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

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Running title: N_2O emission from agricultural peat soil

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ABSTRACT

Our previous research showed large amounts of nitrous oxide (N_2O) emission (> 200 kg N ha^{-1} yr^{-1}) from agricultural peat soil. In this study, we investigated the factors influencing relatively large N_2O fluxes and the source of nitrogen (N) substrate for N_2O in a tropical peatland in Central Kalimantan, Indonesia. Using a static chamber method, N_2O 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_2O emission from two treatments, contribution of the N source for N_2O was calculated. Nitrous oxide concentrations at five depths (5-80 cm) were also measured for calculating net N_2O 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_2O fluxes in the two treatments at each site. Annual N_2O 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_2O emissions in the two treatments at each site. This suggests most of the emitted N_2O was derived from the decomposition of peat. There were significant positive correlations between N_2O and CO_2 fluxes in bare treatment in two croplands where N_2O flux was higher than at another cropland. Nitrous oxide concentration distribution in soil measured in the conventional treatment showed that N_2O was mainly produced in the surface soil down to 15 cm in the soil. The logarithmic value of the ratio of N_2O flux and nitrate concentration was positively correlated with water filled pore space. These results suggest that large N_2O emission in agricultural tropical peatland was caused by denitrification with high decomposition of peat. In addition, N_2O 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_2O) emission (Takakai *et al*. 2006; Terry *et al*. 1981). Increasing atmospheric N_2O 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_2O (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_2O (16.2 Tg N yr^{-1}) (IPCC 1995). There are, however, several studies documenting N_2O 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_2O emission study in agricultural tropical peatland is that factors influencing N_2O emission and the sources of N for N_2O emission have still been unclear. Several studies in agricultural boreal peatland (e.g. in Finland and Norway) have reported that N_2O 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_2O emission from agricultural fields on mineral soils (0.9-6.4 kg N ha^{-1} yr^{-1}, Bouwman *et al.*

2002). On the other hand, N_2O 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^{-1} yr^{-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_2O 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_F) induced by applied N fertilizer, N_2O emission induced by cultivation of peatland is important for the calculation of annual N_2O emission from agricultural fields on peatland. In the subarctic zone, Regina *et al*. (2004) reported N_2O emission from grass, barley and potato vegetation plots (2.6-24.1 kg N ha^{-1} yr^{-1}) were smaller relative to fallow plots (3.8-37 kg N ha^{-1} yr^{-1}) on boreal peatland in Finland. This means N source for N_2O emission from soil organic matter (SOM) was larger than N_2O emission induced by the application of N fertilizer. Moreover, Regina *et al*. (2004) reported that average N_2O emission induced by SOM was 10.4 kg N ha^{-1} yr^{-1}. Although, index of N_2O emission induced by cultivation in tropical peatland was proposed by IPCC (2006) to be 16 kg N ha^{-1} yr^{-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_2O 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 N_2O 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 N_2O dynamics in boreal or temperate peatland to tropical peatland.

Takakai *et al*. (2006) reported large amount of annual N_2O 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, N_2O 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 N_2O emission induced by the cultivation of peatland, and possibly be over- or underestimated. Understanding the mechanisms of such high N_2O production and emission in agricultural tropical peatland will be essential for quantifying N_2O emission and developing the mitigation method for N_2O emission. The objectives of our study were to clarify the factors that influence N_2O emission, identifying the source of N substrate for N_2O, and to quantify annual N_2O 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 m^2 (1m x 0.5m) in area, were established in CL-A, CL-B, and CL-C in April 2004 for estimating N_2O

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 CO_2 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 month from April 2004 to February 2006 and twice a month after March 2006 to March 2007. We followed N_2O and CO_2 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 N_2O and CO_2 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 N_2O 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 (EF_F)

Gas samples stored in Tedlar bags for analysis of CO_2 concentration and in vacuum vials for the analysis of N_2O concentration were analyzed within 12 hour and a month, respectively,

after collecting these samples. Nitrous oxide and CO_2 concentrations were analyzed with a gas chromatograph (GC-14B, Shimadzu, Kyoto, Japan) equipped with an electron-capture detector and CO_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_2O emissions were calculated by linear integration of flux measurements during the measurement period (Toma and Hatano 2007; Toma *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:

$$EF_F\ (\%) = (N_2O_C - N_2O_B) / (\text{applied chemical and organic N}) \times 100$$

where N_2O_C is the annual N_2O emission in the conventional treatment (kg N ha^{-1} yr^{-1}) and N_2O_B is the annual N_2O emission in bare treatment (kg N ha^{-1} yr^{-1}). EF_F was calculated when there was a significant difference in N_2O emission between conventional and bare treatments. Otherwise, EF_F was defined as 0%.

Calculation of net nitrous oxide production rate in soil

Net N_2O production rate is the difference between gross N_2O production rate and gross N_2O consumption rate. Net N_2O production rate was calculated using the following equation based on Fick's Law (gradient method; Granli and Bøckman 1994):

$$\text{Net } N_2O \text{ production rate} = F(I+1) - F(I)$$

where F is the gas flux (mg m^{-2} s^{-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_2O production rate from the soil layer of 0-2.5, 2.5-7.5, 7.5-15, 15-30, and 30-60-cm depths.

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_2O 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_2O fluxes or annual N_2O emissions between conventional and bare treatments were performed using Student's *t*-test (parametric) based on studies that report N_2O flux shows a log-normal distribution (Van-Cleemput *et al*. 1994; Velthof and Oenema 1995). Therefore, values of N_2O flux or annual N_2O 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_2O 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(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_2O 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_2O 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_2O 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_2O 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 $y = 0.023x - 0.584$, $R = 0.55$, $P < 0.05$; CL-B $y = 0.0005x - 0.078$, $R = 0.64$, $P < 0.05$; CL-C $y = 0.0019x - 0.037$, $R = 0.30$, $P = 0.18$; GL $y = 0.0011x - 0.134$, $R = 0.57$, $P < 0.05$). There were no significant differences in N_2O 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 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 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 NH_4^+ and 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 N_2O flux and water table depth, soil temperature, NH_4^+ or NO_3^- contents (Table 4). However, N_2O flux in CL-A, CL-B, and GL significantly increased with increasing WFPS. In addition, N_2O fluxes in CL-A and CL-C, in which N_2O fluxes were relatively high compared with CL-B and GL, were significantly and positively correlated with CO_2 fluxes (Table 4). Although not significant, N_2O increased with increasing 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 N_2O flux and soil NO_3^- concentration at log scale $\{Ln(N_2O/NO_3^-)\}$ were significantly correlated with WFPS (Fig. 5). However, the slope of $Ln(N_2O/NO_3^-)$ 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 N_2O 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 N_2O 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 N_2O emissions in conventional treatments were larger than of those in CL-B or GL. Annual N_2O

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_2O emissions were generally greater than 20 kg N ha^{-1} yr^{-1} (Table 5). Average annual N_2O emissions in bare treatment in CL-A, CL-B, and CL-C were 733, 6.96 and 126 kg N ha^{-1} yr^{-1}, respectively (Table 5). Significant differences in annual N_2O emissions between conventional and bare treatments were observed in CL-B and CL-C during April 2005 to March 2006. Annual N_2O, however, emissions in bare treatments in CL-A, CL-B, and CL-C were parallel to annual N_2O emission in the conventional treatments (Table 5). EF_F was calculated only during April 2005 to March 2006 in CL-B and CL-C site, where annual N_2O emissions between the two treatments were significantly different (Table 5). EF_F in CL-B and CL-C were 0.81 and 3.59 %, respectively. At another site and period, EF_F was 0% because there were no significant differences in annual N_2O emission between the conventional and bare treatments. From these values, annual N_2O emission induced by N fertilizer and derived from N in SOM were estimated to 5.21 and 7.38 kg N ha^{-1} yr^{-1} in CL-B and 38.3 and 35.4 kg N ha^{-1} yr^{-1} in CL-C, respectively, during April 2005 to March 2006. In addition, the proportion of annual N_2O emission derived from SOM N to annual N_2O 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 N_2O fluxes from October to May (Figs. 1g-4g) and significant correlation between 3-month average N_2O flux and precipitation suggest that N_2O was actively produced during the rainy season. Werner-Riddle *et al*. (2007) reported large pulse fluxes of N_2O 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 N_2O flux was significantly correlated with soil NO_3^- concentration at or above 60-70 % WFPS in the same field of this study. While clear relationships between N_2O flux and water table depth, soil temperature, NH_4^+ or NO_3^- concentrations in all sites were not observed (Table 4), significant correlations between N_2O flux and WFPS in CL-A, CL-B, GL or between $Ln(N_2O/NO_3^-)$ and WFPS in all sites indicated that N_2O 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, N_2O is mostly reduced to N_2 when WFPS is greater than 70 % (Davidson *et al*. 2000). However, linear relationships between $Ln(N_2O/NO_3^-)$ and WFPS in the conventional treatment in each site suggested that N_2O was not substantially reduced at high WFPS (Fig. 5). This indicates that N_2O reductase (*nos*) in N_2O-producing microbes in soil might be inactive even at high WFPS (i.e. above 70%). In acidic soils, higher N_2O:N_2 fraction for denitrification were reported (Alexander 1977). Dannenmann *et al*. (2008) reported N_2:N_2O 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 N_2O:N_2 ratio increased with decreasing soil pH. In our study site, pH in surface soil was lower than 6.0. Thus, the reaction of N_2O to N_2 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 *nos* of *Janthinobacterium* spp. Furthermore, Yanai *et al*. (2007) reported N_2O-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 N_2O 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 N_2O flux in both conventional and bare treatments clearly showed the increase in N_2O flux in rainy season. In addition, differences in N_2O fluxes between conventional and bare treatments were not observed (Table 2). Those suggest that N_2O 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 N_2O emission between conventional and bare treatments in CL-A, CL-B, and CL-C also were not observed. Net N_2O 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 N_2O produced in conventional treatment probably did not influence N_2O flux in the bare treatments. Therefore, those indicated the source of N for N_2O production was mainly derived from SOM in peat. Ammonium and NO_3^- concentrations in soil in bare treatments were lower than in the conventional treatments. In addition, CO_2 flux in conventional treatment in CL-A and CL-C, in which high N_2O fluxes were observed, was significantly correlated with N_2O flux (Table 4). Therefore, the limiting factor of N_2O production is the decomposition of SOM in peat. After decomposition of SOM, mineralized

organic N was possibly nitrified and denitrified quickly to N_2O. Takakai *et al*. (2007) reported CO_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_2 emission between conventional and bare treatments in all plots due to the high decomposition rate of SOM (Takakai *et al*. 2007). This indicated that decomposition of SOM in peat was accelerated in rainy season and production of CO_2 was mainly induced by the decomposition of SOM, but not root respiration. Nitrous oxide flux tended to increase with increasing CO_2 flux in bare treatment in CL-A and CL-B. Thus, N_2O production might be closely influenced by the decomposition of SOM in peat. Also, N_2O-producing bacteria or fungi (e.g. *Janthinobacterium* spp., *Fusarium oxysporum*, and *Neocosmospora vasinfecta*) probably were important decomposers of peat during the rainy season (Yanai *et al*. 2007; Hashidoko *et al*. 2008).

Nitrous oxide emission in agricultural peat land

Because there were no significant differences in N_2O flux between conventional and bare treatments in CL-A, CL-B, and CL-C (Table 2), increase in annual N_2O emission could not be due to increase in annual fertilizer N application rate. Thus, the correlation between annual N_2O emission and annual fertilizer N application rate might indicate the influence of long-term management on annual N_2O 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 *et al*. (2003) reported difference in annual N_2O 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_2O 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_2O 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_2O emission from agricultural peat soil in tropical region.

Annual N_2O 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_2O emissions were greater than annual N_2O 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_2O 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_2O emissions in this study were also greater than N_2O 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_2O emission from agricultural fields in our study field might be the highest value reported to date. Absence of the difference in annual N_2O 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_2O in conventional treatment derived from the decomposition of SOM. Therefore, larger annual N_2O emission compared with N_2O 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_2O production by denitrification. Kasimir-Klemedtsson *et al*. (2009) reported N_2O 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_2O 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_2O emission from tropical agricultural peat soil. Currently, there are not many studies about N_2O emission in agricultural fields on tropical peat soil. Additional research regarding N_2O emission from agricultural fields on tropical peat soil, therefore, is needed because large amounts of N_2O 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_2O was derived from the decomposition of SOM. Even when the difference in annual N_2O emission was detected, the ratio of N_2O emission induced by fertilizer N and derived from SOM decomposition was almost equal (48-58.6%). Since annual N_2O 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_2O emission derived from SOM might be influenced by cultivation or land-use change from natural forest to agricultural field. Indeed, the N_2O emission factor induced by the cultivation in tropical peat soil (16 kg N ha^{-1} yr^{-1}) estimated by IPCC (2006) was calculated using the data in boreal peat soil (8 kg N ha^{-1} yr^{-1}). However, estimated N_2O emission originated from

decomposition of SOM exceeded the value provided from IPCC (2007), whereas N_2O emission derived from SOM in other agricultural peat soil reported by Melling *et al*. (2007) and Hadi *et al*. (2005) might be lower because N_2O emissions from those study site were lower than 4 kg N ha^{-1} yr^{-1} despite application of N fertilizer at those sites. This indicated that the N_2O emission derived from decomposition of SOM in tropical agricultural peat soil might vary widely. Thus, additional research on N_2O 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_F value of this study (0-3.59%) was smaller than the range reported by Takakai *et al*. (2006) (1.8-36 %) in our study field. Because Takakai *et al*. (2006) used N_2O emission values from GL as the estimate for N_2O emission in CL-A, CL-B, and CL-C, EF_F may have been overestimated due to spatial variation of N_2O emission among the sites. However, the EF_F values in this study were similar or higher than the 1.00 % value reported by IPCC (2006). Akiyama *et al*. (2006) summarized published data and reported that EF_F in well- and poorly drained soil were 0.32 and 1.40 %, respectively. Bouwman (1996) reported EF_F of chemical and organic fertilizer ranged from 0.1 to 1.6 % on mineral soil. Thus, EF_F values in our study were similar or slightly higher than other agricultural fields on mineral soil. On the other hand, EF_F, on dry and wet Histosols in Netherlands were 4.21 and 1.38 %, respectively (Van Beek *et al*. 2010). Although more work is needed to normalize EF_F values in agricultural peat land in tropical regions, EF_F value in Histosols may be higher than in mineral soils.

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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_2O) 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_2O) 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_2O) 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_2O) 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_2O) 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.

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).

Year	Nitrogen fertilizer application rate (kg N ha^{-1} yr^{-1})								
	CL-A			CL-B			CL-C		
	Chemical	Organic	Total	Chemical	Organic	Total	Chemical	Organic	Total
2002/4-2003/3	818	180	998	760	40	800	1,098	180	1,278
2003/4-2004/3	545	120	665	853	100	953	665	120	785
2004/4-2005/3	1,378	180	1,558	633	140	773	1,011	196	1,207
2005/4-2006/3	1,505	120	1,625	460	184	644	945	120	1,065
2006/4-2007/3	1,458	180	1,638	0	0	0	945	120	1,065
Average (2004/4-2007/3)	1,447	160	1,607	365	108	472	967	145	1,113

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.

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

§ 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.

Depth	Net N_2O production rate (mg N m^{-2} hr^{-1})											
(cm)	CL-A			CL-B			CL-C			GL		
	Average	max	min	Average	max	min	Average	max	min	Average	max	min
0-2.5	-3.34	17.9	-63.2	-0.30	1.13	-8.87	1.67	5.51	-0.09	-3.45	1.28	-16.01
2.5-7.5	4.77	60.2	-19.6	0.61	15.8	-1.40	0.32	2.58	-1.25	4.14	17.48	-0.13
7.5-15	6.36	81.7	-16.2	-0.15	1.81	-6.75	0.35	3.20	-0.30	-0.27	1.22	-4.58
15-30	2.66	23.0	-6.80	-0.02	0.26	-0.43	0.03	0.48	-0.97	-0.09	1.27	-3.30
30-60	-0.95	0.02	-2.31	0.002	0.006	0.001	-0.11	0.01	-0.55	0.09	0.74	-0.53

Table 4 Spearman's rank correlation coefficients of nitrous oxide (N_2O) 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.

	CL-A	CL-B	CL-C	GL
Water table depth (cm)	-0.01	0.03	0.53**	0.26
Soil Temperature (℃)	-0.04	-0.18	0.15	-0.12
WFPS (%)	0.59**	0.52**	0.18	0.66**
NH_4^+ (mg N kg^{-1})	-0.13	0.11	0.08	-0.28
NO_3^- (mg N kg^{-1})	-0.27	0.51**	0.38**	0.06
CO_2 flux (g C m^{-2} hr^{-1})	0.34*	0.28	0.49**	0.24

** $P < 0.01$, * $P < 0.05$

Table 5 Annual nitrous oxide (N_2O) 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_2O emission from April 2002 to March 2004 were cited from Takakai *et al*. (2006). Values between parentheses indicate one-side 95% confidence interval. Asterisk showed there was significant difference in N_2O emission between conventional and bare treatments at 5% significant level.

Year	Annual N_2O emission (kg N ha^{-1} yr^{-1})						
	CL-A		CL-B		CL-C		GL
	Conventional	Bare	Conventional	Bare	Conventional	Bare	Conventional
2002/4-2003/3	121 (28.5)	-	20.8 (3.42)	-	76.9 (19.9)	-	5.08 (0.56)
2003/4-2004/3	229 (32.1)	-	46.1 (5.55)	-	108 (11.9)	-	20.8 (4.20)
2004/4-2005/3	416 (16.1)	-	51.8 (6.28)	-	36.2 (13.0)	-	31.1 (5.50)
2005/4-2006/3	627 (8.25)	608 (24.9)	12.6 (1.95)	7.38 (0.50)*	73.7 (6.12)	35.4 (1.12)*	65.9 (5.38)
2006/4-2007/3	698 (69.1)	858 (37.4)	10.9 (8.86)	6.55 (1.64)	168 (14.5)	216 (2.46)	32.3 (2.16)
Average (2004/4-2007/3)	580	733	25.1	6.96	92.5	126	43.1

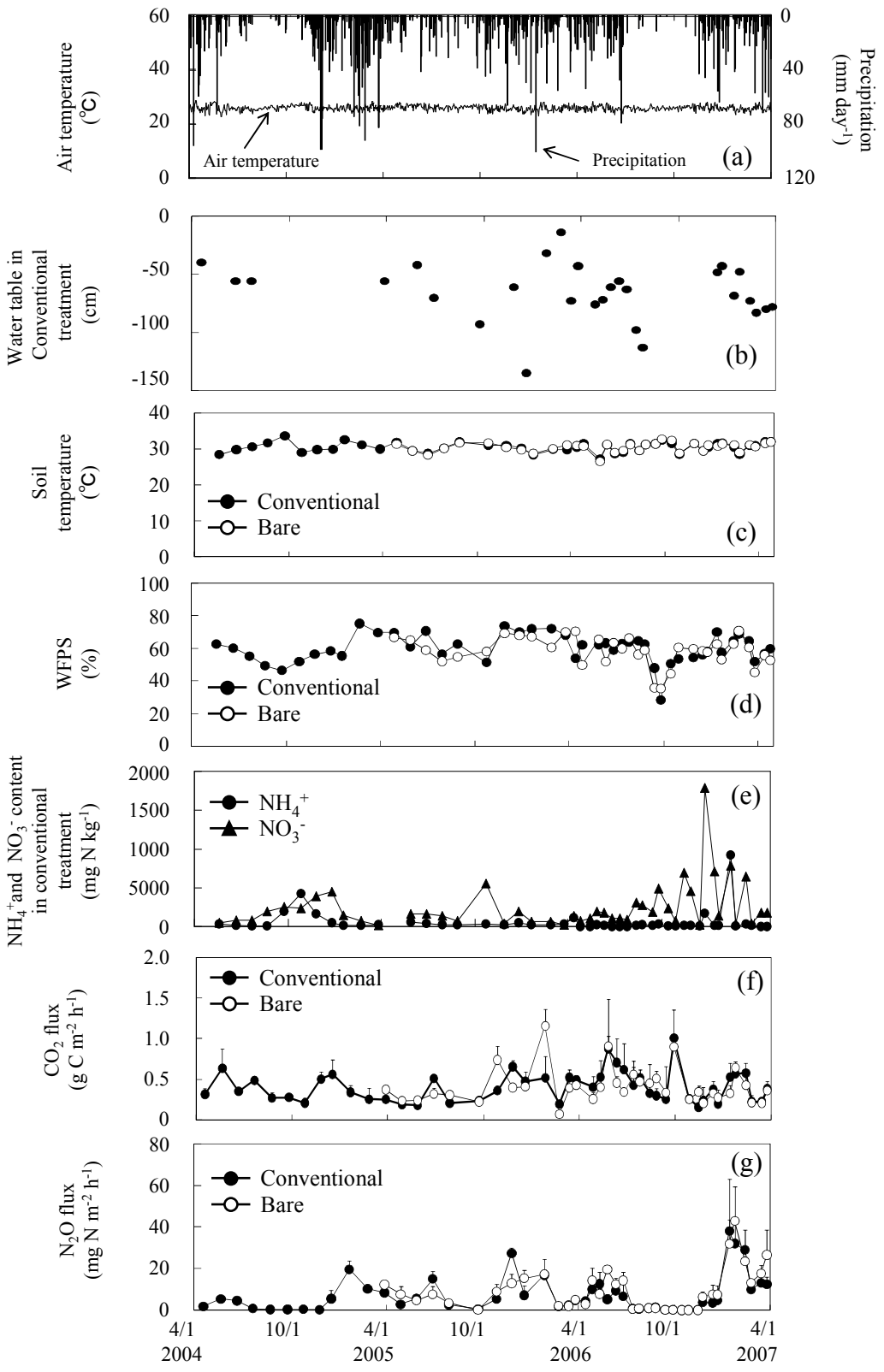

Fig. 1 Seasonal variation in air temperature and precipitation (a), water table (b), soil temperature (c), water filled pore space (WFPS) (d), ammonium (NH_4^+), nitrate (NO_3^-) concentrations (e), and carbon dioxide (CO_2) (f) and nitrous oxide (N_2O) fluxes (g) in cropland A (CL-A) in Central Kalimantan, 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.

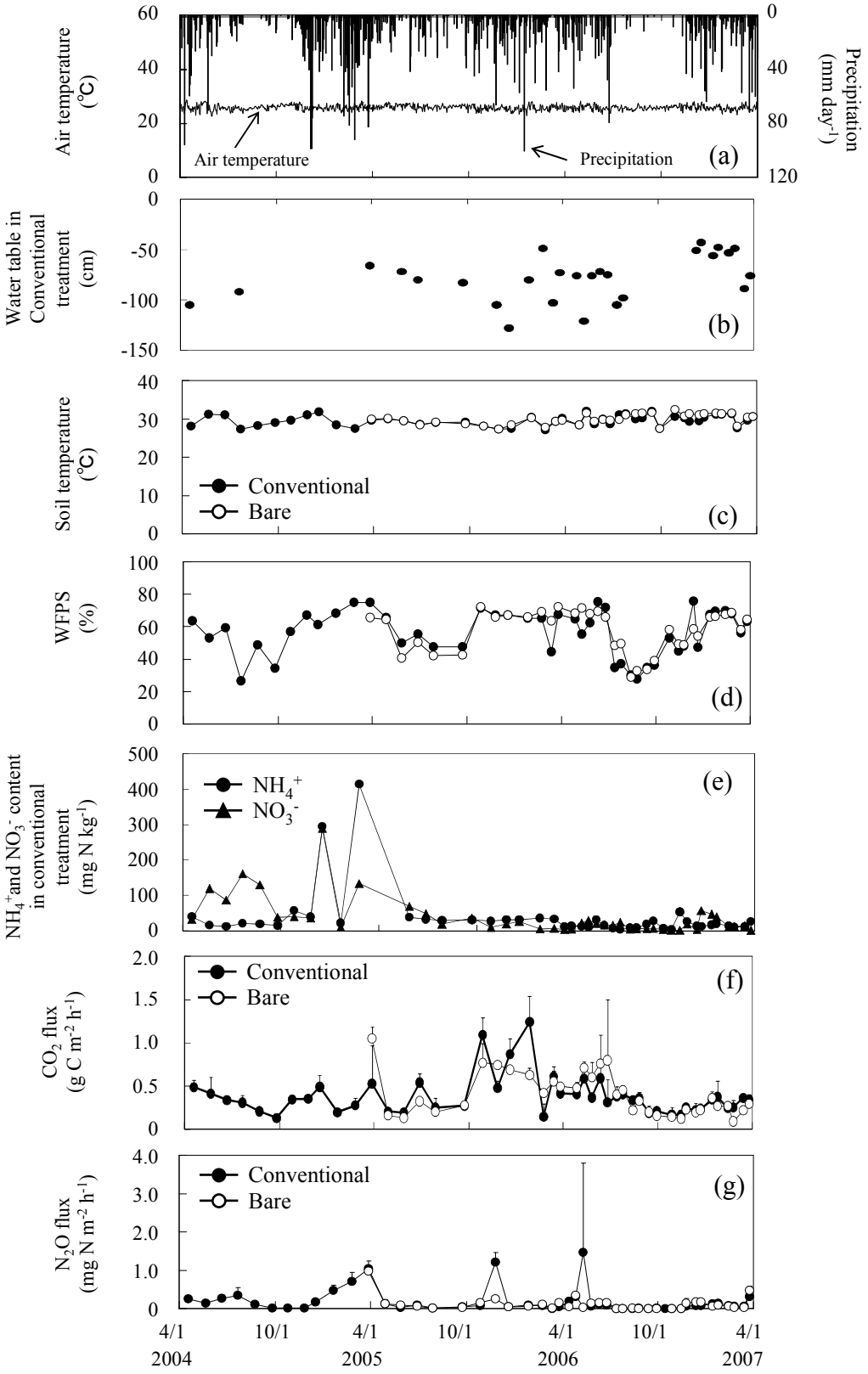

Fig. 2 Seasonal variation in air temperature and precipitation (a), water table (b), soil temperature (c), water filled pore space (WFPS) (d), ammonium (NH_4^+), nitrate (NO_3^-) concentrations (e), and carbon dioxide (CO_2) (f) and nitrous oxide (N_2O) fluxes (g) in cropland B (CL-B) in Central Kalimantan, 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.

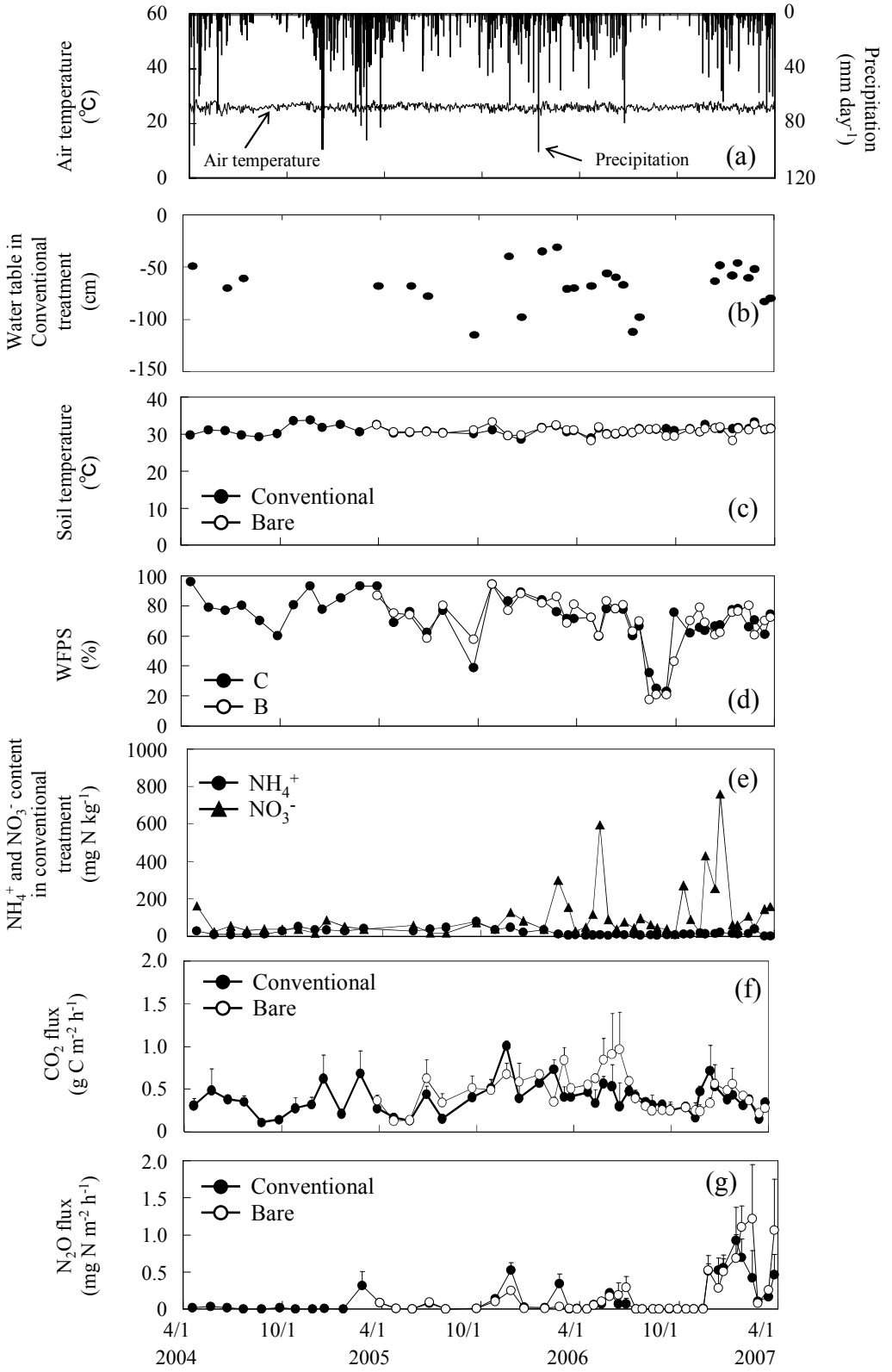

Fig. 3 Seasonal variation in air temperature and precipitation (a), water table (b), soil temperature (c), water filled pore space (WFPS) (d), ammonium (NH_4^+), nitrate (NO_3^-) concentrations (e), and carbon dioxide (CO_2) (f) and nitrous oxide (N_2O) fluxes (g) in cropland C (CL-C) in Central Kalimantan, 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.

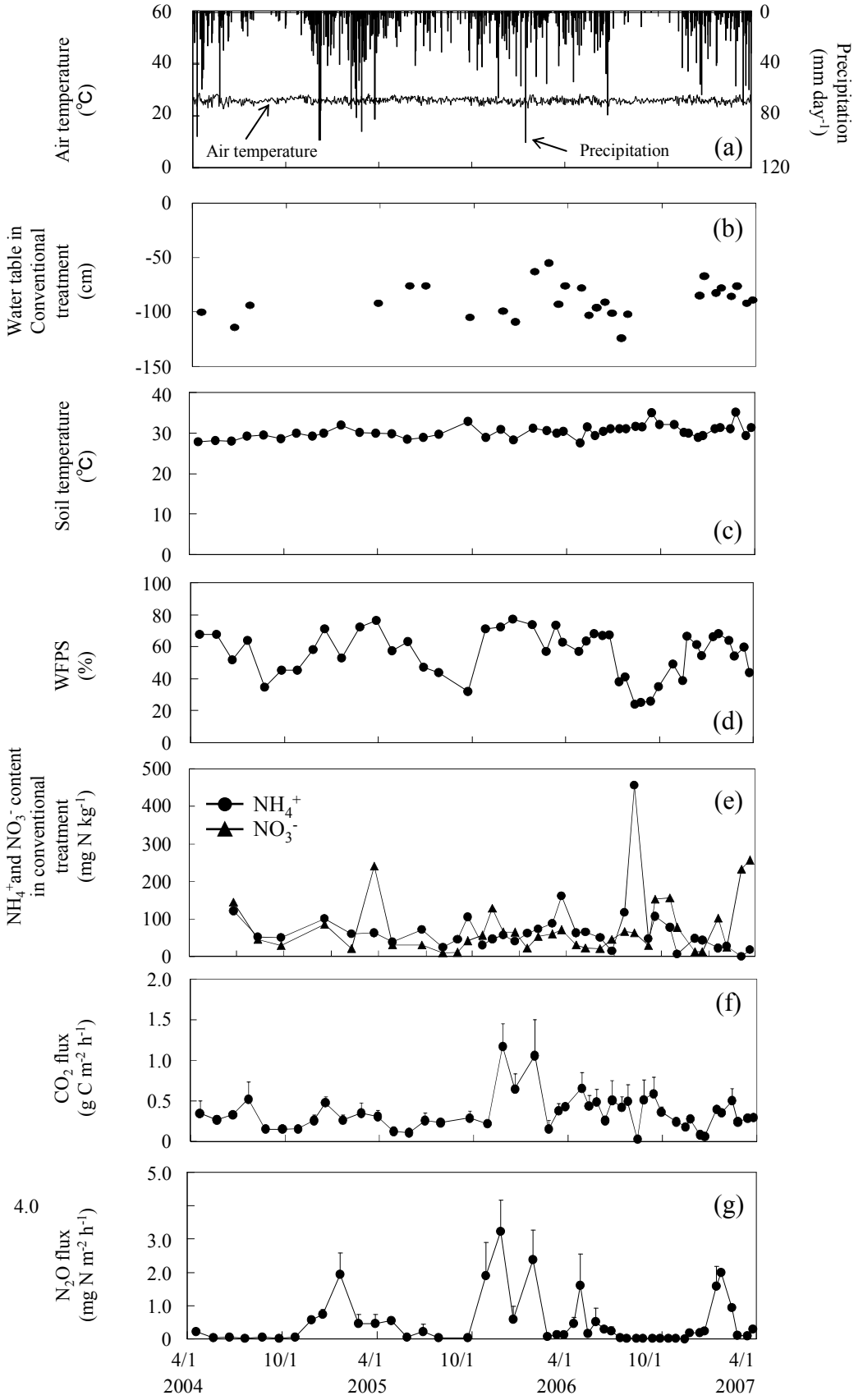

Fig. 4 Seasonal variation in air temperature and precipitation (a), water table (b), soil temperature (c), water filled pore space (WFPS) (d), ammonium (NH_4^+), nitrate (NO_3^-) concentrations (e) , and carbon dioxide (CO_2) (f) and nitrous oxide (N_2O) fluxes (g) in grassland (GL) in Central Kalimantan, Indonesia. Error bars are standard deviation.

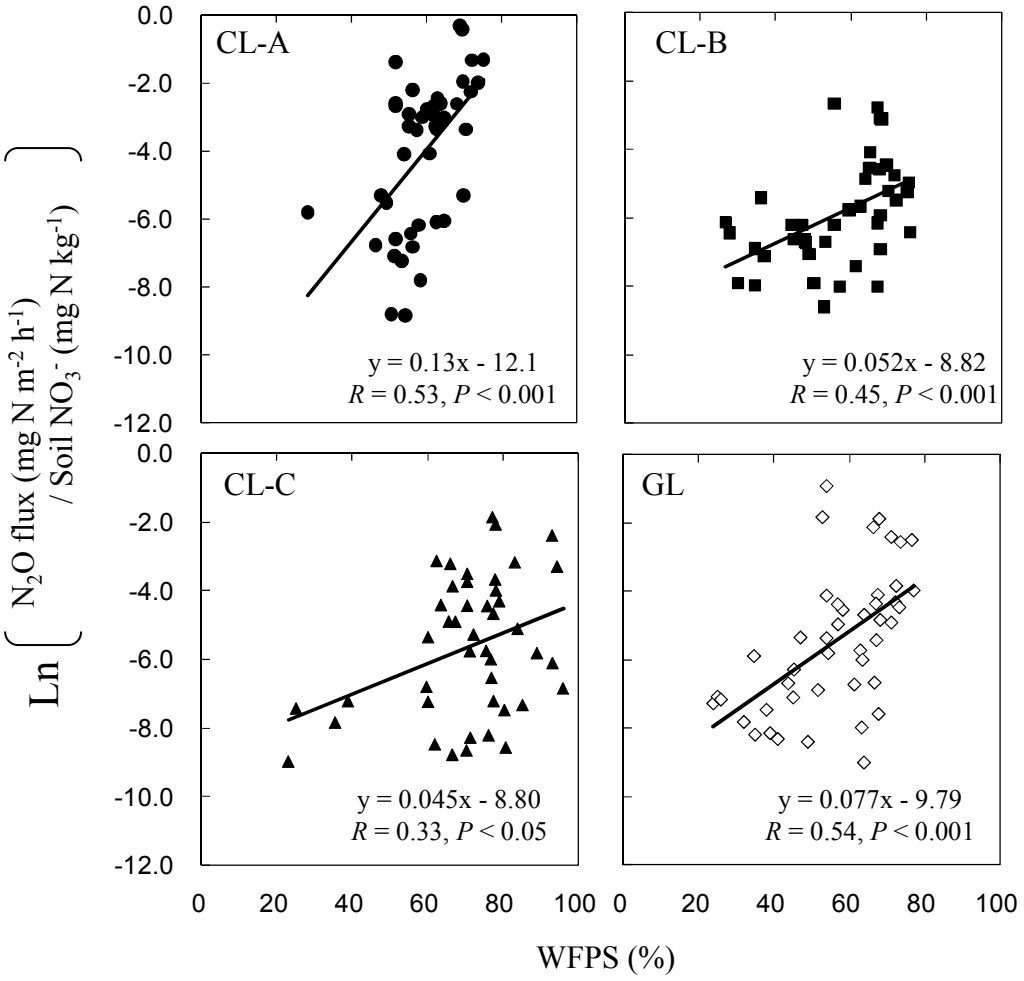

Fig. 5 Relationships between logarithmic value of the ratio of nitrous oxide (N_2O) flux and soil nitrate (NO_3^-) concentration ($Ln(N_2O\ flux / NO_3^-)$) against water filled pore space (WFPS) in conventional treatment in cropland A (CL-A), cropland B (CL-B), cropland C (CL-C), and grassland (GL) in Central Kalimantan, Indonesia.