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Nitrous oxide emission derived from soil organic matter decomposition from tropical agricultural peat soil in Central Kalimantan, Indonesia

Running title: N$_2$O emission from agricultural peat soil

Yo Toma$^1$, Fumiaki Takakai$^2$, Untung Darung$^3$, Kanta Kuramochi$^4$, Suwido H. Limin$^3$, Salampak Dohong$^3$, Ryusuke Hatano$^4$

$^1$Field Science Center for Northern Biosphere, Hokkaido University, Kita 11 Nishi 10, Kita-ku, Sapporo 060-8589, Japan

Yo Toma’s e-mail: toma@fsc.hokudai.ac.jp

$^2$Faculty of Bioresource Sciences, Akita Prefectural University, 241-438 Aza Kaidobata-Nishi, Shimoshinjo, Nakano, Akita 010-0195, Japan

Fumiaki Takakai’s e-mail: takakai@akita-pu.ac.jp

$^3$Faculty of Agriculture, University of Palangka Raya, Palangka Raya 73112, Central Kalimantan, Indonesia

Untung Darung’s e-mail: untdar@yahoo.com

Suwido H. Limin’s e-mail: cimtrop_suvido@yahoo.com

Salampak Dohong’s e-mail: salamdong@hotmail.com

$^4$Research Faculty of Agriculture, Hokkaido University, Kita 9 Nishi 9, Kita-ku, Sapporo 060-8589, Japan

Kanta Kuramochi’s e-mail: kanta@chem.agr.hokudai.ac.jp
Corresponding author: postal address: Field Science Center for Northern Biosphere, Hokkaido University, Kita 11 Nishi 10, Kita-ku, Sapporo 060-8589, Japan; tel: +81-11-706-2854; fax: +81-11-706-3644; e-mail: toma@fsc.hokudai.ac.jp

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ABSTRACT

Our previous research showed large amounts of nitrous oxide (N\(_2\)O) emission (> 200 kg N ha\(^{-1}\) yr\(^{-1}\)) from agricultural peat soil. In this study, we investigated the factors influencing relatively large N\(_2\)O fluxes and the source of nitrogen (N) substrate for N\(_2\)O in a tropical peatland in Central Kalimantan, Indonesia. Using a static chamber method, N\(_2\)O and carbon dioxide (CO\(_2\)) fluxes were measured in three conventionally cultivated croplands (conventional), an unplanted and unfertilized bare treatment (bare) in each cropland, and unfertilized grassland over a 3-year period. Based on the difference in N\(_2\)O emission from two treatments, contribution of the N source for N\(_2\)O was calculated. Nitrous oxide concentrations at five depths (5-80 cm) were also measured for calculating net N\(_2\)O production in soil. Annual N fertilizer application rates in the croplands ranged from 472 to 1,607 kg N ha\(^{-1}\) yr\(^{-1}\). There were no significant differences in between N\(_2\)O fluxes in the two treatments at each site. Annual N\(_2\)O emission in conventional and bare treatments varied from 10.9 to 698 and 6.55 to 858 kg N ha\(^{-1}\) yr\(^{-1}\), respectively. However, there was also no significant difference between annual N\(_2\)O emissions in the two treatments at each site. This suggests most of the emitted N\(_2\)O was derived from the decomposition of peat. There were significant positive correlations between N\(_2\)O and CO\(_2\) fluxes in bare treatment in two croplands where N\(_2\)O flux was higher than at another cropland. Nitrous oxide concentration distribution in soil measured in the conventional treatment showed that N\(_2\)O was mainly produced in the surface soil down to 15 cm in the soil. The logarithmic value of the ratio of N\(_2\)O flux and nitrate concentration was positively correlated with water filled pore space. These results suggest that large N\(_2\)O emission in agricultural tropical peatland was caused by denitrification with high decomposition of peat. In addition, N\(_2\)O was mainly produced by denitrification at high range of WFPS in surface soil.
INTRODUCTION

Tropical peatland in Indonesia comprise nearly 12% (27 Mha) of total global peatland (Maltby and Immirzi 1993). However, large areas of the tropical peatlands, have been damaged by forest fires or agricultural deforestation in Indonesia (Muhanmad and Rieley 2002; Page et al. 2002). In 1995, more than 1 Mha of tropical peat land in Central Kalimantan in Indonesia was reclaimed for agricultural development by the “Mega Rice Project” (Muhanmad and Rieley 2002). Moreover, 28% of peat swamp forest was burned in Central Kalimantan in 1997 (Page et al. 2002). In addition to the large-scale degradation and relatively large amount of carbon dioxide (CO$_2$) release by drainage and associated peat fires (Hooijer et al. 2006; Page et al. 2002), cultivation in tropical peat soil has possibly led to increased nitrous oxide (N$_2$O) emission (Takakai et al. 2006; Terry et al. 1981). Increasing atmospheric N$_2$O concentration appears to have been caused by human activities (IPCC 2007). Nitrous oxide is not only a greenhouse gas, but also one of the major ozone-depleting substances in the atmosphere (Ravishankara et al. 2009). Soil is an important source of atmospheric N$_2$O (Mosier et al. 1998). Nitrous oxide emission from agricultural land has been estimated to be 21.6% (3.6 Tg N yr$^{-1}$) of total global emission of N$_2$O (16.2 Tg N yr$^{-1}$) (IPCC 1995). There are, however, several studies documenting N$_2$O emissions not only from natural tropical peatlands, but also those under cultivation (Hadi et al. 2005; Inubushi et al. 2003; Melling et al. 2007; Takakai et al. 2006; Terry et al. 1981).

An issue of the N$_2$O emission study in agricultural tropical peatland is that factors influencing N$_2$O emission and the sources of N for N$_2$O emission have still been unclear. Several studies in agricultural boreal peatland (e.g. in Finland and Norway) have reported that N$_2$O emissions from drained peatland ranged from 0.1 to 37 kg N ha$^{-1}$ yr$^{-1}$ (Klemedtsson et al. 2005; Maljanen et al. 2003; Regina et al. 2004). These values were notably larger than the N$_2$O emission from agricultural fields on mineral soils (0.9-6.4 kg N ha$^{-1}$ yr$^{-1}$, Bouwman et al.)
For review

On the other hand, N\textsubscript{2}O emission from agricultural tropical peatland is reported to be much more variable. The values have been estimated to range from -1.1 to 259 kg N ha\textsuperscript{-1} yr\textsuperscript{-1} (Hadi et al. 2005; Inubushi et al. 2003; Melling et al. 2007; Takakai et al. 2006; Terry et al. 1981). It is also reported N\textsubscript{2}O emission increased following change in land use from natural peat swamp forest to drained or burned peatland, and to agricultural peatland (Melling et al. 2007; Takakai et al. 2006).

In addition to the emission factor (EF\textsubscript{f}) induced by applied N fertilizer, N\textsubscript{2}O emission induced by cultivation of peatland is important for the calculation of annual N\textsubscript{2}O emission from agricultural fields on peatland. In the subarctic zone, Regina et al. (2004) reported N\textsubscript{2}O emission from grass, barley and potato vegetation plots (2.6-24.1 kg N ha\textsuperscript{-1} yr\textsuperscript{-1}) were smaller relative to fallow plots (3.8-37 kg N ha\textsuperscript{-1} yr\textsuperscript{-1}) on boreal peatland in Finland. This means N source for N\textsubscript{2}O emission from soil organic matter (SOM) was larger than N\textsubscript{2}O emission induced by the application of N fertilizer. Moreover, Regina et al. (2004) reported that average N\textsubscript{2}O emission induced by SOM was 10.4 kg N ha\textsuperscript{-1} yr\textsuperscript{-1}. Although, index of N\textsubscript{2}O emission induced by cultivation in tropical peatland was proposed by IPCC (2006) to be 16 kg N ha\textsuperscript{-1} yr\textsuperscript{-1}, this value was derived from data obtained from mid-latitude peatlands. However, some environmental conditions in peatland are notably different between boreal or temperate and tropical peatland. Mean annual air temperature is lower in boreal peatland (e.g., 5°C in Majnegarden, Sweden (Kasimir-Klemedtsson et al. 2009)) than in tropical peatland (e.g., 26°C in Central Kalimantan, Indonesia (Hirano et al. 2007)). Peat is mainly derived from sphagnum or herbaceous plant species in boreal or temperate peatland and from woody plant species in tropical peatland (Andriesse 1988). These vegetational differences strongly influence the production and emission of N\textsubscript{2}O from peat soil because it is mainly produced by nitrification and denitrification in soil. Combined with warm temperatures and frequent rainfall in tropical climates, application of N fertilizer and high levels of organic matter in soil...
may enhance \( \text{N}_2\text{O} \) production through nitrification and denitrification (Bouwman 1996; Bremner 1997; Tiedje 1994). Warm climates in tropical regions also allow multiple crop cultivations within a single year, which may cause rapid decomposition of peat soil due to plowing. Therefore, it is difficult to simply apply what is known regarding \( \text{N}_2\text{O} \) dynamics in boreal or temperate peatland to tropical peatland.

Takakai et al. (2006) reported large amount of annual \( \text{N}_2\text{O} \) emission (at most 259 kg N ha\(^{-1}\) yr\(^{-1}\)) and high \( EF_F \) value in the cultivated tropical peatland of this study located in Central Kalimantan, Indonesia. For the rough calculation of \( EF_F \), \( \text{N}_2\text{O} \) emission in unfertilized and unplowed grassland was assumed to be that derived from SOM decomposition of peat. As such, their reported \( EF_F \) would be influenced by the \( \text{N}_2\text{O} \) emission induced by the cultivation of peatland, and possibly be over- or underestimated. Understanding the mechanisms of such high \( \text{N}_2\text{O} \) production and emission in agricultural tropical peatland will be essential for quantifying \( \text{N}_2\text{O} \) emission and developing the mitigation method for \( \text{N}_2\text{O} \) emission. The objectives of our study were to clarify the factors that influence \( \text{N}_2\text{O} \) emission, identifying the source of N substrate for \( \text{N}_2\text{O} \), and to quantify annual \( \text{N}_2\text{O} \) emission in tropical agricultural peatland in Central Kalimantan, Indonesia.
MATERIALS AND METHODS

Site description

This study was conducted in Kalampangan Village (2°17’S, 114°1’E) near Palangka Raya City (2°S, 114°E) in Central Kalimantan, Indonesia, from March 2004 to March 2007. In this region, the dry season normally begins in June and ends in October (Takakai et al. 2006).

Four adjacent study plots, which were designated as cropland A, B, and C (CL-A, CL-B, CL-C) and grassland (GL), were located in center of the village and set up in March 2002 (Takakai et al. 2006). In those plots, cultivation practice was managed by owner farmer.

Cultivation has begun in 1980 on CL-A, CL-B, and GL, and in 1996 on CL-C. After plowing, croplands were cultivated with cassava (Manihot esculenta Crants.), maize (Zea mays L.) or vegetables (e.g., egg plants (Solanum melongena), etc.). The vegetation in GL was turf grass which has been harvested or grazed. Crop cultivation and fertilization practice were managed by owner farmers. Average N fertilizer applied in CL-A, CL-B, and CL-C sites were 1,607, 472 and 1,113 kg N ha⁻¹ yr⁻¹, respectively (Table 1). The soil classification according to USDA Soil Taxonomy at all the study sites was Histosols (Typic Tropofibrists, Takakai et al. 2006). Thickness of peat was 2.6-2.8 m. Bulk density and porosity of surface soil (0-10 cm) were approximately 0.4 g cm⁻³ and 73-77 %, respectively. Total C and N concentration in surface soil (0-10 cm) varied from 530 to 632 and 13 to 14.3 g kg⁻¹, respectively. Detail information about soil chemical and physical characteristics and the method of soil analysis was described in Takakai et al. (2006).

Treatments

Fields in CL-A, CL-B and CL-C were defined as conventional cultivation (conventional) treatments. Unplanted and unfertilized bare (bare) treatments, which were 0.5 m² (1m x 0.5m) in area, were established in CL-A, CL-B, and CL-C in April 2004 for estimating N₂O
emission derived from SOM decomposition and were maintained as such for the duration of
the study period. Thin woody plates were installed around the bare treatments down to 20 cm
deep in the soil to prevent root intrusion and soil contamination. In the conventional treatment
in CL-A, CL-B, and CL-C, chemical and organic fertilizers were applied by farmer every
cultivation at the point seeds were sown, which was based on common agricultural practices
in the area. Organic fertilizer was produced from cattle manure kept by farmer and grass.
Fertilizer was not applied during the duration of the study period in GL.

Nitrous oxide and carbon dioxide flux measurements and soil nitrous oxide gas
sampling
Nitrous oxide and CO₂ fluxes were measured with a closed-chamber method with three
replications at each site and treatment (Takakai et al. 2006). Gas fluxes were measured once a
We followed N₂O and CO₂ gas sampling method provided by Takakai et al. (2006), Nakano et
al. (2004) and Toma and Hatano (2007). Air temperature at a height of 1 m was measured
with a thermometer at the same day of N₂O and CO₂ gas fluxes measurement.
We followed a protocol modified after the methods of Takakai et al. (2006) and Morishita
et al. (2003) to sample soil gas sampling and calculate N₂O production and consumption in
soil.

Nitrous oxide and carbon dioxide concentration analysis, calculation of nitrous oxide
and carbon dioxide fluxes, annual emission of nitrous oxide, and nitrogen fertilizer
induced emission factor of nitrous oxide (EFᵣ)
Gas samples stored in Tedlar bags for analysis of CO₂ concentration and in vacuum vials for
the analysis of N₂O concentration were analyzed within 12 hour and a month, respectively,
after collecting these samples. Nitrous oxide and CO\textsubscript{2} concentrations were analyzed with a
gas chromatograph (GC-14B, Shimadzu, Kyoto, Japan) equipped with an electron-capture
detector and CO\textsubscript{2} analyzer (ZFP-9, Fuji Electric Systems, Tokyo, Japan), respectively. Gas
fluxes were calculated following the method provided by Toma and Hatano (2007).
The annual N\textsubscript{2}O emissions were calculated by linear integration of flux measurements during
the measurement period (Toma and Hatano 2007; Toma \textit{et al}. 2010).
Emission factor induced by nitrogen fertilizer (chemical and organic nitrogen) was
calculated by the following equations for data collected in CL-A, CL-B, and CL-C:
\[
EF_{F} (%) = \frac{(N_{2}O_{C} - N_{2}O_{B})}{(\text{applied chemical and organic N})} \times 100
\]
where N\textsubscript{2}O\textsubscript{C} is the annual N\textsubscript{2}O emission in the conventional treatment (kg N ha\textsuperscript{-1} yr\textsuperscript{-1}) and
N\textsubscript{2}O\textsubscript{B} is the annual N\textsubscript{2}O emission in bare treatment (kg N ha\textsuperscript{-1} yr\textsuperscript{-1}). EF\textsubscript{F} was calculated when
there was a significant difference in N\textsubscript{2}O emission between conventional and bare treatments.
Otherwise, EF\textsubscript{F} was defined as 0\%.

\textbf{Calculation of net nitrous oxide production rate in soil}

Net N\textsubscript{2}O production rate is the difference between gross N\textsubscript{2}O production rate and gross N\textsubscript{2}O
consumption rate. Net N\textsubscript{2}O production rate was calculated using the following equation based
on Fick’s Law (gradient method; Granli and Bøckman 1994):
\[
\text{Net N}_{2}\text{O production rate} = F(I+1) - F(I)
\]
where F is the gas flux (mg m\textsuperscript{-2} s\textsuperscript{-1}) and I in the parenthesis is the depth increment number. We
followed the method of Kusa et al. (2008) for the calculation of net N\textsubscript{2}O production rate from
the soil layer of 0-2.5, 2.5-7.5, 7.5-15, 15-30, and 30-60-cm depths.

\textbf{Ancillary measurements}
Soil temperature at a depth of 4 cm, volumetric soil water content from 0 to 6-cm depth, and water table depth were measured during the gas flux measurements. Soil temperature was measured in both conventional and bare treatments using a thermistor thermometer. Amplitude domain reflectometry (ADR, ML2 Theta Probe Delta-T Devices, Cambridge, UK) was used to measure the volumetric soil water content in both conventional and bare treatments. The resulting volumetric soil water content was converted into a value for water-filled pore space (WFPS), which represents the ratio of the volumetric water content to the total porosity of the soil, by assuming that the porosity measured by Takakai et al. (2006) in February 2005 was consistent throughout the measurement period. There were three replications per chamber for the soil temperature and volumetric soil water content measurements. To measure the water table depth, perforated PVC pipes (1.57 inch in diameter) were inserted into the peat soil at each site. Air temperature and precipitation were measured every half hour using a 50-m micrometeorological tower established inside the forest that was about 3 km from the study site (Hirano et al. 2005; 2007). Disturbed soil samples in conventional treatments were collected for soil NH$_4^+$ and NO$_3^-$ concentrations from 0-3-cm and 3-10-cm-depth between March 2004 and February 2006, and from 0 to 10-cm depth between March 2006 and March 2007 at the same day of gas flux measurement. In bare treatment at each site, soil samples were collected only two times in September 2006 (in dry season) and February 2007 (in rainy season). Collected soil samples were frozen until soil NH$_4^+$ and NO$_3^-$ concentrations of those samples were analyzed. Soil pH (H$_2$O basis) was measured with a glass electrode pH meter (pH meter F-22, Horiba, Kyoto, Japan) in a 1:20 soil:deionized water mixture. Concentration of NO$_3^-$ in this suspension was also measured using ion chromatography (Dionex QIC Analyzer, Dionex Japan, Osaka, Japan). Ammonium in the soil was extracted with 2 mol L$^{-1}$ potassium chloride solution (1:20 dried soil:water). Ammonium concentration was determined using colorimetry based on the indophenol-blue
method with a UV-VIS spectrophotometer (UV mini 1240, Shimadzu, Kyoto, Japan).

Ammonium and NO$_3^-$ concentrations in soil samples, which were collected at the 0-10-cm depth from March 2004 to February 2006, were calculated by the weighted average of each concentration in soil samples from the 0-3-cm and 3-10-cm depth.

### Statistical analysis

Comparisons of soil temperature and WFPS between conventional and bare treatments in CL-A, CL-B, and CL-C were analyzed with the Mann-Whitney’s U-test (non-parametric).

Comparisons of N$_2$O fluxes or annual N$_2$O emissions between conventional and bare treatments were performed using Student’s t-test (parametric) based on studies that report N$_2$O flux shows a log-normal distribution (Van-Cleemput et al. 1994; Velthof and Oenema 1995). Therefore, values of N$_2$O flux or annual N$_2$O emission were transformed logarithm values when student’s t-test was carried out. The least significant difference test was used to determine significant differences ($P < 0.05$). One-sided 95 % confidence interval of N$_2$O emission data was calculated by using the following equation:

\[
\text{one-sided 95 % confidence interval} = t(\text{d.f.}, 0.05) \times \text{standard error}
\]

where d.f. is the degree of freedom, and $t(\text{d.f.}, 0.05)$ is the t value at 5% significant level with two-sided alternative. Spearman’s rank correlation coefficient was used for the analysis of relationship between N$_2$O flux and water table depth, soil temperature, WFPS, NH$_4^+$ and NO$_3^-$ concentrations or CO$_2$ flux in conventional treatments during the study period in CL-A, CL-B, CL-C, and GL.
RESULTS

Nitrous oxide fluxes in conventional and bare treatments in all plots increased from November to April (Figs. 1-4). Ranges of N$_2$O fluxes during the study period in conventional treatments in CL-A, CL-B, and CL-C were 0-38, 0-1.46, and 0-9.27 mg N m$^{-2}$ h$^{-1}$, respectively. On the other hand, N$_2$O fluxes in bare treatment in CL-A, CL-B, and CL-C were 0-43, 0-0.98, and 0-12 mg N m$^{-2}$ h$^{-1}$, respectively. Average N$_2$O fluxes in conventional treatment from April to June, July to September, October to December and January to March significantly increased with increasing precipitation in each plot except for CL-C (CL-A y = 0.023x – 0.584, $R^2 = 0.55$, $P < 0.05$; CL-B y = 0.0005x – 0.078, $R^2 = 0.64$, $P < 0.05$; CL-C y = 0.0019x – 0.037, $R^2 = 0.30$, $P = 0.18$; GL y = 0.0011x – 0.134, $R^2 = 0.57$, $P < 0.05$). There were no significant differences in N$_2$O fluxes between conventional and bare treatments in CL-A, CL-B, and CL-C (Table 2). Nitrous oxide production rates were relatively high at 2.5-15-cm depth of soil compared to that below 15-cm depth in all plots (Table 3).

Although the seasonal trend of water table depth was not clear, average water table depths in conventional treatments in CL-A, CL-B, CL-C, and GL were 67.2, 77.1, 67.8, and 87.7 cm, respectively (Figs. 1b-4b). In all plots, soil temperature was stable around 30 °C (Figs. 1c-4c). There were no significant differences in soil temperature between conventional and bare treatments for the duration of the study (Table 2). Water-filled pore space in each plot tended to be high (around 80%) from November to April in all years (Figs. 1-4). There were no significant differences in WFPS between conventional and bare treatments in CL-A, CL-B, and CL-C (Table 2). Clear seasonal trends of soil NH$_4^+$ and NO$_3^-$ concentrations in the plots were not observed (Figs. 1e-4e). The average NH$_4^+$ concentrations in conventional treatments in CL-A, CL-B, CL-C, and GL were 59.4, 35.2, 18.5, and 65.8 mg N kg$^{-1}$, respectively. Average NO$_3^-$ concentrations in conventional treatments in CL-A, CL-B, CL-C, and GL were 249, 40.8, 111, and 63.7 mg N kg$^{-1}$ respectively. Nitrate concentrations in CL-A and CL-C
tended to be higher than in CL-B and GL. Average \( \text{NH}_4^+ \) concentrations in bare treatments in CL-A, CL-B and CL-C were 10.8, 10.8, and 13.6 mg N kg\(^{-1}\), respectively. Average \( \text{NO}_3^- \) concentrations in bare treatments in CL-A, CL-B, and CL-C were 99.9, 2.6, and 12.5 mg N kg\(^{-1}\), respectively. Values of \( \text{NH}_4^+ \) and \( \text{NO}_3^- \) concentrations in soil in bare treatment were lower than the values in conventional treatments in CL-A, CL-B, and CL-C (Figs. 1e-3e).

Water table depth and WFPS were almost equivalent between CL-A and CL-C (Figs. 1d, 4d). There were no consistent relationships at any of the plots between \( \text{N}_2\text{O} \) flux and water table depth, soil temperature, \( \text{NH}_4^+ \) or \( \text{NO}_3^- \) contents (Table 4). However, \( \text{N}_2\text{O} \) flux in CL-A, CL-B, and GL significantly increased with increasing WFPS. In addition, \( \text{N}_2\text{O} \) fluxes in CL-A and CL-C, in which \( \text{N}_2\text{O} \) fluxes were relatively high compared with CL-B and GL, were significantly and positively correlated with \( \text{CO}_2 \) fluxes (Table 4). Although not significant, \( \text{N}_2\text{O} \) increased with increasing \( \text{CO}_2 \) flux in bare treatment in CL-A and CL-B (CL-A \( y = 17.7x - 5.65 \), \( R = 0.36 \), \( P = 0.06 \); CL-B \( y = 0.46x - 0.04 \), \( R = 0.53 \), \( P < 0.01 \); CL-C \( y = 0.35x - 2.40 \), \( R = 0.02 \), \( P = 0.93 \)). In all plots, the ratio of \( \text{N}_2\text{O} \) flux and soil \( \text{NO}_3^- \) concentration at log scale \( \{\ln(\text{N}_2\text{O}/\text{NO}_3^-)\} \) were significantly correlated with WFPS (Fig. 5). However, the slope of \( \ln(\text{N}_2\text{O}/\text{NO}_3^-) \) against WFPS was higher in CL-A (0.13) compared with other plots (0.05 to 0.08). Carbon dioxide flux in bare treatment tended to increase in the rainy season in CL-A, CL-B, and CL-C (Figs. 1f-3f).

Average annual \( \text{N}_2\text{O} \) emissions during the study period in conventional treatment in CL-A, CL-B, CL-C, and GL were 580, 25.1, 92.5 and 43.1 kg N ha\(^{-1}\) yr\(^{-1}\), respectively (Table 5). Significant linear correlations between annual \( \text{N}_2\text{O} \) emission in conventional treatment in all plots and annual mean air temperature or annual precipitation were not observed (mean air temperature, \( P = 0.29 \); annual precipitation, \( P = 0.47 \)). In CL-A and CL-C, in which the average N fertilizer application rate was more than 1,000 kg N ha\(^{-1}\) yr\(^{-1}\) (Table 1), annual \( \text{N}_2\text{O} \) emissions in conventional treatments were larger than those in CL-B or GL. Annual \( \text{N}_2\text{O} \)
emissions in conventional treatments significantly increased with N fertilizer application rate
(y = 17.1exp(1.00x), R = 0.70, P < 0.001). Even though N fertilizer was not applied in GL,
annual N\textsubscript{2}O emissions were generally greater than 20 kg N ha\textsuperscript{-1} yr\textsuperscript{-1} (Table 5). Average annual
N\textsubscript{2}O emissions in bare treatment in CL-A, CL-B, and CL-C were 733, 6.96 and 126 kg N ha\textsuperscript{-1}
yr\textsuperscript{-1}, respectively (Table 5). Significant differences in annual N\textsubscript{2}O emissions between
conventional and bare treatments were observed in CL-B and CL-C during April 2005 to
March 2006. Annual N\textsubscript{2}O, however, emissions in bare treatments in CL-A, CL-B, and CL-C
were parallel to annual N\textsubscript{2}O emission in the conventional treatments (Table 5). EF\textsubscript{F} was
calculated only during April 2005 to March 2006 in CL-B and CL-C site, where annual N\textsubscript{2}O
emissions between the two treatments were significantly different (Table 5). EF\textsubscript{F} in CL-B and
CL-C were 0.81 and 3.59 %, respectively. At another site and period, EF\textsubscript{F} was 0% because
there were no significant differences in annual N\textsubscript{2}O emission between the conventional and
bare treatments. From these values, annual N\textsubscript{2}O emission induced by N fertilizer and derived
from N in SOM were estimated to 5.21 and 7.38 kg N ha\textsuperscript{-1} yr\textsuperscript{-1} in CL-B and 38.3 and 35.4 kg
N ha\textsuperscript{-1} yr\textsuperscript{-1} in CL-C, respectively, during April 2005 to March 2006. In addition, the proportion
of annual N\textsubscript{2}O emission derived from SOM N to annual N\textsubscript{2}O emission was 58.6 and 48.0% in
CL-B and CL-C during April 2005 to March 2006, respectively.
DISCUSSION

Main process of nitrous oxide production

Increases in N₂O fluxes from October to May (Figs. 1g-4g) and significant correlation between 3-month average N₂O flux and precipitation suggest that N₂O was actively produced during the rainy season. Werner-Riddle et al. (2007) reported large pulse fluxes of N₂O in the wet season in tropical rain forests on mineral soil (e.g., Inceptisols, Oxisols) in Kenya (00°8′N–00°23′N, 34°46′–34°58′E). Takakai et al. (2006) reported N₂O flux was significantly correlated with soil NO₃⁻ concentration at or above 60-70 % WFPS in the same field of this study. While clear relationships between N₂O flux and water table depth, soil temperature, NH₄⁺ or NO₃⁻ concentrations in all sites were not observed (Table 4), significant correlations between N₂O flux and WFPS in CL-A, CL-B, GL or between Ln(N₂O/NO₃⁻) and WFPS in all sites indicated that N₂O was mainly produced by denitrification (Table 4, Fig. 5).

Nitrous oxide is generally produced in the processes of nitrification and denitrification (Bouwman 1996; Bremner 1997; Tiedje 1994). In the denitrification process, N₂O is mostly reduced to N₂ when WFPS is greater than 70 % (Davidson et al. 2000). However, linear relationships between Ln(N₂O/NO₃⁻) and WFPS in the conventional treatment in each site suggested that N₂O was not substantially reduced at high WFPS (Fig. 5). This indicates that N₂O reductase (nos) in N₂O-producing microbes in soil might be inactive even at high WFPS (i.e. above 70%). In acidic soils, higher N₂O:N₂ fraction for denitrification were reported (Alexander 1977). Dannenmann et al. (2008) reported N₂:N₂O ratio increased exponentially with increasing pH in the soil Ah horizon between pH values of 6.2 and 7.3 in Germany. This means that N₂O:N₂ ratio increased with decreasing soil pH. In our study site, pH in surface soil was lower than 6.0. Thus, the reaction of N₂O to N₂ in denitrification process might be small due to low soil pH. Hashidoko et al. (2008) found denitrifying bacteria (Janthinobacterium spp.) in the surface soil in CL-A, and suggested the possibility of
inactivity of *Janthinobacterium* spp. Furthermore, Yanai et al. (2007) reported *N₂O*-producing fungi *Fusarium oxysporum* and *Neocosmospora vasinfecta* were isolated in CL-A. Because the inactivity of *nos* in some fungal species were reported (Shoun et al. 2006), *nos* of the fungi in our study sites was possibly inactive. Nitrous oxide-producing bacteria and fungi without *nos* may potentially contribute to the high *N₂O* flux and emission at the study site.

**Origin of the substrate for nitrous oxide productions**

Nitrous oxide flux was not always measured just after fertilizer N application and was measured randomly at most two times a month. However, seasonal variation of *N₂O* flux in both conventional and bare treatments clearly showed the increase in *N₂O* flux in rainy season. In addition, differences in *N₂O* fluxes between conventional and bare treatments were not observed (Table 2). Those suggest that *N₂O* flux induced by applied N fertilizer was unknown or small compared with that by other form of N in soil such as soil organic N, Nitrate and C are required for denitrification as an electron accepter and donor, respectively (Bouwman 1996; Bremner 1997). Except for in CL-B and CL-C from April 2005 to March 2006, differences in annual *N₂O* emission between conventional and bare treatments in CL-A, CL-B, and CL-C also were not observed. Net *N₂O* production rate was mostly high in the soil depth of 2.5-15 cm (Table 3). Root barriers also were installed around bare treatments at 20-cm depth. This suggests *N₂O* produced in conventional treatment probably did not influence *N₂O* flux in the bare treatments. Therefore, those indicated the source of N for *N₂O* production was mainly derived from SOM in peat. Ammonium and NO₃⁻ concentrations in soil in bare treatments were lower than in the conventional treatments. In addition, CO₂ flux in conventional treatment in CL-A and CL-C, in which high *N₂O* fluxes were observed, was significantly correlated with *N₂O* flux (Table 4). Therefore, the limiting factor of *N₂O* production is the decomposition of SOM in peat. After decomposition of SOM, mineralized
organic N was possibly nitrified and denitrified quickly to N\textsubscript{2}O. Takakai \textit{et al.} (2007) reported CO\textsubscript{2} flux in conventional treatment during the rainy season in the same plot of our study field was significantly higher than during the dry season. In addition, there were no significant differences in CO\textsubscript{2} emission between conventional and bare treatments in all plots due to the high decomposition rate of SOM (Takakai \textit{et al.} 2007). This indicated that decomposition of SOM in peat was accelerated in rainy season and production of CO\textsubscript{2} was mainly induced by the decomposition of SOM, but not root respiration. Nitrous oxide flux tended to increase with increasing CO\textsubscript{2} flux in bare treatment in CL-A and CL-B. Thus, N\textsubscript{2}O production might be closely influenced by the decomposition of SOM in peat. Also, N\textsubscript{2}O-producing bacteria or fungi (e.g. \textit{Janthinobacterium} spp., \textit{Fusarium oxysporum}, and \textit{Neocosmospora vasinfecta}) probably were important decomposers of peat during the rainy season (Yanai \textit{et al.} 2007; Hashidoko \textit{et al.} 2008).

\textbf{Nitrous oxide emission in agricultural peat land}

Because there were no significant differences in N\textsubscript{2}O flux between conventional and bare treatments in CL-A, CL-B, and CL-C (Table 2), increase in annual N\textsubscript{2}O emission could not be due to increase in annual fertilizer N application rate. Thus, the correlation between annual N\textsubscript{2}O emission and annual fertilizer N application rate might indicate the influence of long-term management on annual N\textsubscript{2}O emission. Highest mean total N application in conventional treatment in CL-A among the study plots indicated large amount of N fertilizer might have been applied for long time in CL-A compared with those in other plots. Management or history of cultivation prior to this study would change the quality of peat and characteristics of microorganisms. Though there was no referable study on tropical agricultural peatland, study on boreal organic soil in Finland, Maljanen \textit{et al.} (2003) reported difference in annual N\textsubscript{2}O emission between in adjusted forested and cultivated peatlands. In addition, application
of organic and chemical fertilizer improved the nutrient (N, phosphorous, and potassium) levels in soil over a 23-year period under a wheat-wheat-maize cropping system on a silt loam soil in China (Su et al. 2006). Zhong et al. (2010) reported long-term application of chemical and organic fertilizer to mineral soil collected in Jiangxi Province, China changed soil quality and microbial community and diversity. Klemedtsson et al. (2005) reported that when soil C:N ratio of peat in boreal forests in Sweden decreased from 90 to 13, mean annual N$_2$O emission increased from 0.05 to 30 kg N ha$^{-1}$ yr$^{-1}$. There were few differences in soil C:N ratio and soil pH among our study sites (Takakai et al. 2006). Thus, the influence of soil C:N ratio and soil pH on N$_2$O emission were not clear. However, as reported by Klemedtsson et al. (2005), quality of peat and cultivation history may be a good indicator for the estimation of N$_2$O emission from agricultural peat soil in tropical region.

Annual N$_2$O emissions from conventional treatment in CL-A, CL-B, and CL-C, in which fertilizers were applied, ranged from 12.6 to 698 kg N ha$^{-1}$ yr$^{-1}$ (Table 5). These values of annual N$_2$O emissions were greater than annual N$_2$O emission (0.1-56 kg N ha$^{-1}$ yr$^{-1}$) from boreal and temperate peat soils (Kasimir-Klemedtsson et al. 1997; Maljanen et al. 2003; 2004; Regina et al. 2004), and other N$_2$O emission values (0.9-6.4 kg N ha$^{-1}$ yr$^{-1}$) from mineral soil reviewed and summarized by Bouwman et al. (2002). Furthermore, annual N$_2$O emissions in this study were also greater than N$_2$O emissions from tropical agricultural peat soil in South Kalimantan, Indonesia (-1.1-2.03 kg N ha$^{-1}$ yr$^{-1}$, Hadi et al. 2005; Inubushi et al. 2003) and Sarawak, Malaysia (1.2-3.3 kg N ha$^{-1}$ yr$^{-1}$, Melling et al. 2007). Therefore, annual N$_2$O emission from agricultural fields in our study field might be the highest value reported to date. Absence of the difference in annual N$_2$O emission between conventional and bare treatment plots, except for in CL-B and CL-C from April 2005 to March 2006, suggested that most of emitted N$_2$O in conventional treatment derived from the decomposition of SOM. Therefore, larger annual N$_2$O emission compared with N$_2$O emissions in those studies might
be affected by factors other than the amount of N fertilizer application. The agricultural peat
lands in our study sites are cultivated generally three to four times a year. Fertilizer was
applied in each cultivation. Thus, cultivation practices in our study site were different than
that reported of tropical peatland where oil palms (Melling et al. 2007) and sago palm (Hadi
et al. 2005) were cultivated. Intensive cultivation with high N application on drained peat soil
may change the quality of peat suitable for N\textsubscript{2}O production by denitrification. Kasimir-
Klemedtsson et al. (2009) reported N\textsubscript{2}O emission peaked after soil cultivation, plowing and
harrowing in grassland on drained peatland in Sweden (58°20’N, 13°30’E). The period of
cultivation on drained peat land possibly affects the N\textsubscript{2}O emission because the quality of peat
and microbial community changes gradually after drainage (Su et al. 2006; Zhong et al. 2010).
Hence, differences in history and management of cultivation may cause large variation of N\textsubscript{2}O
emission from tropical agricultural peat soil. Currently, there are not many studies about N\textsubscript{2}O
emission in agricultural fields on tropical peat soil. Additional research regarding N\textsubscript{2}O
emission from agricultural fields on tropical peat soil, therefore, is needed because large
amounts of N\textsubscript{2}O likely have been emitted and will continue to be from peat soil after
deforestation and establishment of arable land on peat soil.

In our study site, most N\textsubscript{2}O was derived from the decomposition of SOM. Even when the
difference in annual N\textsubscript{2}O emission was detected, the ratio of N\textsubscript{2}O emission induced by
fertilizer N and derived from SOM decomposition was almost equal (48-58.6%). Since annual
N\textsubscript{2}O emission in agricultural tropical peat land was higher than that in a natural forest, a
regenerated forest after burning, and a burned forest located close to our study site, N\textsubscript{2}O
emission derived from SOM might be influenced by cultivation or land-use change from
natural forest to agricultural field. Indeed, the N\textsubscript{2}O emission factor induced by the cultivation
in tropical peat soil (16 kg N ha\textsuperscript{-1} yr\textsuperscript{-1}) estimated by IPCC (2006) was calculated using the
data in boreal peat soil (8 kg N ha\textsuperscript{-1} yr\textsuperscript{-1}). However, estimated N\textsubscript{2}O emission originated from
decomposition of SOM exceeded the value provided from IPCC (2007), whereas N\textsubscript{2}O emission derived from SOM in other agricultural peat soil reported by Melling \textit{et al.} (2007) and Hadi \textit{et al.} (2005) might be lower because N\textsubscript{2}O emissions from those study site were lower than 4 kg N ha\textsuperscript{-1} yr\textsuperscript{-1} despite application of N fertilizer at those sites. This indicated that the N\textsubscript{2}O emission derived from decomposition of SOM in tropical agricultural peat soil might vary widely. Thus, additional research on N\textsubscript{2}O emission in tropical agricultural peat soil is needed to provide a more accurate value of emission factor for the cultivation in tropical peat soil, its uncertainty, and to determine the factors influencing its variation.

The EF\textsubscript{F} value of this study (0-3.59\%) was smaller than the range reported by Takakai \textit{et al.} (2006) (1.8-36 \%) in our study field. Because Takakai \textit{et al.} (2006) used N\textsubscript{2}O emission values from GL as the estimate for N\textsubscript{2}O emission in CL-A, CL-B, and CL-C, EF\textsubscript{F} may have been overestimated due to spatial variation of N\textsubscript{2}O emission among the sites. However, the EF\textsubscript{F} values in this study were similar or higher than the 1.00 \% value reported by IPCC (2006). Akiyama \textit{et al.} (2006) summarized published data and reported that EF\textsubscript{F} in well- and poorly drained soil were 0.32 and 1.40 \%, respectively. Bouwman (1996) reported EF\textsubscript{F} of chemical and organic fertilizer ranged from 0.1 to 1.6 \% on mineral soil. Thus, EF\textsubscript{F} values in our study were similar or slightly higher than other agricultural fields on mineral soil. On the other hand, EF\textsubscript{F}, on dry and wet Histosols in Netherlands were 4.21 and 1.38 \%, respectively (Van Beek \textit{et al.} 2010). Although more work is needed to normalize EF\textsubscript{F} values in agricultural peat land in tropical regions, EF\textsubscript{F} value in Histosols may be higher than in mineral soils.
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Takakai F, Toma Y, Morishita T, Darung U, Dohong S, Limin SH., Hatano R 2007:

Contribution of organic matter decomposition and root respiration to CO₂ emissions


FIGURE LEGENDS

Fig. 1 Seasonal variation in air temperature and precipitation (a), water table (b), soil temperature (c), water filled pore space (WFPS) (d), ammonium (NH$_4^+$), nitrate (NO$_3^-$) concentrations (e), and carbon dioxide (CO$_2$) (f) and nitrous oxide (N$_2$O) fluxes (g) in cropland A (CL-A) in Central Kalimantan, Indonesia. Conventional and Bare represents conventional cultivation treatment and bare treatment, respectively. Ammonium and NO$_3^-$ concentrations (e) are only in conventional treatment. Error bars are standard deviation.

Fig. 2 Seasonal variation in air temperature and precipitation (a), water table (b), soil temperature (c), water filled pore space (WFPS) (d), ammonium (NH$_4^+$), nitrate (NO$_3^-$) concentrations (e), and carbon dioxide (CO$_2$) (f) and nitrous oxide (N$_2$O) fluxes (g) in cropland B (CL-B) in Central Kalimantan, Indonesia. Conventional and Bare represents conventional cultivation treatment and bare treatment, respectively. Ammonium and NO$_3^-$ concentrations (e) are only in conventional treatment. Error bars are standard deviation.

Fig. 3 Seasonal variation in air temperature and precipitation (a), water table (b), soil temperature (c), water filled pore space (WFPS) (d), ammonium (NH$_4^+$), nitrate (NO$_3^-$) concentrations (e), and carbon dioxide (CO$_2$) (f) and nitrous oxide (N$_2$O) fluxes (g) in cropland C (CL-C) in Central Kalimantan, Indonesia. Conventional and Bare represents conventional cultivation treatment and bare treatment, respectively. Ammonium and NO$_3^-$ concentrations (e) are only in conventional treatment. Error bars are standard deviation.

Fig. 4 Seasonal variation in air temperature and precipitation (a), water table (b), soil temperature (c), water filled pore space (WFPS) (d), ammonium (NH$_4^+$), nitrate (NO$_3^-$) concentrations (e), and carbon dioxide (CO$_2$) (f) and nitrous oxide (N$_2$O) fluxes (g) in
grassland (GL) in Central Kalimantan, Indonesia. Error bars are standard deviation.

Fig. 5 Relationships between logarithmic value of the ratio of nitrous oxide (N$_2$O) flux and soil nitrate (NO$_3^-$) concentration (Ln(N$_2$O flux / NO$_3^-$)) against water filled pore space (WFPS) in conventional treatment in cropland A (CL-A), cropland B (CL-B), cropland C (CL-C), and grassland (GL) in Central Kalimantan, Indonesia.
Table 1 Amount of nitrogen fertilizer application rate in cropland A (CL-A), B (CL-B), C (CL-C) from April 2002 to March 2007 in Central Kalimantan, Indonesia. Data from April 2002 to March 2004 were cited from Takakai et al. (2006).

<table>
<thead>
<tr>
<th>Year</th>
<th>CL-A Chemical</th>
<th>Organic</th>
<th>Total</th>
<th>CL-B Chemical</th>
<th>Organic</th>
<th>Total</th>
<th>CL-C Chemical</th>
<th>Organic</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002/4-2003/3</td>
<td>818</td>
<td>180</td>
<td>998</td>
<td>760</td>
<td>40</td>
<td>800</td>
<td>1,098</td>
<td>180</td>
<td>1,278</td>
</tr>
<tr>
<td>2003/4-2004/3</td>
<td>545</td>
<td>120</td>
<td>665</td>
<td>853</td>
<td>100</td>
<td>953</td>
<td>665</td>
<td>120</td>
<td>785</td>
</tr>
<tr>
<td>2004/4-2005/3</td>
<td>1,378</td>
<td>180</td>
<td>1,558</td>
<td>633</td>
<td>140</td>
<td>773</td>
<td>1,011</td>
<td>196</td>
<td>1,207</td>
</tr>
<tr>
<td>2005/4-2006/3</td>
<td>1,505</td>
<td>120</td>
<td>1,625</td>
<td>460</td>
<td>184</td>
<td>644</td>
<td>945</td>
<td>120</td>
<td>1,065</td>
</tr>
<tr>
<td>2006/4-2007/3</td>
<td>1,458</td>
<td>180</td>
<td>1,638</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>945</td>
<td>120</td>
<td>1,065</td>
</tr>
<tr>
<td>Average (2004/4-2007/3)</td>
<td>1,447</td>
<td>160</td>
<td>1,607</td>
<td>365</td>
<td>108</td>
<td>472</td>
<td>967</td>
<td>145</td>
<td>1,113</td>
</tr>
</tbody>
</table>
Table 2 Statistical analysis of the difference in nitrous oxide ($N_2O$) flux, soil temperature, and water filled pore space (WFPS) between conventional and bare treatments in cropland A (CL-A), cropland B (CL-B), and cropland C (CL-C) from April 2004 to March 2007 in Central Kalimantan, Indonesia. Nitrous oxide flux was converted to logarithm value. Difference in $N_2O$ was analyzed by Student’s $t$-test and soil temperature or WFPS were analyzed by Mann-Whitney’s $U$-test.

<table>
<thead>
<tr>
<th></th>
<th>CL-A Conventional</th>
<th>CL-A Bare</th>
<th>CL-B Conventional</th>
<th>CL-B Bare</th>
<th>CL-C Conventional</th>
<th>CL-C Bare</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_2O$ flux $^\S$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n$</td>
<td>36</td>
<td>35</td>
<td>36</td>
<td>35</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>Average</td>
<td>0.87</td>
<td>0.91</td>
<td>-3.14</td>
<td>-3.15</td>
<td>-1.39</td>
<td>-1.46</td>
</tr>
<tr>
<td>$s^2$</td>
<td>4.50</td>
<td>2.33</td>
<td>5.39</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t$</td>
<td>0.04</td>
<td>0.02</td>
<td>0.06</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P$</td>
<td>&gt;0.1</td>
<td>&gt;0.1</td>
<td>&gt;0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil temperature</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n$</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Median</td>
<td>31.0</td>
<td>30.9</td>
<td>29.7</td>
<td>29.9</td>
<td>31.1</td>
<td>31.1</td>
</tr>
<tr>
<td>$U$</td>
<td>616</td>
<td>526</td>
<td>652</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$z$</td>
<td>0.04</td>
<td>-1.02</td>
<td>0.46</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P$</td>
<td>0.96</td>
<td>0.31</td>
<td>0.64</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WFPS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n$</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>Median</td>
<td>62.1</td>
<td>59.6</td>
<td>62.6</td>
<td>64.3</td>
<td>71.3</td>
<td>72.3</td>
</tr>
<tr>
<td>$U$</td>
<td>698</td>
<td>588</td>
<td>579</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$z$</td>
<td>1.00</td>
<td>-0.29</td>
<td>-0.39</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P$</td>
<td>0.31</td>
<td>0.77</td>
<td>0.69</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^\S$ $N_2O$ flux was converted to logarithm value
Table 3 Net nitrous oxide ($N_2O$) production rate in soil in conventional treatments in cropland A (CL-A), B (CL-B), C (CL-C), and grassland (GL) from April 2004 to March 2007 in Central Kalimantan, Indonesia.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Net $N_2O$ production rate (mg N m$^{-2}$ hr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CL-A</td>
</tr>
<tr>
<td></td>
<td>Average</td>
</tr>
<tr>
<td>0-2.5</td>
<td>-3.34</td>
</tr>
<tr>
<td>2.5-7.5</td>
<td>4.77</td>
</tr>
<tr>
<td>7.5-15</td>
<td>6.36</td>
</tr>
<tr>
<td>15-30</td>
<td>2.66</td>
</tr>
<tr>
<td>30-60</td>
<td>-0.95</td>
</tr>
</tbody>
</table>


Table 4 Spearman's rank correlation coefficients of nitrous oxide (N$_2$O) flux and water table depth, soil temperature, water filled pore space (WFPS), ammonium (NH$_4^+$) and nitrate (NO$_3^-$) concentrations, or CO$_2$ flux in conventional treatments from April 2004 to March 2007 in cropland A (CL-A), B (CL-B), and C (CL-C) and grassland (GL) in Central Kalimantan, Indonesia.

<table>
<thead>
<tr>
<th></th>
<th>CL-A</th>
<th>CL-B</th>
<th>CL-C</th>
<th>GL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water table depth (cm)</td>
<td>-0.01</td>
<td>0.03</td>
<td>0.53**</td>
<td>0.26</td>
</tr>
<tr>
<td>Soil Temperature (℃)</td>
<td>-0.04</td>
<td>-0.18</td>
<td>0.15</td>
<td>-0.12</td>
</tr>
<tr>
<td>WFPS (%)</td>
<td>0.59**</td>
<td>0.52**</td>
<td>0.18</td>
<td>0.66**</td>
</tr>
<tr>
<td>NH$_4^+$ (mg N kg$^{-1}$)</td>
<td>-0.13</td>
<td>0.11</td>
<td>0.08</td>
<td>-0.28</td>
</tr>
<tr>
<td>NO$_3^-$ (mg N kg$^{-1}$)</td>
<td>-0.27</td>
<td>0.51**</td>
<td>0.38**</td>
<td>0.06</td>
</tr>
<tr>
<td>CO$_2$ flux (g C m$^{-2}$ hr$^{-1}$)</td>
<td>0.34*</td>
<td>0.28</td>
<td>0.49**</td>
<td>0.24</td>
</tr>
</tbody>
</table>

** P < 0.01, * P < 0.05
Table 5 Annual nitrous oxide (N\textsubscript{2}O) emission in conventional and bare treatments from 2002 to 2007 in cropland A (CL-A), B (CL-B), C (CL-C), and grassland (GL) in Central Kalimantan, Indonesia. Data of N\textsubscript{2}O emission from April 2002 to March 2004 were cited from Takakai \textit{et al.} (2006). Values between parentheses indicate one-side 95% confidence interval. Asterisk showed there was significant difference in N\textsubscript{2}O emission between conventional and bare treatments at 5% significant level.

<table>
<thead>
<tr>
<th>Year</th>
<th>CL-A Conventional</th>
<th>CL-A Bare</th>
<th>CL-B Conventional</th>
<th>CL-B Bare</th>
<th>CL-C Conventional</th>
<th>CL-C Bare</th>
<th>CL-C Conventional</th>
<th>CL-C Bare</th>
<th>GL Conventional</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002/4-2003/3</td>
<td>121 (28.5)</td>
<td>-</td>
<td>20.8 (3.42)</td>
<td>-</td>
<td>76.9 (19.9)</td>
<td>-</td>
<td>20.8 (4.20)</td>
<td>-</td>
<td>5.08 (0.56)</td>
</tr>
<tr>
<td>2003/4-2004/3</td>
<td>229 (32.1)</td>
<td>-</td>
<td>46.1 (5.55)</td>
<td>-</td>
<td>108 (11.9)</td>
<td>-</td>
<td>20.8 (4.20)</td>
<td>-</td>
<td>20.8 (4.20)</td>
</tr>
<tr>
<td>2004/4-2005/3</td>
<td>416 (16.1)</td>
<td>-</td>
<td>51.8 (6.28)</td>
<td>-</td>
<td>36.2 (13.0)</td>
<td>-</td>
<td>31.1 (5.50)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2005/4-2006/3</td>
<td>627 (8.25)</td>
<td>608 (24.9)</td>
<td>12.6 (1.95)</td>
<td>7.38 (0.50)*</td>
<td>73.7 (6.12)</td>
<td>35.4 (1.12)*</td>
<td>65.9 (5.38)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2006/4-2007/3</td>
<td>698 (69.1)</td>
<td>858 (37.4)</td>
<td>10.9 (8.86)</td>
<td>6.55 (1.64)</td>
<td>168 (14.5)</td>
<td>216 (2.46)</td>
<td>32.3 (2.16)</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>580</td>
<td>733</td>
<td>25.1</td>
<td>6.96</td>
<td>92.5</td>
<td>126</td>
<td>43.1</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

Average (2004/4-2007/3)
Fig. 1 Seasonal variation in air temperature and precipitation (a), water table (b), soil temperature (c), water filled pore space (WFPS) (d), ammonium (NH$_4^+$), nitrate (NO$_3^-$) concentrations (e), and carbon dioxide (CO$_2$) (f) and nitrous oxide (N$_2$O) fluxes (g) in cropland A (CL-A) in Central Kalimantan, Indonesia. Conventional and Bare represents conventional cultivation treatment and bare treatment, respectively. Ammonium and NO$_3^-$ concentrations (e) are only in conventional treatment. Error bars are standard deviation.
Fig. 2 Seasonal variation in air temperature and precipitation (a), water table (b), soil temperature (c), water filled pore space (WFPS) (d), ammonium (NH$_4^+$), nitrate (NO$_3^-$) concentrations (e), and carbon dioxide (CO$_2$) (f) and nitrous oxide (N$_2$O) fluxes (g) in cropland B (CL-B) in Central Kalimantan, Indonesia. Conventional and Bare represents conventional cultivation treatment and bare treatment, respectively. Ammonium and NO$_3^-$ concentrations (e) are only in conventional treatment. Error bars are standard deviation.
Fig. 3 Seasonal variation in air temperature and precipitation (a), water table (b), soil temperature (c), water filled pore space (WFPS) (d), ammonium (NH$_4^+$), nitrate (NO$_3^-$) concentrations (e), and carbon dioxide (CO$_2$) (f) and nitrous oxide (N$_2$O) fluxes (g) in cropland C (CL-C) in Central Kalimantan, Indonesia. Conventional and Bare represents conventional cultivation treatment and bare treatment, respectively. Ammonium and NO$_3^-$ concentrations (e) are only in conventional treatment. Error bars are standard deviation.
Fig. 4 Seasonal variation in air temperature and precipitation (a), water table (b), soil temperature (c), water filled pore space (WFPS) (d), ammonium (NH$_4^+$), nitrate (NO$_3^-$) concentrations (e), and carbon dioxide (CO$_2$) (f) and nitrous oxide (N$_2$O) fluxes (g) in grassland (GL) in Central Kalimantan, Indonesia. Error bars are standard deviation.
Fig. 5 Relationships between logarithmic value of the ratio of nitrous oxide (N$_2$O) flux and soil nitrate (NO$_3^-$) concentration ($\ln$($N_2O$ flux / $NO_3^-$)) against water filled pore space (WFPS) in conventional treatment in cropland A (CL-A), cropland B (CL-B), cropland C (CL-C), and grassland (GL) in Central Kalimantan, Indonesia.