and lower PSI in the oil palm ecosystem, which make it more conducive for denitrification under flooded conditions, that is, at the lower soil depths, which were near or under the water table.

We conclude that the primary regulating processes of N_2O emissions are located at different soil horizons for different ecosystems on tropical peatland.

Factors associated with nitrous oxide emission

In our study, there was a significant ecosystem \times time interaction (Table 3), which indicated that the temporal trend in N_2O emissions varied with the ecosystems. The monthly N_2O emissions in the sago ecosystem showed a distinct trend with a high peak in October 2002 just before the rainy season (Fig. 2). In fact, its N_2O emissions were lower in the wet season. This might be attributed to the controlled high water table in the sago ecosystem as part of its agricultural practices (Table 1), which subjected the land to frequent flooding during the period of high rainfall. The flooded conditions would reduce the gaseous exchange between the soil and the atmosphere and enhance the complete denitrification of N_2O to N_2 (Inubushi *et al.* 2003), resulting in a lower emission of N_2O to the atmosphere.

Results of this study indicated that the correlation between N_2O emissions and environmental variables was low, suggesting that there was no clear common factor affecting the N_2O emissions in the three ecosystems. Instead, the N_2O emissions in each ecosystem were affected by different factors as revealed by the multiple regression analysis done separately (Table 5). This might be expected because the conversion of the forest ecosystem on tropical peatland to sago and oil palm had resulted in major changes to the environment and soil properties, which influenced N_2O emissions.

The water table is one of the most commonly reported environmental variables that controlled N_2O

Table 5 Output of multiple regression analysis on environmental factors regulating N₂O emission

Ecosystem	R ²	Corrected R ²	P-value	Durbin Watson, d
All ecosystems: N ₂ O = -370.24 + 13.41 Tempf + 0.65 WT + 1.70 C:N-s	0.32	0.23	0.03	1.69
Forest: N ₂ O = 31.50 + 0.49 WT - 0.29 NH ₄ ⁺ -s	0.57	0.44	0.05	1.96
Sago: N ₂ O = -1185.18 + 43.54 Tempf + 0.09 NO ₃ ⁻ -o	0.63	0.52	0.03	1.96
Oil palm: N ₂ O = 513.42 - 1.01 WFPS - 15.45 Tempf - 0.10 NH ₄ ⁺ -o	0.48	0.23	0.24	3.09

NO₃⁻-o, soil nitrate at 0–25 cm (mg N kg⁻¹); NH₄⁺-o, soil ammonium at 0–25 cm (mg N kg⁻¹); NH₄⁺-s, soil ammonium at 25–50 cm (mg N kg⁻¹); WT, water table (cm); WFPS, water-filled pore space (%); Tempf, soil temperature at 5 cm (°C); C:N-s, C:N at 25–50 cm.

emissions in peatland (Maljanen *et al.* 2001; Regina *et al.* 1999). This is because the depth of the water table affects the degree of anaerobicity of the peat, which is essential for denitrification, and the thickness of the aerobic layer, which determines the soil volume for nitrification rate. Both processes regulate N₂O production. Despite this well-known phenomenon, we found that the water table affected the N₂O emissions in the forest ecosystem only. This maybe because of its low water table at most times and, therefore, the loss of N₂O depended on the amount that was oxidized to NO₃⁻ because it diffuses through the aerobic layer (Beauchamp 1997).

The WFPS was negatively related to N₂O emission in the oil palm ecosystem only. This might be attributed to compaction of the peat before planting, resulting in a reduction in macropore volume and an increase in WFPS, which in turn decreased gas diffusivity in the peat, inhibited the escape of N₂O and enhanced the conversion of N₂O to N₂.

Soil temperature at 5 cm was found to be one of the key factors for both the sago and oil palm ecosystems. Stevenson and Cole (1999) reported that denitrification increases at temperatures of 25°C and above. Other researchers have also reported that the optimum range for nitrification in soils is usually between 25°C and 35°C (Bock *et al.* 1986; Haynes 1986). The soil temperatures at 5 cm in both the sago and oil palm ecosystems were approximately 28°C, which favored the above processes and, therefore, has an effect in regulating N₂O production. In the forest ecosystem, the soil temperature at 5 cm was below the critical level, resulting in its lack of effect on N₂O production (Fig. 1b).

As expected, different N compounds were found to be the key factors in regulating the N₂O emissions in each ecosystem (Table 5). Soil NH₄⁺ was found to be the regulating soil variable for both the forest and oil palm ecosystems, which agreed with Robertson (1994). In both ecosystems, which were basically under aerobic conditions, the nitrification process was probably the major source of N₂O. Based on the multiple regression analysis (Table 5), soil NH₄⁺ was negatively correlated with N₂O emissions in both the forest and oil palm ecosystems.

There was seasonal variability in soil NH₄⁺ and NO₃⁻ concentrations in the forest ecosystem. N mineralization was higher during the dry season resulting in an accumulation of both soil NH₄⁺ and NO₃⁻ concentrations towards the end of the season (Fig. 2). During the dry season, diffusion of ions is restricted to the thin water films (Papendick and Campbell 1981) and, therefore, nitrification probably occurs at the sites of mineralization where there is an accumulation of inorganic N. During the wet season, diffusion is no longer restricted and the accumulated inorganic N becomes available for microbial activity throughout the peat profile, which quickly utilizes these N pools and emits N₂O. There was no increase in mineral N after fertilizer application in May for the oil palm plantation (Fig. 2). This might be because of a sudden increase in relative humidity at the trial site in May 2003 (Melling *et al.* 2005), which would favor NH₄⁺ volatilization. Moreover, the N₂O flux in May for all ecosystems might have masked the NH₄⁺ from urea, especially when the rate of urea application was less than 120 kg ha⁻¹.

The properties of peat, being acidic with a pH less than 4 and low base saturation, generally decrease the rate of nitrification (Simek and Cooper 2002; Strauss *et al.* 2002). The inhibition of nitrification then leads to an accumulation of NH₄⁺ (Aulakh and Bijay-Singh 1997; Veldkamp *et al.* 1998), thus, reducing the amount of N₂O production (Cockx and Simonne 2003; Erickson *et al.* 2001), which probably explains the negative correlation between soil NH₄⁺ and N₂O emissions. The high NH₄⁺ concentration may also result from the effect of low population sizes or low activities of nitrifiers (Erickson *et al.* 2001). The accumulation of NH₄⁺ would actually enhance the nitrogen use efficiency of the respective ecosystem (Aulakh and Bijay-Singh 1997).

In the sago ecosystem, soil NO₃⁻ was found to be one of the key factors regulating N₂O emissions, which was indicative of denitrification being the most important process in N₂O production under its anaerobic conditions. Other researchers had also reported that N₂O emission generally increases with soil NO₃⁻ (Matson *et al.* 1990; Mosier *et al.* 1983) when high WFPS dominates the system (Ryden 1983).

Effect of ecosystem type on N₂O emission

Forest ecosystem

Although nitrous oxide emissions in the forest ecosystem were low, it was a net source of N₂O. There was only one uptake event in the forest ecosystem in March 2003, even when soil NH₄⁺ concentration at 25–50 cm soil depth was low (Fig. 4). This single event did not follow the general trend obtained from the multiple regression analysis shown in Table 5. This may be because of the exceptionally low rainfall in March 2003. It also agrees well with the findings of Ryden (1981, 1983), and Glatzel and Stahr (2001), who found N₂O uptake under low concentration of inorganic N in grassland in the United Kingdom and Germany. It is also not unusual for forest soils, which are generally a net source of N₂O, to sometimes act as N₂O sinks (Inubushi *et al.* 2003). Regina *et al.* (1996) also mentioned that boreal peatland could be small sinks for N₂O.

Sago ecosystem

The sago ecosystem showed the highest annual N₂O emission. This was mainly related to the higher depth of its water table, causing consistently high WFPS with a mean of 78%. In January 2003, when the sago ecosystem was flooded, N₂O emission was almost negligible. This might be attributed to poor gas exchange between the soil and atmosphere under flooded conditions and the complete reduction of N₂O to N₂ being promoted during denitrification under these conditions (Inubushi *et al.* 2003; Smith *et al.* 2003). Therefore, as suggested by Denmead *et al.* (1979), flooded soils may contribute less N₂O but more N₂ to the atmosphere.

The C:N ratio is usually reflective of the stage of decomposition of organic matter in tropical peatland and, therefore, the availability of soluble C and N. The sago ecosystem with the lowest C:N ratio (Table 2) probably has more soluble C, which might further explain its high N₂O emission because denitrification is usually enhanced under the conditions of low C:N ratio with sufficient soluble C (Bremner and Blackmer 1981; Kiese and Butterbach-Bahl 2002).

Oil palm ecosystem

The N₂O fluxes in the oil palm ecosystem were related to soil NH₄⁺ concentration and WFPS, which agrees with Lemke *et al.* (1998). Drainage and compaction are prerequisites for oil palm cultivation on peat to lower the water table and increase the peat bulk density (Melling *et al.* 2005). These anthropogenic changes resulted in a 71% increase in N₂O production (Table 3) compared with the forest ecosystem. A decrease in the water table generally leads to higher N mineralization in peat

(Flessa *et al.* 1998; Updegraff *et al.* 1995) and enhances nitrification (Duxbury and Bouldin 1982; Maljanen *et al.* 2001; Terry *et al.* 1981), which promotes N₂O fluxes (Kliewer and Gilliam 1995; Martikainen *et al.* 1993; Regina *et al.* 1996; 1999). Moreover, the relatively more compacted peat in the oil palm ecosystem might improve N₂O emission as reported by other researchers (Flessa *et al.* 2002; Teepe *et al.* 2004).

For oil palm cultivation on peat, N fertilization was required to maximize growth and production. An increase in soil inorganic N can be expected with the application of urea, thus, increasing N₂O fluxes (Akiyama *et al.* 2006; Mosier 1997). However, the effects of urea application on N₂O flux in November 2002 and May 2003 were generally small (Fig. 2). This agrees with Augustine *et al.* (1998) who reported that N fertilization of less than 120 kg N ha⁻¹ was considered a moderate N supply and would hardly increase the release of N₂O. The lack of response to added N may also occur if nitrifiers were not N-limited (Bowden *et al.* 2000), which was probably the case with the fertilized oil palm ecosystem where soil NH₄⁺ and NO₃⁻ concentrations commonly exceeded 40 and 50 mg kg⁻¹. Apart from this, there was a possibility that the increase in N₂O fluxes after fertilization may not have been measured because of the timing and location of fertilizer placement relative to gas sampling and rainfall events (Palm *et al.* 2002; Veldkamp and Keller 1997).

Conclusion

Cultivated peatland can behave like an upland ecosystem as in the case of the oil palm or remain as a wetland as for sago. However, both ecosystems emitted more N₂O annually compared with the forest ecosystem. In the fertilized oil palm ecosystem, the increase in annual N₂O production over the forest ecosystem was 71% compared with 371% by the flooded sago ecosystem. Monthly rainfall and water table seemed to be the dominant parameters controlling the high N₂O fluxes in tropical peatland. It was also observed that N₂O emissions in each ecosystem on tropical peatland were regulated by different factors, which were related to their specific environment, soil properties and agricultural practices.

Oil palm and sago plantations are now the dominant agricultural land use on tropical peatland in Malaysia and Indonesia. With their continuous expansion on tropical peatland, regional N₂O emissions will probably increase. The findings from this study clearly show that the estimation of net N₂O production from tropical peatland should take into consideration ecosystem type.

ACKNOWLEDGMENTS

We thank Margaret Abat, Zakri bin Besri, Donny Sudid and Gan bin Haip for assistance in the laboratory and

field. We also wish to thank Dr Takuji Sawamoto for his assistance in verifying the methods. We acknowledge Gan Huang Huang for her assistance with the statistical analyses. This research was funded by an Intensified Research Priority Area (IRPA) Grant (no. 01-03-09-1005) for Scientific Research from the Ministry of Science, Technology and Environment, Malaysia.

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