WORKING PAPER

# Conversion of intact peat swamp forest to oil palm plantation

## Effects on soil $CO_2$ fluxes in Jambi, Sumatra


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Working Paper 110

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Fertilization in an oil palm plantation on peat in Jambi, Sumatra

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# 1. Introduction

Tropical peatlands cover only a small portion of the Earth's total land area (approximately 0.25%; 368 500 km$^2$) yet they store an important fraction of the total terrestrial organic carbon (50 Gt C) because their soils are deep (up to 20 m) and have a C content of up to 55% (Page and Banks 2007; Yu *et al.* 2010). Due to these large C pools, tropical peatlands may, if altered, become the highest emitter of $CO_2$ among all soil types worldwide (Iiyama and Osawa 2010). However, the relevance of C dynamics in tropical peatlands for the global C cycle and climate change remains unclear (Frolking *et al.* 2011).

Peat swamp forests form in tropical humid zones where water-saturated soils inhibit wood and roots from decomposing entirely; large amounts of peat therefore accumulate over time. However, logging and hydrological disturbances such as drainage can reverse the process of peat accumulation and release substantial amounts of $CO_2$ (Rieley *et al.* 1993; Hirano *et al.* 2012). Growing demand for palm oil is a key driver of tropical peat swamp forest clearance and drainage (Carlson *et al.* 2012), especially in Southeast Asia, where 68% of the world's tropical peatlands are located (Yu *et al.* 2010). From 1990 to 2010, forest cover in the peatlands of Malaysia, Sumatra and Borneo fell from 77% to 36% (Li *et al.* 2007). If land-use change on intact peatlands continues at this rate, all undisturbed peat swamp forests will have vanished by 2030 (Koh *et al.* 2011; Miettinen *et al.* 2011).

Since 2005, a growing number of studies have been carried out to quantify stocks and fluxes of C in different land uses in the tropical peatlands of Southeast Asia (Jauhiainen *et al.* 2005, 2012; Melling *et al.* 2005; Li *et al.* 2007; Page *et al.* 2009; Couwenberg *et al.* 2010; Hergoualc'h and Verchot 2011; Hirano *et al.* 2012). Taken together, the findings from C dynamics studies can be used to generate an adequate assessment of the scale of peat-derived greenhouse gases transferred to the atmosphere and provide data for C emissions reduction policies. However, no quantitative data comparing soil $CO_2$ fluxes in an intact peat swamp forest, a transitional logged and drained forest, and an oil palm plantation located on the same alluvial peat plain (peat dome) have been published. The objective of this work was to provide such an assessment using a case study in Jambi, Sumatra, Indonesia.

# 2. Materials and methods

## 2.1 Study sites

The sites are located on Sumatra's deep peat coastal plain in the Indonesian province of Jambi. Three land uses were studied: a primary peat swamp forest (PF), a drained logged forest (DegF) and a 7-year-old oil palm plantation (OP). The PF was less than 60 km from the other two land uses. The climate in the region is tropical humid. Long-term records from the Jambi airport weather station indicated that the average annual rainfall is 2466 mm y$^{-1}$, with June, July and August the driest months, and the mean minimum and maximum monthly temperatures are 22.7°C and 32.7C, respectively (Siderius 2004).

The PF is located in Berbak National Park (1°27'S, 104°21'E). The study plot was set up in the core of the park, which remains undisturbed. The forest was classified as a mixed peat swamp forest and the soil as Lignic Hemic Ombric Histosol dystric (IUSS Working Group WRB 2006). The average peat depth was calculated to be 4.5 m.

The DegF and OP are near each other (1°39'S, 103°52'E). The 50 ha DegF belongs to a local community and is affected by the drainage canals of the surrounding oil palm plantations. Most of the large trees had been logged by the time of the study, but logging activities stopped when the plot was set up and measurements began. The DegF represents an intermediate disturbance point between the intact forest and the oil palm plantation. The OP is an industrial plantation belonging to PT. SNP (Bakrie Sumatera Plantations). The palms (*Elaeis guineensis*) were planted in 2005 in a triangular design at a density of 148 palms ha$^{-1}$. Each year, the palms received 148 kg urea ha$^{-1}$ or 69 kg N ha$^{-1}$ in two applications. Additional agrochemicals were sprayed several times a year to control pests and weeds, mostly in the harvesting lines. In these rows, the soil was bare, whereas in the other lines, where fronds were left to decompose, the soil was covered by ferns. The average peat depth at the DegF and OP was 6 m. The land was drained in 2003 and the company maintains the water table in the OP at between 50 and 100 cm. In the OP, a 1.5-m-deep secondary drainage canal flows perpendicular to the palm lines and 75-cm-deep tertiary canals are located parallel to the palm lines with one canal every eight lines. In the DegF, a 75-cm-deep canal surrounds the forest. This tertiary canal is connected to the OP secondary canal network located 250 m from the forest edge. The soils at both sites were classified as Folic Hemic Histosol dystric drainic (IUSS Working Group WRB 2006).

## 2.2 Experimental design

Soil $CO_2$ efflux was measured using dynamic closed chambers (Parkinson 1981; van Straaten *et al.* 2010). An infrared gas analyzer (IRGA) (LI-840A; LI-COR Biosciences, Lincoln, NE, USA) was connected to circular polyvinyl chloride (PVC) chambers (inner diameter, 0.27 m; height, 0.20–0.25 m) and recorded the $CO_2$ concentration every second for 4–5 min.

To minimize soil disturbance, chambers were installed at least 1 month before the experiment began. During installation, chamber bases were pushed 5–10 cm into the soil surface. In all three land uses, to allow for the spatial variation in soil $CO_2$ fluxes, the chambers were placed in pairs, with one positioned close to a tree/palm and the other at mid-distance to the next tree/palm. In the DegF, this position coincided with the presence of a hummock around the tree and a hollow further from the tree. Chambers in the DegF were located 10–20 m from the tertiary canal. In the OP, one chamber in a pair was placed close to a palm and its partner at mid-distance to the next palm along the path used for harvesting. Chambers in the OP were located at least 10 m and no more than 100 m from the secondary canal perpendicular to the plot, and at the mid-point between two tertiary drainage canals. In each land use, 10 pairs of chambers were deployed, with a distance of approximately 10 m between each pair. In the OP, eight additional chambers were installed: four in a line where fronds were left to decompose and four in tertiary drainage canals, which were dry during the dry months. The total 20 (in the PF and DegF) and 28 (in the OP) chambers covered about 1 ha in each land use.

Measurements in the three land uses were made monthly from January to September 2012 and systematically between 09:30 and 14:30. Before each measurement, the chamber height was recorded from four positions in order to calculate the average headspace volume inside the chamber. Before the flux was measured, any $CO_2$ that had accumulated in the chamber was removed by fanning the headspace for 30 s. After the chamber had been closed, the air in the headspace was circulated between the chamber and the IRGA at a rate of 2 L $min^{-1}$ using a small battery-operated pump. Carbon dioxide concentrations, air moisture and atmospheric pressure were recorded using a Toshiba notebook computer connected to the IRGA. The $CO_2$ flux was calculated from a 1–3-min time window during which $CO_2$ concentrations increased linearly ($R^2 > 0.98$). The IRGA was calibrated before each sampling expedition using a scrubber column of soda lime and $CO_2$ standard gas (700 or 1500 ppm). Concomitant with $CO_2$ flux measurements, air and soil (10 cm depth) temperatures were measured with a thermometer at each pair of chambers and at each of the eight additional chambers in the OP. The water table level was also recorded. In each land use, a piezometer (PVC pipe, 3 cm diameter, 2 m long) was installed between the two chambers in each pair. Hourly rainfall and air temperature were monitored using two weather stations (HD2013, Delta Ohm, Padova, Italy): one placed at the Simpang Malaka station located on the river near the PF plot and the other within the oil palm plantation at mid-distance between the DegF and OP plots.

An N fertilizer experiment was carried out on five palms in the OP. The dose of N applied followed the company's usual fertilization practices for adult oil palms on peat soil. Urea (47% N) was applied on 20 March 2012, at a dose of 0.5 kg per palm. The fertilizer was homogeneously sprinkled by hand within a 1.5 m radius around the trunks of the palms. At each fertilized palm, one chamber was placed inside the fertilization area (1 m from the palm trunk) and another was placed outside (at mid-distance to the next palm along the path used for harvesting). The dose of fertilizer applied to the chambers in the fertilization area was calculated as the surface area ratio between the chamber and fertilization area multiplied by the dose applied to the fertilization area. In each chamber, the $CO_2$ flux was measured 1 day before, immediately after and 2, 6, 7, 16, 21 and 33 days after fertilization. Carbon dioxide flux measurements were made in the same fashion as the monthly measurement described above.

## 2.3 Statistical analysis

Statistical analysis was performed using the software InfoStat (2004). Statistical significance was set at a probability level of 0.05. The t test and the nonparametric Mann–Whitney test were used to compare two means for normally and non-normally distributed variables, respectively. For multiple comparisons, ANOVA and the nonparametric

Kruskal–Wallis test were performed, respectively, on normally and non-normally distributed variables. The distribution of the variables was tested using the Shapiro–Wilk test. Relationships between soil $CO_2$ fluxes and abiotic variables were tested using linear regression models.

# 3. Results

## 3.1 Environmental parameters

The 2012 annual rainfall amounted to 1554 mm in the PF and 1659 mm in the DegF and OP. The rainfall patterns differed between the two sites, with May and June markedly dryer in the PF than in the DegF and OP (Figure 1). The water table level was significantly higher ($P$ < 0.001) in the PF (–16.4 ± 7.2) than in the DegF (–75.4 ± 4.5) and OP (–75.7 ± 3.9). In these latter two land uses, the water table was relatively stable throughout the monitoring period with the exception of a decrease in August, whereas in the intact forest it dropped steadily from June. Air temperature was significantly lower ($P$ = 0.04) in the intact forest (28.1 ± 0.6) than in the converted land uses (30.0 ± 0.5 and 33.4 ± 1.9 in the DegF and OP, respectively). The air temperature was particularly high in the OP from May to July. Soil temperature also varied significantly ($P$ = 0.01) between land uses, with a smaller average value in the PF (27.2 ± 0.6) than in the OP (28.9 ± 1.4) and an intermediate value in the DegF (27.6 ± 0.5). The high air temperature observed in the OP in June and July coincided with a high soil temperature.

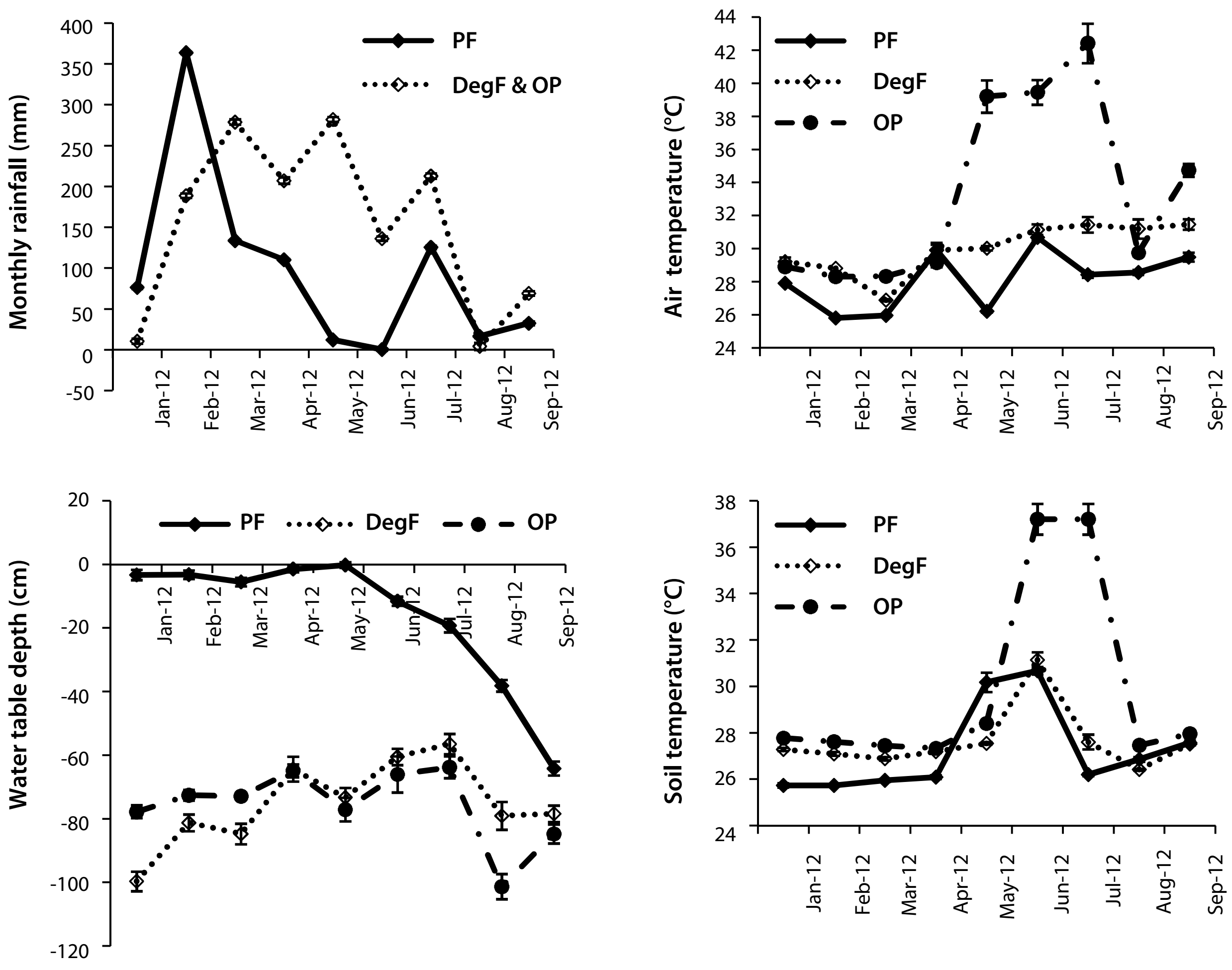


**Figure 1. Average monthly rainfall, air temperature, water table depth and soil temperature in the intact peat swamp forest (PF), the drained logged forest (DegF) and the 7-year-old oil palm plantation (OP). Error bars indicate the standard error associated with the average.**

## 3.2 Soil $CO_2$ fluxes

Soil $CO_2$ emissions were logarithmically distributed. Emissions were in the ranges 17–91, 29–66 and 58–156 kg C-$CO_2$ $ha^{-1}$ $d^{-1}$ in the PF, DegF and OP, respectively (Figure 2). A seasonal trend was observed in the PF: as the water table level dropped from June, the fluxes steadily increased; no such clear trend was observed in the other systems. In the OP, the highest emissions were recorded in January, April and July. Notably, July also had the highest air and soil temperatures in the OP (Figure 1). Over the monitoring period, the fluxes were significantly larger ($P < 0.0001$) in the OP (28.4 ± 1.2 Mg C-$CO_2$ $ha^{-1}$ $y^{-1}$) than in the DegF (18.5 ± 0.7 Mg C-$CO_2$ $ha^{-1}$ $y^{-1}$) and in the PF (16.0 ± 1.2 Mg C-$CO_2$ $ha^{-1}$ $y^{-1}$).

Spatial variation in soil $CO_2$ emissions was also observed. The fluxes were significantly larger close to the trees/palms than far from them in January, March and May in the PF and in August and September in the OP (Figure 3). By contrast, in the DegF in January, the emissions were significantly larger far from the trees than close to them. In the OP, the amount of soil $CO_2$ emitted from the line with decomposing fronds was significantly smaller than the amounts emitted close to the palms and far from the palms in the harvesting line in June only. In the tertiary drainage canals, high emissions were recorded in May and July, but the fluxes were not consistently different from those from the other spatial positions.

Soil emissions of $CO_2$ were intensively monitored after the fertilization in March. The emissions were significantly larger in the fertilized area (i.e. close to the palms) than in the non-fertilized area (i.e. far from the palms) on days 1 and 7 after nitrogen application (Figure 4). However, the average fluxes during the period when large $CO_2$ pulses resulting from fertilizer application can be expected (from the day of application until 33 days afterward) were not significantly larger than the average fluxes during the rest of the monitoring period, in either the fertilized or non-fertilized areas.

## 3.3 Relationships between soil $CO_2$ fluxes and environmental variables

Soil $CO_2$ emissions were correlated neither to air temperature nor to soil temperature. A significant but weak ($R^2 = 0.3$) linear relationship was found between the water table depth and $CO_2$ emissions in the PF, indicating increased fluxes with decreased water level:

$$CO_2 = -1.08\ (\pm\ 0.13) \times WT + 25.79\ (\pm\ 3.5)$$

where $CO_2$ denotes soil emissions of $CO_2$ (kg C $ha^{-1}$ $d^{-1}$) and WT is the water table depth (cm) expressed as a negative value when the water was below the soil surface.

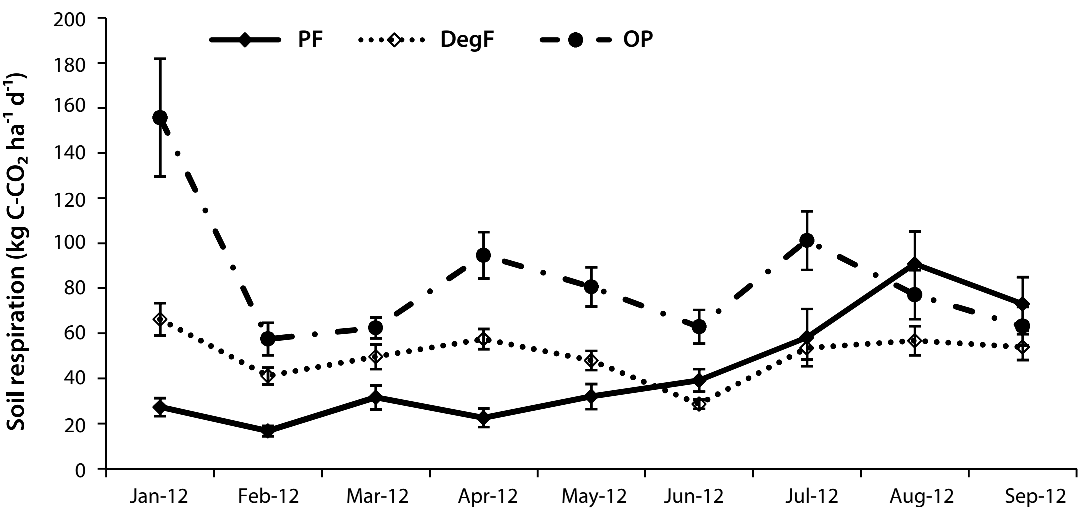


**Figure 2. Average monthly soil $CO_2$ emission rates in the intact peat swamp forest (PF), the drained logged forest (DegF) and the 7-year-old oil palm plantation (OP). Error bars indicate the standard error associated with the average.**

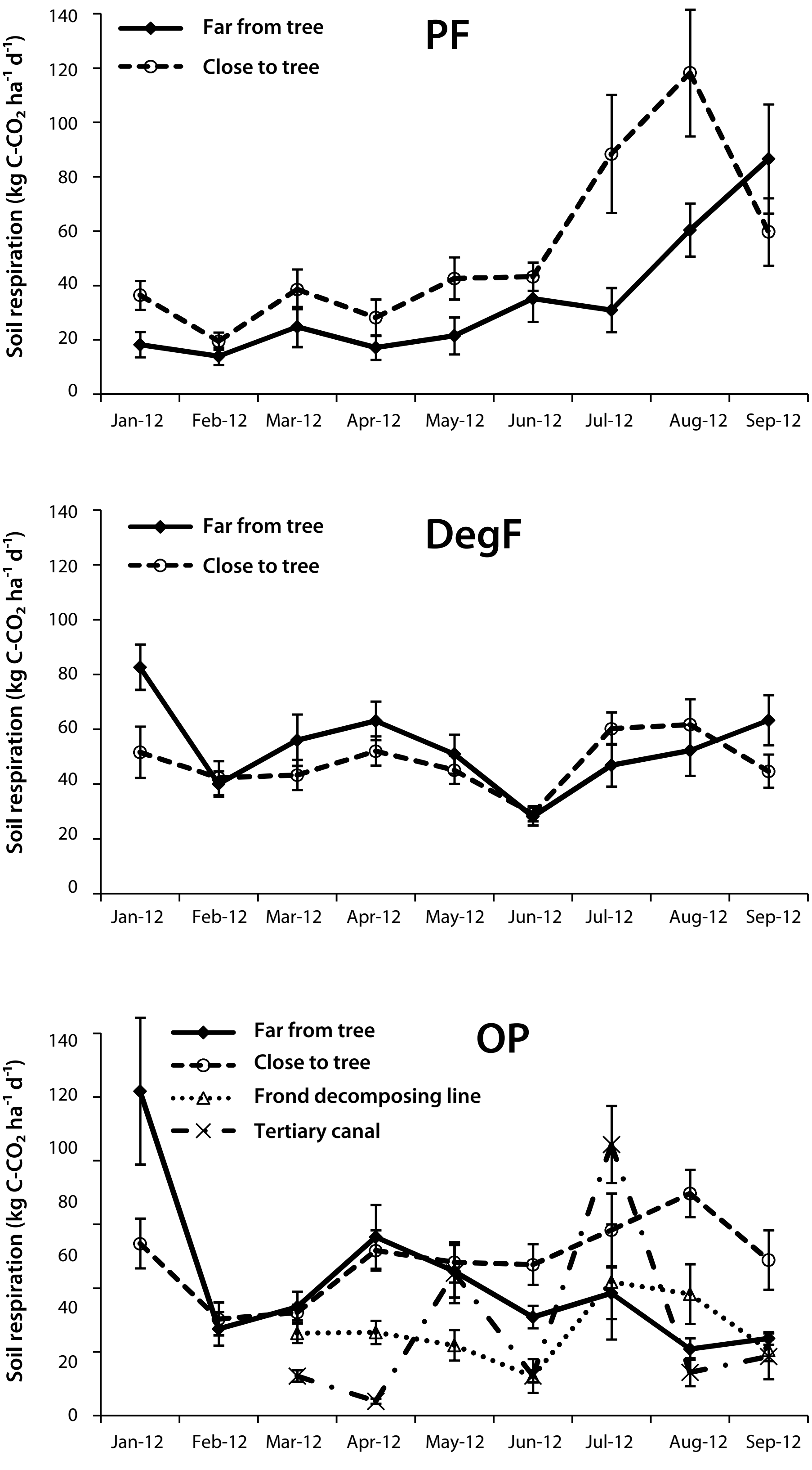


**Figure 3. Average daily soil $CO_2$ emissions far from and close to trees/palms in the intact peat swamp forest (PF, top), the drained logged forest (DegF, middle) and the 7-year-old oil palm plantation (OP, bottom). Fluxes in the line with decomposing fronds and the tertiary drainage canals are also indicated for the oil palm plantation. Error bars indicate the standard error associated with the average.**

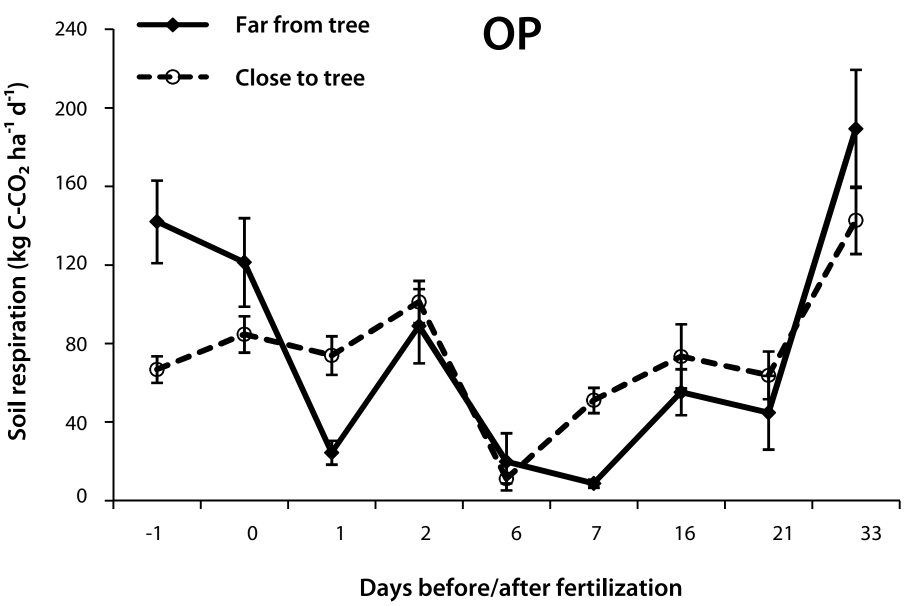


**Figure 4. Average daily soil $CO_2$ emissions in the non-fertilized area (far from palm) and in the fertilized area (close to palm) following N fertilizer application in the 7-year-old oil palm plantation. Error bars indicate the standard error associated with the average.**

## 4. Discussion

Our results show that soil emissions of $CO_2$ increased gradually and significantly along the transition from intact peat swamp forest to drained and logged peat forest to oil palm plantation. These results are in contrast to the findings of Melling *et al.* (2005) of larger soil $CO_2$ efflux in a peat swamp forest compared with that in a 4-year-old oil palm plantation on peat in Sarawak, Malaysia. The difference may be attributable to the impacts of drainage at the forest site studied by Melling *et al.* (2005), where the annual average water table level was –45.3 cm. In the PF in our study, the average water table level over the monitoring period was –16 cm, and the inclusion of the data for October, November and December would likely increase the annual average, as rainfall generally increases during this period (Siderius 2004). The annual emission rate in the PF was similar to the average for virgin peat swamp forests of 13 ± 2.4 Mg C $ha^{-1}$ $y^{-1}$ assessed by Hergoualc'h and Verchot (2011). The emissions in the DegF were significantly larger than that in the PF but only by 2.5 Mg C $ha^{-1}$ $y^{-1}$, despite the impact of drainage on the water table level. Hirano *et al.* (2009) also found only a small difference in soil respiration between a non-drained peat swamp forest and a drained clear-felled regenerating forest.

In the PF, there was a strong seasonal variation in the fluxes and the water table depth, which was not observed in the other land uses, in which the drainage was controlled. As a result, the fluxes were not correlated with the water table depth in the OP or DegF. However, in the OP, one of the largest monthly fluxes coincided with the highest air and soil temperatures. This suggests that the relationship between soil $CO_2$ emissions and underlying environmental factors differs in each land use, which was also observed by Melling *et al.* (2005). Furthermore, the spatial variation was not consistent across the land uses. In the PF, where the microtopography of the soil is rather homogeneous, larger emissions were at times observed close to the trees than further from them. A thicker root mat involving larger root respiration may explain the difference, especially during the dry months. In the DegF, the floor microtopography is more variable, with the presence of hummocks around the trees and hollows further from the trees. Jauhiainen *et al.* (2008) measured slightly higher soil respiration rates in hummocks than in hollows in a drained and logged peat forest in Kalimantan, Indonesia; that pattern was not observed here. In the OP, the larger $CO_2$ emissions close to the palm than far from it during the dry and hot months could, as in the PF, arise from a difference in root density and root respiration between the two positions. The unexpected large pulse of emissions from the tertiary drainage canals underlines the importance of including this spatial position in the experimental design when monitoring fluxes in oil palm plantations on peat.

The magnitude of annual soil $CO_2$ emissions in the OP was about twice the amount of 15.4 ± 6.4 Mg C $ha^{-1}$ $y^{-1}$ measured by Melling *et al.* (2005), even though the water table was deeper at our study site than at theirs. Although differences in intrinsic peat properties, local climate and land-use management may partly explain the variation in flux between sites, the experimental design and method used for gas sampling are also essential factors. Melling *et al.* (2005) removed all green vegetation from their plots, whereas our experimental design was based on the least-disturbance principle. Furthermore, Melling *et al.* (2005) sampled the gas in their chambers just before closure and 6 min afterward. Our IRGA measurements, conducted in chambers of very similar size to those of Melling *et al.* (2005), showed that after about 4 min, the $CO_2$ flux in the chamber headspace no longer increased linearly, but had reached a plateau. Thus, the calculation of the flux using the difference between the sample taken 6 min after closure and that before closure may have substantially underestimated the actual emission rate. Although a pulse of soil $CO_2$ emissions was expected to follow N fertilization as a result of an increase in both root respiration and soil organic matter decomposition, this effect was not detected during the experiment. The low rainfall during the first 4 days following the fertilizer application (25.1 mm over 4 days) combined with high air temperature may have favored N losses by volatilization.

The potential contribution of tropical peatlands to either exacerbating climate change when altered or mitigating it when preserved is of global concern. Throughout Southeast Asia, peat swamp forests are increasingly being converted to oil palm plantations, but scientific assessments on the impact of these conversions on the release of greenhouse gases are critically lacking. This study demonstrated that soil respiration almost doubled after the conversion of intact peat swamp forest to oil palm. To determine net atmospheric impacts on the climate system of this land-use change, further analytical steps would include separating the soil $CO_2$ flux into its auto- and heterotrophic components, calculating the soil balance of carbon in- and outputs, and assessing carbon losses from biomass changes.

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Tropical peatlands are among the largest pedologic pools of organic carbon. This study compared soil $CO_2$ fluxes in an intact peat swamp forest, a transitional logged drained forest and an oil palm plantation located on the same alluvial peat plain (peat dome) in Jambi, Sumatra, Indonesia. Dynamic closed chambers were used to measure soil $CO_2$ efflux from January to September 2012. Chambers were placed in pairs, with one close to a tree/palm and the other at mid-distance to the next tree/palm. In the oil palm plantation additional chambers were placed in frond decomposing lines and tertiary drainage canals. During the experiment, air and soil temperatures, water table level and rainfall were recorded. The fluxes were significantly larger in the oil palm plantation (28.4 ± 1.2 Mg C-$CO_2$ ha–1 y–1) than in the transitional logged drained forest (18.5 ± 0.7 Mg C-CO2 ha–1 y–1) and in the intact peat swamp forest (16.0 ± 1.2 Mg C-$CO_2$ ha–1 y–1). The $CO_2$ fluxes were spatially variable according to distance to tree/palm or when emitted from tertiary drainage canals but no clear trend was detected. A significant but weak relationship was found between $CO_2$ fluxes and water table level in the peat swamp forest. Soil $CO_2$ emissions in oil palm plantations were higher than those reported from Borneo by other authors. The soil $CO_2$ flux should be separated into its auto- and heterotrophic components and balanced with C inputs and other C outputs in further studies to determine soil net atmospheric impacts on the climate system of this land-use change.

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