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Nitrous oxide fluxes from tropical peat with different disturbance history and management

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Abstract

Tropical peatlands are one of the most important terrestrial ecosystems in terms of C stocks, and greenhouse gas emissions following disturbances such as deforestation, drainage or wildfire. Nitrous oxide dynamics in tropical peat systems is still poorly known. We quantified in situ N_2O fluxes using closed chamber methods and compared them with CO_2 and CH_4 fluxes at sites representing differing land uses and land use change intensities, i.e. non-drained and drained selectively logged peat swamp forest, clear-felled drained recovering forest, deforested drained and burned peat, and agriculture on peat.

The mean N_2O flux rates (N_2O-N $\pm$ SD, mg m^{-2} h^{-1}) varied as follows: drained forest (0.112 ± 0.293) > agricultural peat in Kalampangan site (0.012 ± 0.026) > drained burned peat (0.011 ± 0.018) > agricultural peat in Marang site (0.0072 ± 0.028) > nondrained forest (0.0025 ± 0.053) > clear-felled drained recovering forest (0.0022 ± 0.021). Most N_2O fluxes were < 0.05 mg N_2O-N m^{-2} h^{-1} efflux, but some modest peat N_2O influx readings were also detected. Many very high flux rates (deviating markedly from the majority of observations) occurred both spatially and over time, and further studies using continuous flux monitoring methods are needed to better understand the contribution of these to cumulative emissions.

The widest N_2O flux amplitude was detected in the drained forest with moderately drained peat (max. 2.312 and min. -0.043 mg N_2O-N m^{-2} h^{-1}). At the other sites the flux amplitude remained about 10 × smaller. Annual cumulative peat surface N_2O emissions expressed as CO_2 equivalents as a percentage of the total greenhouse gas (N_2O, CO_2 and CH_4) emissions was at the highest 9.2 %, but typically ~1 %.

1 Introduction

Global warming is strongly linked to the atmospheric concentrations of the greenhouse gases (GHGs), where especially carbon dioxide (CO_2), methane (CH_4),

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chlorofluorocarbon CFC-12, and nitrous oxide (N_2O) have the highest radiative forcing impact (Solomon et al., 2007). The atmospheric concentration of N_2O has increased already by 44 ppb (17 %) since pre-industrial times. N_2O is very stable in the atmosphere with a lifetime of approximately 114 years, and it has the global warming potential (GWP) of 298 times that of CO_2 on a 100-year perspective.

Soil is considered to be one of the key sources of N_2O to the atmosphere and to contribute approximately 60 % of the emissions globally (Ehhalt et al., 2001). N_2O exchange between soil and the atmosphere is concurrent with CO_2 and CH_4 exchange. Processes involved in the dynamics of these GHG gases are controlled by several factors, including soil moisture status, temperature and mineral nitrogen concentration (e.g. Martikainen et al., 1993; Maljanen et al., 2003; Melling et al., 2007). CH_4 emissions are highest under strictly anaerobic conditions in soil, whereas CO_2 emissions are promoted by aerobic conditions (Moore and Knowles, 1989). N_2O emissions from soils are produced by the microbiological processes of nitrification (conversion of NH_4^+ to NO_3^-) and denitrification (NO_3^- to N_2O or N_2), and maximum emissions are typical for intermediate conditions between aerobic and anaerobic states in soil (Davidson et al., 2000). The source of N_2O is often uncertain because denitrification and nitrification processes can occur simultaneously in the same soil aggregate (Davidson et al., 1986). Although the main gas flux direction is from soil surface to the atmosphere, also influxes (gas uptake to soil) have been detected for N_2O (e.g. Pihlatie et al., 2005; Takakai et al., 2006; Hyvönen et al., 2009) and CH_4 (e.g. Mäkiranta et al., 2007; Jauhainen et al., 2008; Maljanen et al., 2010). Methane influx can take place under aerobic conditions where methanotrophic bacteria use CH_4 as an energy source and the gas consumption exceeds the production in soil. The mechanisms of N_2O influx to soil are uncertain.

Most of the published data on N_2O fluxes in organic soils are for boreal (Maljanen et al., 2010, and references therein) peatlands, whereas limited data are available for tropical peatland (e.g. Hadi et al., 2000; Inubushi et al., 2003; Kiese et al., 2003; Furukawa et al., 2005; Takakai et al., 2006; Melling et al., 2007). Tropical peat swamp forests may form one of the most efficient terrestrial ecosystems reducing global atmospheric GHG

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increase because this ecosystem combines high carbon sequestration capacity, and also carbon accumulation and conservation (as peat) in the forest floor that is annually waterlogged for prolonged periods of time. The estimated current tropical peat carbon store is 88.6 Gt (range 81.7–91.9 Gt) and it comprises 15–19 % of the global peat carbon resources (Page et al., 2011). An extensive conversion and drainage of tropical peatlands in South-East Asia has enhanced carbon losses by reducing peatland carbon sink potential, and increasing carbon emissions by fires and biological oxidation, in which estimated oxidative emissions were 355–855 Mt yr^{-1} in 2006 (Hooijer et al., 2010). The role of tropical peat as a GHG sink and source has been evaluated mainly by considering only CO_2 and CH_4 gas fluxes. Possibilities to compare fluxes on all three major peat related GHG gases, i.e. CO_2, CH_4 and N_2O, and their combined GWP impact is limited in most tropical peat studies.

In this study we measured N_2O flux direction and rate at the peat surface in typical in situ hydrological conditions in tropical peat and compared cumulative N_2O fluxes with the concurrent other two most important GHG fluxes. Firstly, we determined N_2O flux dynamics and cumulative fluxes in relation to peat hydrology in typical conditions prevailing in nondrained and drained peat under five land use types (non-drained forest, drained forest, drained recovering forest, clear-felled mismanaged peat, and agricultural land). Secondly, we compared the cumulative N_2O fluxes with concurrent CO_2 and CH_4 emissions at the same monitoring sites.

2 Methods

2.1 Study sites

Study sites were within ~20 km of Palangkaraya city in Central Kalimantan Province, Indonesia. The climate in the area is characterized by relatively unvarying temperature, high humidity, and high rainfall intensity. The mean monthly temperature varies between 24 °C and 27 °C. The mean annual rainfall varies between 1900 mm

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and 3000 mm along the southern coast of Borneo, with an overall average of around 2700 mm in the study area. The wettest months are December–February and the driest months are August and September. Evapotranspiration exceeds average monthly rainfall typically in July–September. The average evapotranspiration is fairly constant with an annual total of around 1350 mm (Hooijer et al., 2008).

The selected five gas flux monitoring sites included 3 under forest, i.e. nondrained forest (NDF), drained forest (DF), and clear-felled but recovering forest (DRF). Clear-felled open peat areas included a drained burned site (DBP) and 2 sites drained for agriculture (AP_Ka and AP_Ma) but where subsequent N fertilizer input was either very low or did not occur. Most of the sites were located near the northeast corner of the Block-C in the Ex-Mega Rice Project (EMRP) area. The EMRP is currently one of the largest continuous areas of degraded tropical peat (about 1 000 000 ha) in Central Kalimantan. In this area, land largely located on deep peat was clear-felled for food production purposes, and the area was drained in the mid 1990's. The area is abandoned for most parts because it was found unsuitable for intended food production, primarily due to difficulties in controlling peat water table depth and demanding physico-chemical peat properties for agriculture. Three gas flux monitoring sites (drained and clear-felled recovering forest, drained burned site) were close to the northwestern border of the EMRP area at Sebangau river. The non-drained forest site was in an extensive forest area starting on the other side of the river Sebangau, and the two agricultural sites (Kalampangan and Marang) were also outside the EMRP area. Peat thickness ranged from 2 m to 3 m at the nondrained forest and Marang agricultural land sites, and was about 4 m at the other sites. Site characteristics and gas flux monitoring setups on sites are summarized in Table 1 and the locations are shown in Fig. 1.

2.2 Sample collection, analysis and data processing

Air samples used for gas analysis were collected from closed-chambers installed on low topography (hollow) surfaces in order to obtain a relatively flat, uniform and sufficiently large area for the measurement installations. Another reason for

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selecting hollows was that peat on higher microtpography (hummocks) at forest sites was filled with roots, and damage to live roots and vegetation would have been likely. Square-shaped open-top aluminium frames with dimensions (W × L × H) 60 × 60 × 40 cm equipped with a groove for water sealing on the upper edging were permanently installed into the peat to a maximum depth of 15 cm from the lower frame edging. The area enclosed by the frame was kept free of vegetation. Prior to each sampling event, the frame groove was filled with water, and a 10 cm high lid placed on the groove to close the chamber. A fan mounted inside the chamber mixed the air. Air samples were drawn into 60 ml syringes from the inlet of the chamber lid at 5 min intervals over a 20 min enclosure period. For sample storage before analysis, 20 ml glass vials filled with nitrogen (99.5 % N_2) and closed with rubber septa were prepared beforehand, vials were flushed with 40 ml of the sample air and over-pressurized with the remaining 20 ml. From 2002 onwards, 12 ml evacuated glass vials (Labco Extainer) were used for sample storage by filling each vial with 20 ml of the sample air. For ensuring gas impenetrability during transportation, an additional seal using hot-melt glue was applied on the caps.

Nitrous oxide concentrations from gas samples collected during 1999–2002 were analyzed with a gas chromatograph (GC) (Hewlett Packard Series II, Palo Alto, US) equipped with two two-meter long packed columns (Hayesep Q (80/100 mesh), Porapak S (80/100 mesh) and an electron capture detector for N_2O analysis. After 2002, N_2O concentrations were analyzed with a GC (Agilent 6890N, Agilent Technologies Deutschland GmbH, Waldbronn, Germany) equipped with a peristaltic pump (Minipuls 3, Gilson Inc., Middleton, WI, USA) an autosampler (Gilson autosampler 222XL, Gilson Inc., Middleton, WI, USA) and an electron capture detector for N_2O analysis. Details of concurrent CO_2 and CH_4 analyses are provided in references shown in Table 2.

An automated water table level logger (Keller DCX-22, Winterthur, Switzerland) installed in one hollow at the most far-off gas flux sampling location from the canal was used to record peat water table depth at the DF and DBP sites. For the NDF, DRF and AP_Ka sites, water table data collected with KADEC-UN and -UP data loggers

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(Kona System C. Ltd., Sapporo, Japan) was used. During the gas sampling events, water table depth was also measured manually from dipwells next to gas monitoring locations. Temperatures were measured during the gas flux monitoring at each gas sampling location in the shade 5 cm above the soil surface, and at 5, 10, and 30 cm depths below the soil surface.

Nitrous oxide fluxes were calculated from a linear temporal change of gas concentration inside the closed chamber. Each N_2O flux reading was studied for linearity based on concentrations in consecutive air samples forming a flux reading, and also compared with deviation in GC standard gas concentration (reading was rejected if the change in consecutive sample concentration was lower than the deviation in the standard gas samples). Each flux reading was compared with the rest of the flux data from the chamber and with rest of the data from the site in order to check for likely anomalies in fluxes. Then the data was divided into classes according to the contemporary peat water table depths during gas sampling. Each of the water table depth classes covered a 10 cm range and was named based on the mean water table depth (i.e. the water table depth range 0.05 m to 0.15 m was specified as "0.1 m class", etc.). In the results, the mean flux rate in each of the water table classes and standard error (SE) or standard deviation (SD) is presented when applicable.

To produce cumulative N_2O fluxes integrated over one year periods, mean flux rate for the site (data from the sub sites pooled together) in each water table depth class was multiplied by the respective number of days of the water table depth class, and the resultant cumulative fluxes were then summed together. For this, daily averaged water table (logger) data covering one year periods was used for five sites. Linear or nonlinear models were not applied for the gas flux vs. water table depth calculations because such models would have likely undervalued the occasional highly deviating N_2O flux observations. The long-term logger water table depth data used was the same as applied in formerly published CO_2 and CH_4 studies (e.g. Jauhiainen et al., 2005; 2008; Hirano et al., 2009), and allows comparison of cumulative N_2O fluxes with concurrent CO_2 and CH_4 fluxes at the sites. At the drained forest DF and open DBP

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sites gas flux monitoring intensity at the five fixed locations was conducted at about 2 week intervals, when the water table was at or below the peat surface, which provides basis for scrutinizing temporal and spatial variation in N_2O fluxes during the monitoring period 2004–2007. This N_2O flux change over time and space was made by plotting N_2O fluxes and instantaneous water table depths in five gas flux monitoring locations at these two sites on graphs, and selecting arbitral flux level "cut off" points for dividing highly deviating fluxes from typical flux levels at the sites. Limits of highly differing N_2O fluxes (mg N_2O-N m^{-2} h^{-1}) were set to $\geq$0.45 for the DF site, and to $\geq$0.02 and ≤ -0.02 for the DBP site data.

We acknowledge that the sampling methods we used may not have sampled well the highly irregular (including short-lived pulses of very high emissions) nature of N_2O fluxes that commonly occurs in natural ecosystems. Further work using continuous measuring approaches is required to determine whether such irregular high fluxes represent an important component of the annual N_2O flux in these tropical ecosystems. This issue is considered further in the discussion section below.

3 Results

3.1 Site variation in N_2O flux dynamics

Typically N_2O flux readings were small and close to zero at all sites, but a wider scatter of individual flux readings was found at narrow water table depth ranges. This wider scatter in fluxes usually occurred when the water table depth was near the peat surface, and when both soil N_2O influx and efflux occurred in the data. The widest N_2O flux amplitude occurred in the drained forest (DF). Measured maximum and minimum flux rates at the DF site were 2.312 and -0.043 mg N_2O-N m^{-2} h^{-1}, respectively (Fig. 2). At the DF site, N_2O flux scatter was especially high at water table depths' between 0.1 m and 0.3 m, and the highest mean flux (0.289 mg N_2O-N m^{-2} h^{-1}) was at the 0.3 m water table depth class (Fig. 2). Under water saturation, the flux direction was primarily into the peat at the DF site. The DF site N_2O flux amplitude was about 10 ×

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higher than at other sites. The next highest amplitude in N_2O flux rates (max. 0.266 and min. $-0.010\,N_2O\text{-}N\,m^{-2}\,h^{-1}$) occurred in the non-drained forest (NDF) (Fig. 2). The highest mean flux was $0.0493\,mg\,N_2O\text{-}N\,m^{-2}\,h^{-1}$ when the water table was within ± 5 cm of the peat surface (Fig. 2). At the DRF site, the widest flux scatter occurred under flooded conditions (max. 0.045 and min. $-0.063\,N_2O\text{-}N\,m^{-2}\,h^{-1}$), but because no flux data is available for moderately drained conditions (data gap), proper flux scatter amplitude remains unknown for the site (Fig. 2).

The deforested burned site (DBP) showed a somewhat wider scatter (max. 0.089 and min. $-0.071\,N_2O\text{-}N\,m^{-2}\,h^{-1}$) in N_2O flux readings at moderate (0.1–0.3 m) water table depths (Fig. 2). Flooding conditions and near to peat surface water tables were not present in either of the two permanently drained agricultural sites, but the widest flux scatter were at the shallowest water table depth conditions at the sites (Fig. 2).

The decreasing order of mean N_2O flux rates (mean ± SE, $mg\,N_2O\text{-}N\,m^{-2}\,h^{-1}$) at the various sites was as follows; DF (0.112 ± 0.019) > AP_Ka (0.012 ± 0.0044) > DBP (0.011 ± 0.0015) > AP_Ma (0.0072 ± 0.028) > NDF (0.0025 ± 0.0072) > DRF (0.0022 ± 0.0048).

3.2 Spatial and temporal variation in N_2O fluxes

For the analysis of observed high N_2O flux rates in relation to instantaneous water table depths, and spatial distribution among the gas flux monitoring locations, a set of, data "cut-off" points were applied. Datasets collected from 5 flux monitoring locations at the drained forest (DF) site included 38–49 gas flux readings in each (total 209) and 15 flux readings (7 % of the total) from these were above the arbitrarily set $0.45\,mg\,N_2O\text{-}N\,m^{-2}\,h^{-1}$ cut point upper limit (Fig. 3). Contribution of specific flux monitoring locations to the extreme flux values group was; 0 %, 7 %, 27 %, 53 %, 13 %, in order of increasing distance to the drainage canal on the ~300–350 m long flux monitoring transect (Fig. 3). Two flux monitoring locations positioned farthest from the drainage canal covered 10 readings out of the 15 extreme fluxes.

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Cut points of highly deviating efflux and influx rates for the deforested burned peat (DBP) site data were set to ≥0.02 and ≤−0.02 mg N_2O-N m^{-2} h^{-1}, and thus the highly deviating fluxes at the DBP site were much lower than at the DF site. The severely disturbed DBP site gas flux data from each of the 5 flux monitoring locations included 19–25 gas flux readings (total 109), from which 20 flux readings (18.3 % of the total) were rated to deviate notably from typical flux readings (Fig. 3). At the DBP site, data contribution of each chamber to the group of extreme values was; 17 %, 6 %, 6 %, 56 %, 17 %, in order of increasing distance to the drainage canal on the ∼300–350 m long flux monitoring transect. Two gas flux monitoring locations further away from the drainage canal covered 13 readings out of the 18 extreme efflux readings. The 2 extreme negative flux rates were detected near the drainage canal and, further away, at 4th location on the transect.

High N_2O effluxes occurred mostly when the water table depth was relatively close to peat surface (Figs. 2 and 3). At the DF site, high N_2O effluxes occurred at the higher and more narrow water table depth range (mean ± SD; 0.33 ± 0.8 m) in comparison to water table depth (0.49 ± 0.33 m), at the DBP site (Fig. 3). In addition, these high flux rates tended to occur in conditions when the water table depth in the monitoring location was in the rising phase after the dry season, especially at the DF site (Fig. 3). N_2O fluxes at the DBP site did not differ between the gas flux observation periods 2001/02 and 2004–2007. At the DF site, flux rates in 2001/02 (mean ± SE, 0.011 ± 0.045) were lower ($p. < 0.05$) than those monitored in the later sampling period (0.131 ± 0.020), especially when water tables were relatively near the peat surface (Fig. 2).

3.3 Cumulative N_2O fluxes

Annual cumulative N_2O emission on the drained DF forest site (1581.3 mg N_2O-N m^{-2} yr^{-1}) is about 28 × higher than 55.9 mg N_2O-N m^{-2} yr^{-1} emission on the nondrained NDF site (Table 2). The deforested DBP site annual N_2O emission (76.4 mg N_2O-N m^{-2}) was comparable with the annual N_2O emission from the NDF

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(during typical wet year), but it was much higher than for the agricultural AP_Ka peat land (20.6 mg N_2O-N m^{-2}) emission (Table 2).

Comparison of cumulative N_2O emissions to the total GHG emissions from N_2O, CO_2 and CH_4, indicates that the N_2O contribution to the total would be at highest 9.2 % (Table 2). This GWP contribution (~740 g CO_{2e}) was at the DF site, while the N_2O contribution to the total was ≤1.3 % at the other 3 sites (Table 2).

4 Discussion

4.1 Site variation in N_2O fluxes

Fluxes measured in this study are either similar or slightly higher than those measured by others in tropical peat systems. The closest comparisons for the highest N_2O fluxes at the drained forest (DF) site, are nearly 10× smaller maximum fluxes observed in Padang Alan (~0.200 mg N_2O-N m^{-2} h^{-1}) and mixed swamp forest (~0.270 mg N_2O-N m^{-2} h^{-1}) in Sarawak (Melling et al., 2008), and secondary forest (max. 0.584 mg N_2O-N m^{-2} h^{-1}) in Amuntai, Indonesia (Hadi et al., 2005). In general, the DF site mean flux rate is the among the highest detected for tropical forest peat sites and compares with mean flux of 0.157 mg N_2O-N m^{-2} h^{-1} detected in secondary forest in Barabai in Indonesia (Hadi et al., 2000) and a mean flux of 0.086 mg N_2O-N m^{-2} h^{-1} in regenerating forest in Central Kalimantan (Takakai et al., 2006). Mean N_2O fluxes at the NDF site and DRF site are within the range (i.e. −0.020–0.1 mg N_2O-N m^{-2} h^{-1}), found in other forest sites (Inubushi et al., 2003; Furukawa et al., 2005; Takakai et al., 2006; Melling et al., 2007, 2008). Fluxes for DBP peat (from −0.07 to 0.09 mg N_2O-N m^{-2} h^{-1}) are somewhat wider than other reported values for abandoned lands, but the mean flux is near the lower end of reported values (range −0.030–0.120, and mean 0.026 mg N_2O-N m^{-2} h^{-1}) for abandoned land (Hadi et al., 2000; Takakai et al., 2006).

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At the unfertilized agricultural sites (AP_Ka and AP_Ma), both the N_2O flux range (from −0.10 to 0.09 mg N_2O-N m^{-2} h^{-1}) and mean flux rates are much lower compared to those reported (mean of the reported average fluxes is 0.442 mg N_2O-N m^{-2} h^{-1}) for cultivated agricultural sites (Hadi et al., 2000; Furukawa et al., 2005; Takakai et al., 2006). Furukawa et al., (2005) reported even lower mean N_2O flux rates than in our study for some peat areas used for growing pineapple, coconut, and paddy. The N_2O flux rates derived from various studies and site types appear to vary considerably, which creates a challenge when attempting to generalize N_2O emissions by land use types.

Typically the N_2O flux mean, and flux scatter around the mean, reached a maximum when the water table was near or at the peat surface. At the drained forest (DF) site the mean N_2O fluxes were notably high at under 0.4–0.2 m water table depths. The DF represents the site type where such water table conditions are maintained by balance between high precipitation and drainage to a close-by canal (see Jauhiainen et al., 2008), and thus forest vegetation and other biota can maintain a high rate of organic matter production under moderately moist and oxic conditions also during the wet season. Aerobic decomposition under such moderately drained and stable conditions can proceed fast (see Jauhiainen et al., 2005; 2008) and a considerable proportion of the nitrogen in decomposing litter, not captured by vegetation in this ombrotrophic system, may be emitted to atmosphere as pulse of N_2O.

Studies from boreal water logged peatlands have shown that denitrification, limited by the supply of mineral nitrogen, may increase after drainage, as diffusion of oxygen to the peat increases enhancing both mineralisation of organic matter and especially strictly aerobic nitrification. Enhanced nitrification further supplies nitrate for denitrification in the aerobic/anaerobic interface, which can be seen as increased N_2O emissions (e.g. Martikainen et al., 1993). At the non-drained forest (NDF) site both N_2O in-/efflux rates and flux intensities increased during water logging, and wetness in hollows is a typical condition during the wet season at the site (Takahashi et al., 2002). However, water table close to the peat surface had rather limited effect on the N_2O fluxes at

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the NDF site although it could be expected that water level drawdown and increase in moderately moist and aerobic peat enhances fluxes, such as can be seen in the DF site data. Flux data was collected at the NDF site during late phase of dry season (in August-September) and thus any flux peak during water level draw-down during commencing dry season may have been missed. It may also be that vegetation can recapture released nitrogen efficiently at the NDF, or that annual water logging in the hollows restricts fine root, hyphae and microbial activity in peat more than at the drained DF site. A higher number of observations derived from a longer period of frequent flux monitoring at the NDF site would have likely increased confidence in interpretation of water table depth – N_2O flux dependence. Due to the gap in the DRF data, any effect of water table depth on N_2O fluxes at the site cannot be adequately compared with the other forest sites.

At the open DBP and agricultural sites, nitrogen input in litter is minimal due to the loss of tree cover and subsequent fires that have restricted vegetation regeneration. Vegetation and peat fires on the sites could have enhanced N_2O production (see, Takakai et al., 2006) but as the last fires had been at least 2 years prior to the gas flux monitoring, the effect can be considered minimal. Severe fires in 1997 (see Page et al., 2002) had consumed several decimetres of the surface peat and most of the vegetation at the DBP site. At the AP_Ka site, which has been permanently drained for a long time, burning during land management had promoted loss of the topmost peat. Recalcitrant peat, exposed by fire and oxidation, provides a poor organic matter resource for N-mineralization at these sites (Jauhiainen, unpublished). Also, the surface peat porosity at these two sites is lower than in forest peat (Takakai et al., 2006) and thus the peat physical structure may also promote creation of anoxic conditions and limit creation of a suitable redox-environment in the peat profile for bacteria to produce N_2O. Low litter input and peat decomposition potential at the DBP and AP_Ka sites, in comparison to the forest sites, can also be seen in relatively low oxidation CO_2 emission rates from the peat (Jauhiainen et al., 2005; 2008; Hirano et al., 2009). Only modest background information is available for the AP_Ma site, but low farming

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intensity and poor water management (drainage was limited by water outflow from surrounding poorly drained areas), and relatively short period from the initial drainage are the suggested reasons for the higher N_2O flux variation at the site in comparison to fluxes at the AP_Ka and DBP sites. At the AP_Ka and AP_Ma sites there was some increase in the N_2O flux scatter at deep water table depths (~0.6–0.8 m), i.e. at the deepest drainage conditions, which could result from exposure of less decomposed materials to oxic conditions during exceptionally deep water table depth conditions on the sites.

N_2O influx was detected at all the sites, with rates well within the GC detection limits. Most often influxes were detected in the wettest, but not necessary in flooded conditions. At sites where the original peat surface was lost by oxidation after drainage and fires (DBP, and both AP sites), influxes occured also under deeper drainage conditions which may be the result of anaerobic conditions, for example after rain events, in compacted surface peat (see Davidson et al., 2000). On average, influx rates were closer to zero than effluxes in respective water table depths (Figs. 2 and 3). Similar N_2O influx rates have also been reported in other studies on tropical peat under various land uses, e.g. abandoned crops field and secondary forest (Inubushi et al., 2003), deforested burned peat and regenerating forest (Takakai et al., 2006), oil palm and sago palm plantations and drainage-affected forest (Melling et al., 2007). Also, other soil types at other climates have recorded influx (see, for example, Pihlatie et al., 2005; Hyvönen et al., 2009; Phillips and Podrebarack 2009; Liu et al., 2010). Although the precondition of labile carbon pool was met especially at the DF site, uncertainty remains on the actual mechanism as the existence of bacterial strains capable of expressing the N_2O reductase enzyme, or nitrate availability in peat were not quantified. In general, the mechanisms of soil absorbing N_2O are not very clear and need to be further studied.

A change in land use from forest to agriculture has been found to increase N_2O production on tropical peat (Takakai et al., 2006; Melling et al., 2007). This may be because land clearance for cropping and drainage result in an initial increase in the

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availability of decomposable organic matter (also N availability) for decomposers, and later on intensive N-fertilization is needed for enhanced productivity in agriculture and plantation forestry performed on nutrient deficient peat. Increase in N-mineralization is the main source of NO_3^-, and it creates the potential for enhanced N_2O emissions from soils. Such change in land use can result in enrichment of N_2O-producing microorganisms (fungi and bacteria), and thus stimulation of N_2O production in the soil (Yanai et al., 2007; Hashidoko et al., 2008). This study suggests that such an increase in N_2O emission from peat can be a transient phenomenon if high N-availability is not maintained by (i) N release through high turnover of easily decomposable biomass in the upper peat profile and (ii) moderate drainage conditions. Cropping results in modest N inputs in litter, and the peat substrate becomes recalcitrant and poor in easily extractable N-content over time unless artificial fertilization is applied. Over time in drained areas, the proportion of peat compounds subject to aerobic decomposition are increasingly complex polysaccharides and thus poor nitrogen sources (Jauhiainen, unpublished). In such areas, artificial fertilization and fire may result in enhancement in N_2O production especially in moderately drained soils (Takakai et al., 2006). In this respect, more data from relatively deep drainage demanding crops, such as oil palm and acacia plantations, of various age (representing differing age from initial land drainage) and fertilization practices would be valuable.

4.2 Spatial and temporal variation in N_2O fluxes

A major challenge in monitoring N_2O emissions is how to capture the infrequent but very high fluxes that may occur (see Inubushi et al., 2003; Hadi et al., 2005; Takakai et al., 2006). There is a risk that high observations may be ignored/rejected as outliers or analytical errors, especially if the number of total observations is small, and thus potentially the most important observations may be excluded. Almost all studies are limited both by the low number of flux monitoring locations and gas sampling events, which likely results in underestimation of N_2O flux between peat and the atmosphere. Gas sampling in this study was more extensive, but observations covered at the best

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only 0.36 m^2 sample area and included only 20 min long period at 2 week intervals at each monitoring location. Still, the data is able to show notable spatial differences in N_2O flux potential e.g. one flux monitoring location out of five resulted in about 60 % of the very high flux readouts in a seemingly uniform forest landscape over a few hundred meters distance at the DF site. Similar findings occurred at the clear-felled sparse vegetation DPB site, although due to lesser flux levels the cut point had to be set at a much lower level. Temporal differences in N_2O pulses are also possible, with high effluxes tending to be associated with rising water tables in early wet season. Thus the "temporal" effect could be phrased also as "condition dependent". Takakai et al. (2006) collected data from the same area as the DF and DRF sites, which shows clearly increased scatter in N_2O fluxes after the onset of wet season in November, while low soil moisture resulted in low efflux. In addition to favourable moisture and oxygen availability in the upper peat profile, nitrogen released from litter deposited during the preceding dry season is likely to contribute to the pulse of emissions. It remains to be established how frequent very high N_2O flux pulses are, how long they last, and what is true the spatial distribution and coverage of such flux hot spots.

4.3 Cumulative gas fluxes

In this study, mature forest sites had higher cumulative N_2O emissions compared with open peatlands. The DF site annual N_2O emission was at least 4× higher than the next highest reported emission (0.06–0.4 g N_2O-N m^{-2} yr^{-1}) by Takakai et al., (2006). N_2O emission at the DF site is also well above other reported mean emissions from forest growing on tropical peat, excluding the secondary forest site (1.34 g N_2O-N m^{-2} yr^{-1}) in Amuntai, Indonesia (Hadi et al., 2005). In the Takakai et al. (2006) study made at the same DF forest area, emissions were calculated by direct extrapolation from monthly flux measures compared with this study that used a different cumulative flux calculation approach.

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Nondrained forest (NDF) annual N_2O emission is in the range reported for forest growing on tropical peat, i.e. −0.05–1.34 g N_2O-N m^{-2} yr^{-1}, though well below the mean (0.37 g N_2O-N m^{-2} yr^{-1}), (Inubushi et al., 2003; Takakai et al., 2006; Melling et al., 2007; 2008). The closest match among nondrained forest emission rates is 0.12 g N_2O-N m^{-2} yr^{-1} from Padang Alang forest in Loagan Bunut National Park, Sarawak (Melling et al., 2007). The drained recovering DRF forest cumulative N_2O emissions were not calculated in this study, but Takakai et al., (2006) reported annual emissions of 0.04 and 0.4 g N_2O-N m^{-2} yr^{-1} for the same area.

Deforested burned DBP peat site annual N_2O emission is close to the earlier measured emissions (0.097 and 0.15 g N_2O-N m^{-2} yr^{-1}) for this same area (Takakai et al., 2006). Inubushi et al. (2003) reported notable annual N_2O influx (−0.037 and −0.110 g N_2O-N m^{-2}) for old abandoned croplands. Annual cumulative emission for the agricultural AP_Ka site was the lowest in our study and it is also slightly below the lowest reported emission (0.025 g N_2O-N m^{-2}, Hadi et al., 2005) for peat used for agriculture. The reported mean annual emissions from agricultural peat is 7.29 g N_2O-N m^{-2}, and rates vary between 0.0247 and 25.9 g N_2O-N m^{-2} (Hadi et al., 2000, 2005; Furukawa et al., 2005; Takakai et al., 2006), probably mainly due to different N fertilizer practices.

Most of the published data on N_2O fluxes are for boreal and temperate ecosystems. Ombrotrophic peatlands in these regions are in natural non-drained condition typically treeless and the peat is formed mainly from residues of *Sphagnum* mosses. Maljanen et al. (2010) summarize nondrained ombrotrophic peat annual N_2O balance to be in average less than < 0.01 g N_2O-N m^{-2} (range < 0.01–0.01 g m^{-2} yr^{-1}). Tropical peat under various land uses has higher N_2O emissions than non drained ombrotrophic peat in northern latitudes. Annual mean N_2O emissions for drained boreal peat under perennial grass swards was 0.81 g N_2O-N m^{-2} (range 0.1–3.5 g m^{-2} yr^{-1}), for regularly ploughed and fertilized barley 1.09 g N_2O-N m^{-2} (range 0.8–1.5 g m^{-2} yr^{-1}), and 1.36 g N_2O-N m^{-2} (range 0.8–2.5 g m^{-2} yr^{-1}) for fallow peat sites (Maljanen et al.,

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2010). Reclaimed tropical peat fluxes for abandoned lands and at the AP_Ka and DBP sites in our study are lower than those from (low- or unfertilized) grasslands and for fallow boreal peat. There was no heavily fertilized agricultural peat in our study, but in general, fertilized tropical peatlands (see discussion above) have much higher N_2O emissions in comparison to fertilized crop peatlands in boreal areas.

4.4 N_2O and GWP

Carbon dioxide was the main emitted GHG at all sites, and contributed 98 % or more of the total GWP from emissions of CO_2, CH_4 and N_2O. The high end GWP cumulative N_2O contribution (9.2 % of the total) was at the DF site. Worth noting is that cumulative CO_2 emissions at the DF were the highest (~7283 g m^{-2} yr^{-1}) among the sites, which adds greater significance to the N_2O contribution. Only at the NDF site, did the effects of CH_4 losses exceed those of N_2O impact (Table 2, Jauhiainen et al., 2005). In other studies, annual N_2O flux contributed −0.5–5.1 % of the GWP of all GHGs (based on Inubushi et al., 2003; Hadi et al., 2005; Melling et al., 2005a, 2005b, 2007, 2008). The highest annual N_2O (626.7 g CO_{2e}, 4.7 % of the GWP) contribution was at secondary forest in Amuntai (Indonesia), where the CO_2 emission was also very high (12 687 g m^{-2} yr^{-1}), and CH_4 emissions accounted for 1.1 % of the GWP (Hadi et al., 2005).

In non-forest systems, N_2O emissions represented 3.7 % of the GWP in sago and 1.0 % in oil palm systems (Melling et al., 2005a; 2005b; 2007). In the study by Hadi et al. (2005), the relative contribution of N_2O to GWP was 1.3 % in a rice-soybean rotation field, and 0.2 % in a paddy field, while methane formed the second most important GHG source (1.1–11.3 % of the GWP) after CO_2 at these sites. It should be remembered that the reported CO_2 emissions from tropical peat do not separate autotrophic-emissions generated by live plants from heterotrophic emissions resulting from decomposition, which complicates CO_2 comparisons with the GWP contribution of N_2O and CH_4. Therefore, N_2O may have much higher relative contribution to GWP in reality.

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5 Conclusions

Artificial drainage in tropical ombrotrophic forest system increases organic matter mineralization rates in peat, but the litter deposition may remain relatively unaffected. This results in enhanced GHG emissions from peat, especially as CO_2 and N_2O. Increased emission rates of N_2O from peat can be a transient phenomenon if N-availability is not maintained high by providing (i) biological or artificial N-source and (ii) moderate drainage conditions in peat. Drained forest N_2O fluxes were $>10\times$ higher than from other sites, and the very high flux rates which occurred were also $>10\times$ higher. For clear-felled sites (agricultural areas and deforested burned peat) emission rates were relatively modest, presumably due to low N-availability from litter, recalcitrant peat substrate, and because no fertilization was applied to soil. N_2O flux rates showed high spatial and temporal variability. Carbon dioxide has outstanding GWP impact ($>90\,\%$) in tropical peat when concurrent CO_2, CH_4 and N_2O fluxes are compared across various tropical peat land use types. For CH_4 and N_2O gases, the GWP impact is usually $<2\,\%$ of the total. However, we stress that further continuous observations are required to be confident that the impacts of very high but short-lived fluxes are properly accounted for.

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Table 1. Key characteristics of the gas flux monitoring sites, and details of the gas flux sampling regimes used in the study.

Site/ Acronym/ Coordinates/ Reference	Site characteristics	Gas flux monitoring arrangements
Nondrained forest/ NDF/ 2°19′18.2" S, 113°54′07.7" E/ Jauhiainen et al., 2005	– forest, selectively logged prior to 1998 – hummock-hollow microtopography – not fire affected – nondrained – mean/min./max. water table depth 0.1/0.57/+0.18 m	– three sub-sites at about 500–1000 m distances – 3 monitoring locations within ~100 m radius at each sub-site – 3–5 weeks intensive monitoring during dry and wet season in 2000 and 2001
Drained forest/ DF/ 2°20′42.06" S, 114°2′12.18" E/ Jauhiainen et al., 2008	– forest, selectively logged prior to 1998 – hummock-hollow microtopography – not fire affected – drained (uncontrolled) – mean/min./max. water table depth 0.56/1.57/+0.03 m	– one monitoring transect with 4–5 gas monitoring locations at ~50 m intervals – 3–5 weeks intensive flux monitoring during dry and wet season in 2001 and 2002, and frequent monitoring in 2004–2007
Drained recovering forest/ DRF/ 2°20′26.74" S, 114°2′16.48" E/ Hirano et al., 2009	– practically clear-felled prior to 1998 but tree vegetation was recovering – hummock-hollow microtopography – peat fire affected in 1997 – drained (uncontrolled) – mean/min./max. water table depth 0.31/1.09/+0.12 m	– one monitoring transect with 4 gas monitoring locations at ~50 m intervals – 3–5 weeks intensive flux monitoring during dry and wet seasons in 2001 and 2002
Drained burned peat/ DBP/ 2°20′16.60" S, 114°8′46.74" E/ Jauhiainen et al., 2008	– practically clear-felled since 1998, grow mostly ferns – secondary hummock-hollow microtopography – reoccurred fire events during 1997/98 and 2002 – drained (uncontrolled) – mean/min./max. water table depth 0.43/0.38/+0.19 m	– one monitoring transect with 4–5 gas monitoring locations at ~50 m intervals – 3–5 weeks intensive flux monitoring during dry and wet season in 2001 and 2002, and frequent monitoring in 2004–2007
Agricultural peat in Kalampangan/AP_Ka/ 2°17′24.11" S, 114°1′0.32" E/ Hirano et al., 2009	– clear-felled and drained in 1980s, fallow peat, bare peat – flat peat surface – repeatedly burnt surface peat – drained (shallow) – mean/min./max. water table depth 0.43/0.78/0.14 m	– one monitoring sub-site with 3 gas monitoring locations within ~100 m radius – 3–5 weeks intensive flux monitoring during dry and wet season in 2001 and 2002
Agricultural peat in Marang/ AP_Ma/ 2°4′27.30" S, 113°46′33.10" E/ –	– cleared for household farming in late 1990's, fallow land taken over by grasses – flat peat surface – burnt – drained (shallow) – mean/min./max. water table depth 0.43/0.69/0.12 m	– one monitoring sub-site with 3 gas monitoring locations within ~100 m radius. – 3–5 weeks intensive flux monitoring during dry and wet season in 2001 and 2002

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Table 2. Annual cumulative N_2O (as N_2O-N), CO_2 and CH_4 fluxes in peat. Actual and relative contribution to three gases' total GWP, and the total GWP of the gases are shown. Cumulative CO_2 and CH_4 flux rates refer to references provided on respective rows.

Site/ Acronym	Time period	N_2O-N $mg\,m^{-2}\,yr^{-1}$ ($g\,CO_{2e}\,m^{-2}\,yr^{-1}$) [% GWP]	CO_2[1] $g\,m^{-2}\,yr^{-1}$ (–). [% GWP]	CH_4[1] $g\,m^{-2}\,yr^{-1}$ ($g\,CO_{2e}\,m^{-2}\,yr^{-1}$) [% GWP]	Total GWP [2] $g\,CO_{2e}\,m^{-2}\,yr^{-1}$
Nondrained forest/ NDF	09.1994–08.1995	55.9 ± 10.3 (26.2 ± 4.9) [0.9 %]	2895 ± 335 (–) [98.0 %]	1.36 ± 0.57 (34.00 ± 14.25) [1.2 %]	2955
Drained forest/ DF	07.2005–06.2006	1581.3 ± 41.7 (740.4 ± 19.5) [9.2 %]	7283 ± 1787 (–) [90.9 %]	−0.37 ± 0.09 (−9.22 ± 2.20) [−0.1 %]	8014
Deforested burned peat/ DBP	07.2005–06.2006	76.4 ± 2.8 (35.8 ± 1.3) [1.3 %]	2809 ± 278 (–) [98.5 %]	0.28 ± 0.14 (6.88 ± 3.60) [0.2 %]	2852
Agricultural peat/ AP_Ka	365d (typical conditions)	20.6 ± 7.8 (9.6 ± 3.6) [0.6 %]	1716 ± 16 (–) [99.3 %]	0.11 (2.75) [0.2 %]	1728

[1] References for CO_2, CH_4 and water table depth data; NDF, Jauhiainen et al. (2005); DF and DBP, Jauhiainen et al., (2008), AP_Ka, Hirano et al. (2009).

[2] Radiative forcing in 100 years perspective, i.e. CO_2 = 1, CH_4 = 25, N_2O = 298 (Solomon et al., 2007), applied in calculus of CO_2 equivalents (CO_{2e}).

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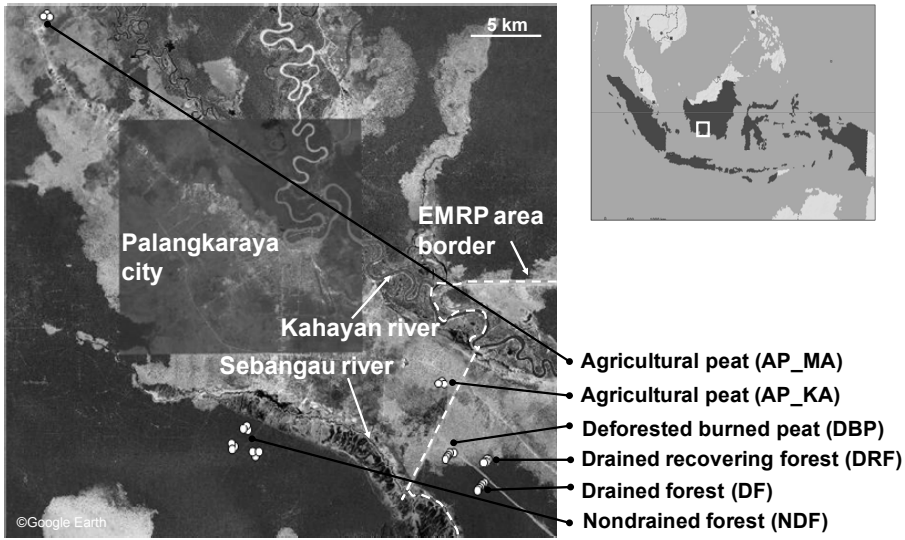

Fig. 1. Greenhouse gas flux monitoring sites in Central Kalimantan, Indonesia. North-East border of Ex-Mega Rice Project area is outlined by white dotted line.

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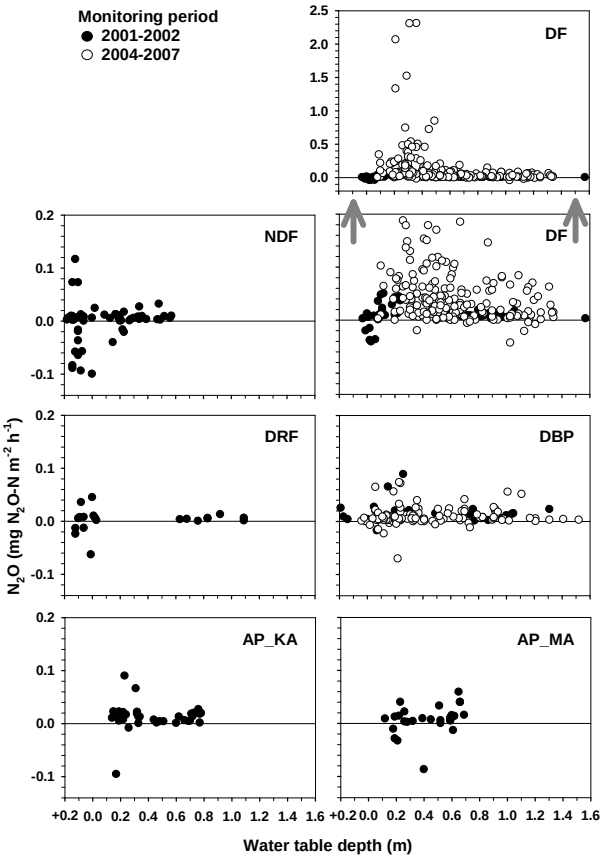

Fig. 2. N_2O flux ($mg\,N_2O\text{-}N\,m^{-2}\,h^{-1}$) at various water table depths (m). Different forms in symbols (if applicable) refer to different gas flux monitoring periods. Site types are defined in Fig. 1.

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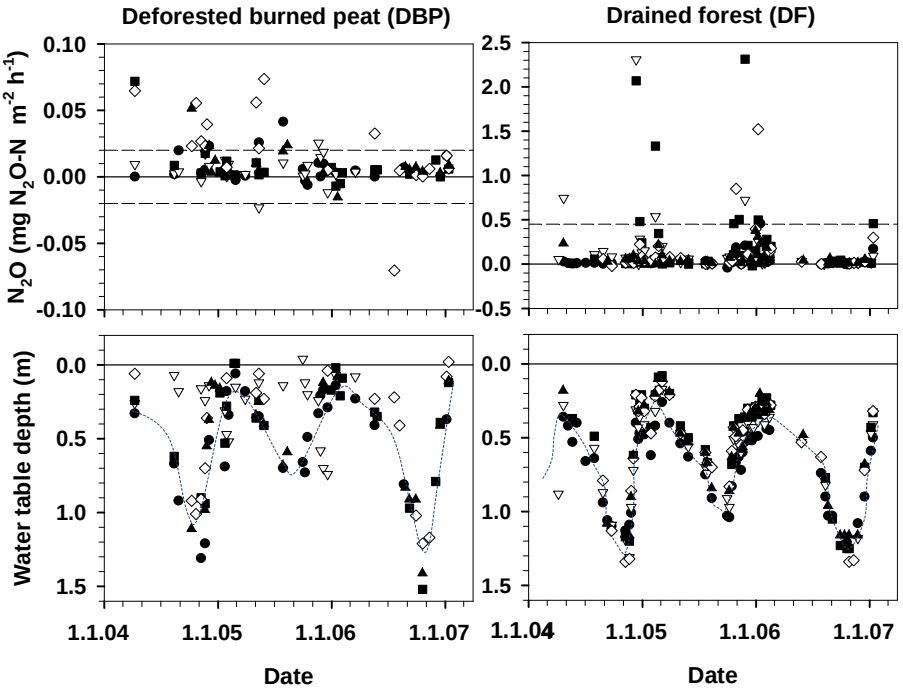

Fig. 3. N_2O fluxes and the respective water table depth in the gas flux monitoring locations at the DF and DBP sites during period 2004–2007. Limits of highly differing fluxes (dash lines) are; ≥0.45 (mg N_2O-N m^{-2} h^{-1}) at the DF site, ≥0.02 and ≤−0.02 (mg N_2O-N m^{-2} h^{-1}) at the DBP site. Differing symbols denote specific five gas flux monitoring locations on the site.

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