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4. How do the heterotrophic and the total soil respiration of an oil palm plantation on peat respond to nitrogen fertilizer application.

Louis-Pierre Comeau[1,2,*], Kristell Hergoualc'h[1], Jodie Hartill[1,2], Jo Smith[2,], Louis V. Verchot[1,4], Peak Derek[3], Agus Mohammad Salim[1]

[1] Forests and Environment Programme, Center for International Forestry Research (CIFOR), Bogor, Indonesia

[2] Institute of Biological and Environmental Science, University of Aberdeen, 23 St Machar Drive, Aberdeen, UK, AB24 3UU

[3] Department of Soil Science, University of Saskatchewan, Saskatoon, Saskatchewan, Canada

[4] Center for Environmental Sustainability, Earth Institute, Columbia Universty. Schermerhorn Extension, 1200 Amsterdam Avenue New York, NY 10027-5557

*Corresponding author:

Email: comeau_louis@hotmail.com

Telephone: +44 (0)1224 272702

4.1. Abstract

Increasing oil palm (OP) plantation establishment on tropical peatlands over the last few decades has major implications for the global carbon (C) budget. This study quantified total and heterotrophic soil carbon dioxide (CO_2) emissions in an industrial OP plantation (7 year old, 149 trees ha^{-1}) on peat located in the eastern coast of the Sumatra Island, Indonesia, after two doses of nitrogen (N) fertilizer application at rates typical of local practice. The first dose applied in March 2012 (first Fertilization event FE) consisted of 0.5 kg urea per palm (equivalent to 371 kg N ha^{-1} at the base of the palm which when extrapolated across the plantation was 35 kg N ha^{-1}) and the second dose applied in February 2013 (second FE) amounted to 1 kg urea per palm. Soil CO_2 fluxes were measured using an infrared gas analyzer (IRGA) in dark closed chambers. The measurements were made daily from 1 day before to 7 days after fertilizer application. Soil heterotrophic respiration (Rh) and total soil respiration (Rs) were measured in trenched plots (where root respiration was excluded) and non-trenched plots, respectively. Concomitant with CO_2 flux measurements, air and soil temperatures, rainfall and the water table level were measured. To estimate the fertilizer effect during the different times of the day, CO_2 fluxes were monitored every 3 h during a 24 h period on days 2 and 3 after fertilizer application during the second FE. Shortly after fertilizer application, substantial pulses of CO_2 were detected in the IRGA chambers where the fertilizer was applied. Even though the fertilized area represents 9.4% of the plantation area only, the impact of fertilizer application at the plantation scale on CO_2 fluxes was noteworthy when compared to non-fertilized control treatments. The Rs was 36.9 kg CO_2-C ha^{-1} (7 days)$^{-1}$ greater in the fertilized than in the non-fertilized plots after the first FE but no enhancement was observed after the second FE. The Rh was 340.5 and 98.9 kg CO_2-C ha^{-1} (7 days)$^{-1}$ greater in the fertilized than in the non-fertilized plots after the first and second FE, respectively. The larger CO_2 flux enhancement in Rh as compared to Rs may be the result of fertilizer uptake by the palm roots in the un-trenched plots, while in the trenched ones where roots were absent, microorganisms used the fertilizer to accelerate soil organic matter mineralization. Although the response of Rh to N addition and the priming effect were high as compared to results in the literature, the impacts were short-term only and may not have implications on the annual C budget of the plantation.

Keywords

Urea, N-induced respiration, tropical peatland, heterotrophic soil respiration

4.2. Introduction

Worldwide the area under oil palm is currently estimated as 10.7 million hectares. Demand for edible or biofuel palm oil along with other derivatives (e.g. soap and makeup) has increased the planted area at an average annual rate of 6% since 2003 (FAO, 2011). This expansion is often made to the detriment of tropical rain forest and peat swamp forest in particular (Carlson et al., 2012; 2013) as oil palm (*Elaeis guineensis*, OP) is one of the few crops that can produce high yields on tropical peatlands (Boehm et al., 2013; Miettinen et al., 2012; Ramdani and Hino, 2013). If land-use change, chiefly driven by industrial enterprises, is maintained at the current rate, all the undisturbed peat swamp forest may vanish by 2030 *(*Koh et al., 2011*;* Lee et al., 2014; Miettinen et al., 2011; Rudel et al., 2009*).* Peatlands of Southeast Asia store a significant amount of carbon (C) (>50 Gt) in their soil. However, these peatlands are concentrated in a few areas of mainly Borneo, Sumatra and Papua (total 247.700 km^2) (Page et al., 2011; Yu et al., 2010). Contrasting with peatlands of the temperate and boreal zone, peat in Southeast Asia accumulates under tall rainforest and can reach depth up to 20 m (Posa et al., 2011).

The conversion of tropical peat swamp forest into OP plantation requires drainage which typically accelerates the rate of peat mineralization (Hergoualc'h and Verchot, 2011; 2014) and enhances soil CO_2 emissions to the atmosphere. The large carbon dioxide (CO_2) fluxes from tropical peatlands play an important role in global climate change (Frolking et al., 2011); therefore promoting policies and strategies to manage peatlands more sustainably is of global concern (Murdiyarso et al., 2010). For climate change mitigation mechanisms such as REDD+ (reducing emissions from deforestation and forest degradation) or for national greenhouse gas accounting, accurate emission factors of C dynamics are essential. A number of recent studies have evaluated the effect of nitrogen

(N) fertilizer on CO_2 emissions in tropical peatlands.Of those, Sakata et al. (2015) and Watanabe et al. (2009) did not find any significant effect of fertilizer on emissions, whereas Jauhiainen et al. (2014) observed an increase in CO_2 flux from agricultural land and a decrease from degraded land after N fertilizer application. No study has assessed the short-term changes in peat-derived CO_2 fluxes following N fertilizer application (priming effect) in oil palm plantations.

Recommended fertilizer application rates in oil palm plantations vary according to climatic conditions, soil type, age of palms, and palm yield potential (Comte et al., 2012). Malaysian recommendations for peat soil range from 50 to 100 kg N ha^{-1} y^{-1} for immature (less than 3 year old) palms and from 120 to 160 kg N ha^{-1} y^{-1} for mature ones (Mutert et al., 1999). Present application in major growing areas on peat for 4-10 year old palms amounts to 0.45 kg N per palm (68 kg N ha^{-1} y^{-1} for a density of 150 palms ha^{-1}; von Uexkull, 2014). Fertilizer is typically spread in a circle which radius is defined by the longest fronds or in a circular area with a radius of ~2.5 m from the palm trunk (FAO, 2012; Lim et al., 2012). Timing of fertilizer application is site-specific, based on plant demand and is made at any moment during the year except during high rainfall periods (Lim, 2005).

Several long-term studies, carried out on mineral soils, have shown that an adequate fertilizer application rate leads to increased crop yields and that crop residues can enhance soil organic matter (SOM) levels without affecting the turnover of native SOM (Snyder et al., 2009). It has also been reported that application of N fertilizer can chemically stabilize soil C, which limits the rate of soil C decline or can even increase the levels of C in the soil (Lemke et al., 2010; Minasny et al., 2012; Paustian et al., 1997; Wilts et al., 2004). However, drained tropical peat soils cropped to OP, display high mineralization rates that greatly exceed C increases through residue inputs (Hergoualc'h and Verchot, 2014). This can be attributed to the fact that SOM with a C:N ratio greater than 20 typically requires additional N for decomposition to occur (Elser et al., 2007; Snyder et al., 2009). Because tropical peats commonly have a C:N ratio greater than 30, N fertilizer application is expected to enhance organic matter mineralization in these soils and increase CO_2 emissions.

Little is known about the impact of applying N fertilizer to tropical peat soils. Simulation models of peat C dynamics such as ECOSSE require information about the effect of fertilizer application on SOM mineralization and CO_2 fluxes (Smith et al., 2010). In turn, the Roundtable on Sustainable Palm Oil (RSPO) seeks reliable scientific data to issue N fertilizer recommendations for tropical peats to achieve optimal production with reduced environmental impacts (Lim et al., 2012). The aim of this research was to quantify total and heterotrophic soil CO_2 emissions from an OP plantation on a tropical peat soil after two customary doses of N fertilizer.

4.3. Materials and methods

4.3.1. Study site

The research site was a 7 year old OP plantation located on a deep peat coastal plain in the province of Jambi, Sumatra, Indonesia (Fig. 4.1). The climate in the region is tropical humid. The average annual rainfall is 2,466 mm with a season drier than the rest of the year from June to August. The minimum and maximum values of the mean monthly temperatures are 22°C and 33°C, respectively (NOAA, 2011; Siderius, 2004). The OP site was situated in the Bakrie Sumatera Plantation of SNP (Sumber-Tama Nusa Pertiwi) (1°39'S, 103°52'E), which is an 8000 ha typical industrial plantation. The landscape was flat in the study area. The palms were planted in 2005 at a density of 149 palms ha^{-1} in a triangular design (8.8 m distance between palms) and usually received, after reaching maturity in 3 years, 149 kg urea ha^{-1} yr^{-1} (70 kg N ha^{-1} yr^{-1}) in either one or two applications. Agrochemicals were used to control pests and weeds within the harvesting rows where the soil was maintained free of vegetation. In the non-harvesting rows, fronds were left to decompose and the soil was covered by ferns. The average peat depth in the plots was 5.75 ± 1.5 m. The drainage system was dug when the land was deforested in 2004 and the water table had been maintained between -50 and -100 cm since 2005. Drainage in the plot consisted of a 1.5 m deep secondary drainage canal perpendicular to the palm rows, and 75 cm deep tertiary canals parallel to the palm rows with one canal every 8 rows. The soil was classified as a Hemic Histosol (Dystric, Drainic) (IUSS-Working-Group-WRB, 2006).

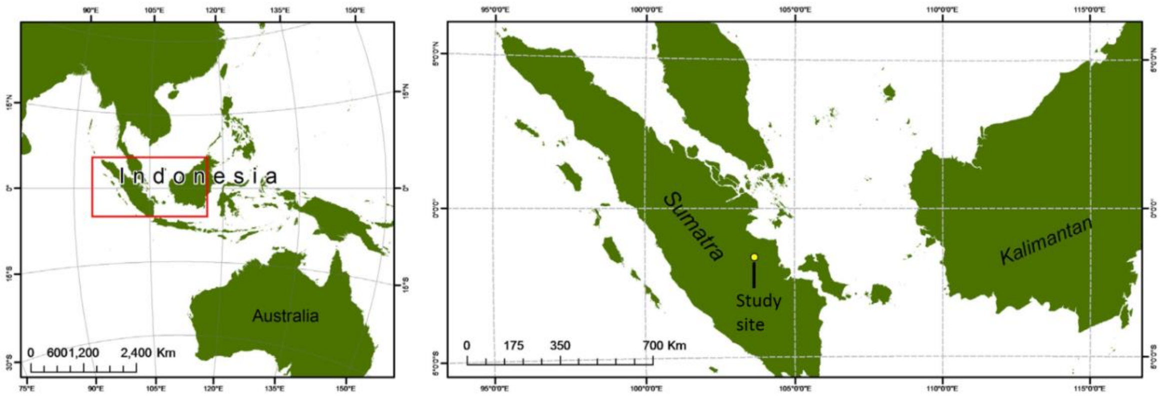

Fig. 4.1: Location of the research site.

4.3.2. Experimental design

A longer-term experiment monitoring Rs and Rh was established in September 2011. The emissions after fertilizer applications were measured in March 2012 and February 2013, six and seventeen months after the start of longer-term monitoring.

The experimental design consisted of two sections of about 500 m^2, one fertilized and the other one non-fertilized (Fig. 4.2). The two sections, located in an area assigned by the plantation administration, were about 30 m apart along the same harvesting row to ensure no fertilizer contamination from the fertilized section to the non-fertilized one. Within each section ten 2.5 X 2.5 m plots were delineated; half of them were trenched (root exclusion technique) while the other half were not. The non-trenched plots were used for measuring total soil respiration (Rs) while the trenched plots where root respiration was excluded, were used to measure heterotrophic soil respiration (Rh). In the following text Rs and Rh correspond to the CO_2 flux measured in the non-trenched and trenched treatments, respectively. Each plot was associated with one oil palm. The trenched and non-trenched plots were paired along the non-harvesting row and located about 8 m apart (Fig. 4.2). In each trenched and non-trenched plot two soil respiration collars were installed, one close to the palm tree (close-to-tree) at a 1 m distance from the trunk and the other one further from the trunk (far-from-tree) at a distance of 2.5 m (Fig. 4.2). The far from tree collars were outside canopy and rooting zone. Previous root and CO_2 measurement studies made on the same plots showed that 1 and 2.5 m distance from the palm trunk were representative of the dense and low root areas at the plantation scale (Farmer 2013). In the fertilized section, urea was applied to all collars located close to the palms in both trenched and non-trenched plots. In the non-fertilized section, no fertilizer was applied. The effect of N fertilizer application on Rs and Rh was evaluated by comparing the fertilized—non-trenched to the non-fertilized—non-trenched treatments and the fertilized—trenched to the non-fertilized—trenched treatments, respectively.

To exclude the roots in the trenched plots, trenches of 2.5 m X 2.5 m X 1 m deep were dug using a chainsaw. The trenches were located at about 25 cm from their corresponding palm trunk. The 0.5 m wide inner side of the trenches was lined with five layers of construction plastic and the trenches were backfilled. Therefore the area inside the trenches where the collars were positioned was 4 m^2. A potential dead root decomposition effect was minimal since the first FE took place six months after trenching. Several trenching studies made on none-tropical mineral soils have shown that decomposition of freshly severed roots takes place in the first two to six months after excision (Hanson et al., 2000; Kelting et al., 1998; Lavigne et al., 2004). The trenched plots were kept free of seedlings and herbaceous vegetation throughout the experiment by hand weeding.

As the practice of the company was to apply the fertilizer in either two applications or a single one, both scenarios were tested. During the first fertilizer application event in March 2012 (first FE), half of the yearly dose was applied while during the second one in February 2013 (second FE), the palms received the yearly dose of 1 kg urea ($CO(NH_2)_2$) (equivalent to 743 kg N ha^{-1} at the base of the palm which when extrapolated across the site was 70 kg N ha^{-1}). In both cases the fertilizer was applied at 9 a.m. to avoid potential urea volatilization during warmer daytime periods. The urea was homogeneously spread by hand to the 10 palms of the fertilized section inside a radius of 1.5 m around the trunks.

The dose of urea applied to the collars located close-to-tree (3.6 and 1.3 g urea collar^{-1} for the first and second FE) was calculated as the ratio between the collar area (0.045 and 0.008 m^2 for the first and second FE, respectively) and fertilizer application area (6.3 m^2) multiplied by the dose applied (500 and 1000 g urea palm^{-1}). The fertilizer application area considered a 1.5 m radius circle around the palm (7.1 m^2) to which was subtracted the palm basal area (0.79 m^2).

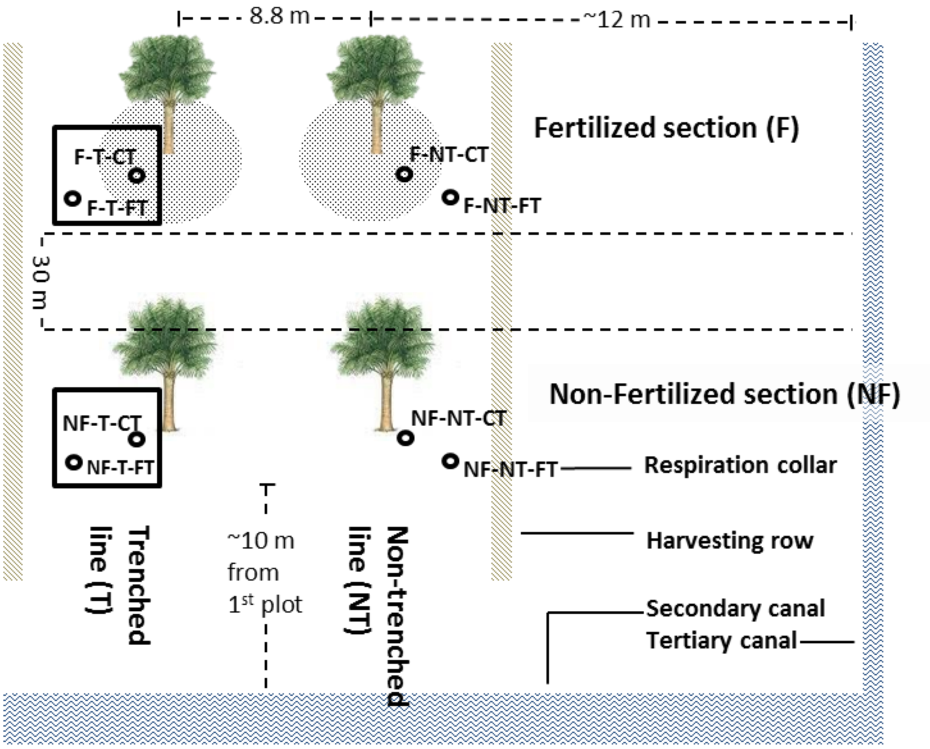

Fig. 4.2: Diagram of the experimental design. Acronyms used in the top part of the figure are: F-T-CT, collar located in the fertilized section, in the trenched plots line, close to the palm tree; F-T-FT, collar located in the fertilized section, in the trenched plots line, far from the palm tree ; F-NT-CT, collar located in the fertilized section, in the non-trenched plots line, close to the palm tree; F-NT-FT, collar located in the fertilized section, in the non-trenched plots line, far from the palm tree. The same acronyms were used in the non-fertilized section (NF) located at the bottom of the figure for indicating the absence/presence of trenching and the position of the collar.

4.3.3. Soil CO_2 flux and environmental variables measurement

Soil CO_2 flux was measured using dynamic closed chambers (Parkinson, 1981; van Straaten et al. 2010). During the first FE an infrared gas analyzer (IRGA) LI-840A (LI-COR Biosciences, Lincoln, NE, U.S.A) was connected to circular polyvinyl chloride (PVC) collars (inner diameter, 0.24 m; height, 0.20 to 0.25 m). During installation, chamber bases were pushed 5 cm into the soil surface. Soil disturbance was minimal given that the chambers were installed 6 months before the beginning of the first FE. The LI-840A recorded CO_2 concentration every second for 4 to 5 minutes. Measurements were made 24 days and 1 day before, 1 hour after fertilizer application (March 20th 2012) and 1, 2, 6, 7 and 16 days after fertilizer application. Days 3, 4 and 5 were not recorded due to equipment failure. The measurements were made between 10:00 a.m. and 2:30 p.m. Contrasting with other diurnal CO_2 flux studies made on tropical peat (Husnain et al., 2014; Jauhiainen et al., 2012; 2014), preliminary results made on the same plots showed that CO_2 flux measurements made at this time are representative of a daily average flux in this agroecosystem (Comeau et al., 2014). Concurrently with CO_2 flux measurements, air and soil (10 cm depth) temperatures were measured with a thermometer at each chamber. The water table level was recorded using perforated PVC pipes (3 cm diameter, 2 m long) located between each per pair (close-to-tree and far-from-tree) of collars. Due to small hummocks around the palm trunks, these water level monitoring pipes were approximately 5 cm lower than the close-to-tree chambers and 5 cm higher than the far-from-tree chambers. Hourly precipitation and air temperature were monitored using a weather station (HD2013, Delta Ohm, Padova, Italy) located less than 1 km from the experimental site.

During the second FE, soil CO_2 flux was measured using a portable IRGA EGM-4 (Environmental Gas Monitor, PP Systems, UK) attached to a soil respiration chamber (SRC-1, PP Systems, UK). Measurements were made in 5 cm tall, 10 cm diameter PVC collars, which were inserted into the soil surface at the same position as the previously used LI-COR collars. As for the LI-COR chambers the EGM-4 collars were installed six months before the beginning of the second FE. The CO_2 flux was measured 14 and 1 day before, 1 h after fertilizer application (February 2nd 2013) and 1, 2, 3, 4, 5, 6, 7 and 14 days after fertilizer application. In the same manner as during the first FE, the environmental variables were recorded concurrently with the CO_2 fluxes. In addition, between days 2 and 3, CO_2 measurements (along with environmental variables) were taken every 3 hours from 8 a.m. on February 4th to 9 a.m. on February 5th 2013 to analyze the initial CO_2 emission pulse after fertilizer application. The measurement scheduled at 11 p.m. on day 2 was postponed to 0 a.m. due to rainfall. During the 24 h measurement, 24 IRGA collars i.e. three replicates per treatment (close-to-tree & far-from-tree in each trenched & non-trenched and fertilized & non-fertilized; Fig. 4.2) were used instead of the 40 IRGA collars (five replicates per treatment) routinely used. To show the prevailing conditions in the different treatments, we present CO_2 fluxes, water table and soil temperature measurements made monthly in the same fashion as described above from January 2012 to January 2013 (excluding data from first and second FE).

4.3.4. Flux calculation

Carbon dioxide fluxes were expressed as kg CO_2-C ha^{-1} d^{-1} even for the hourly measurements between days 2 and 3 of the second FE, for comparability purposes. Fluxes in the non-trenched and trenched plots are here referred as total soil respiration (Rs) and heterotrophic soil respiration (Rh), respectively. The % of Rh close to the palms was calculated as:

$$\% \, Rh = \left[\frac{T-CT}{NT-CT}\right] \times 100 \qquad \text{eq. 4.1}$$

where *% Rh* is the % of heterotrophic respiration, *T-CT* is the CO_2 fluxes from the trenched—close-to-tree position and *NT-CT* is the CO_2 fluxes from the non-trenched—close-to-tree position.

During the first and second FE this calculation was done with the collars of the non-fertilized section only (n=5 per day). Whereas during the longer-term measurement it was done with all the close-to-tree collars (n=10 per month for 13 months). The daily fluxes, from days 0 to 7, were integrated using a linear interpolation between measurement days as:

$$F_{CO_2}\,(t) = \frac{24 \times (M_{CO_2}(t) + \; M_{CO_2}(t+1)\,)}{2} \qquad \text{eq. 4.2}$$

where $FCO_2(t)$ is the total flux on day t (kg C ha^{-1} day^{-1}) and $MCO_2\,(t)$ is the CO_2-C flux measured on day t (kg C ha^{-1} hr^{-1}).

In each section (fertilized and non-fertilized) and for each trenched and non-trenched treatment, the cumulated CO_2-C fluxes (Ccum) at the two spatial positions (close-to-tree and far-from-tree) were calculated as:

$$Ccum = \sum_{t=1}^{t=7} F_{CO_2}\,(t) \qquad \text{eq. 4.3}$$

where *Ccum* is the total C flux over the 7 day measurement period (kg C ha^{-1}).

Subsequently, the amount of C added through urea application (159 and 318 kg C ha^{-1} for the first and second FE, respectively) was subtracted from Ccum of the fertilized—close-to-tree collars (in both non-trenched and trenched plots) because urea ($(CO(NH_2)_2)$) hydrolysis is usually complete within 3 days of application and its C volatilises as CO_2 (Choi et al., 2007; Conde et al., 2005).

The fertilized area (a 1.5 m radius circle around each palm minus the palm basal area) represented 9.4% of the section area therefore the plot-scale fluxes for each trenched and non-trenched treatments were calculated as:

$$PS\ Ccum\ = (Ccum\ CT \times 0.094) + (Ccum\ FT \times 0.906) \qquad \text{eq. 4.4}$$

where *PS Ccum* is the 7 days C flux at the plot-scale, *Ccum CT* is the total C flux over the 7 days measurement period in the position close-to-tree, and *Ccum FT* is the total C flux over the 7 days in the position far-from-tree.

In each trenched and non-trenched treatment and for each fertilizer application, the N-induced CO_2-C emissions were calculated as fertilized plot-scale Ccum minus non-fertilized plot-scale Ccum. The sensitivity of CO_2 emissions to N addition (the amount of CO_2 emitted per amount of N applied over a determined period) was calculated following Choi et al. (2011) as:

$$S.to.N = \frac{PS\ Ccum\ F - PS\ Ccum\ NF}{N\ fertilizer\ rate} \qquad \text{eq. 4.5}$$

where *S.to.N* is the sensitivity ratio of CO_2 emissions to N addition, *PS Ccum F* is the 7 days C flux at the plot-scale in the fertilized section, *PS Ccum NF* is the 7 days C flux at the plot-scale in the non-fertilized section and N fertilizer rate is 35 and 70 kg N ha^{-1} for the first and second FE, respectively.

The percent of emissions attributable to a priming effect was calculated following Hamer and Marschner (2005) as:

$$PE = \frac{PS\ Ccum\ F - PS\ Ccum\ NF}{PS\ Ccum\ NF} * 100$$

eq. 4.6

where *PE* is the percent of priming effect.

The CO_2 flux percentage increase resulting from fertilization was calculated for each spatial position and at the plot scale as the difference in Ccum between the fertilized and non-fertilized plots divided by Ccum of non-fertilized plots.

4.3.5. Soil and root biomass analysis

Prior to the fertilization experiments, three soil pits were dug between the fertilized and non-fertilized sections and used to characterize the soil profile using the morphological description provided by Schoeneberger et al. (2002). The pits were 1 m deep and were located at 1, 2.5 and 4.5 m distance from a palm trunk, respectively. The soil was classified according to the World Reference Base (IUSS-Working-Group-WRB, 2006). Samples were collected from the top 0-20 cm soil layer for chemical analysis. Soil samples were fractionated into very light fraction plus light fraction (VLF+LF, density less than 1.25 g ml^{-1}) and medium weight fraction plus heaviest peat fraction (MWF+HF, density more than 1.25 g ml^{-1}) with a dense liquid (NaI) following Gregorich et al. (2006). The fractionated materials were dried, finely ground with a ball mill, and subsequently analyzed for total C and N content using a Costech Elemental Combustion System (Costech Analytical 191 Technologies, Inc.) coupled to a Delta V Advantage Mass Spectrometer (Thermo Fisher 192 Scientific Inc.). Soil pH (H_2O 1:4) was determined according to van Reeuwijk (2002) from 80 top soil samples taken several times between

2012 and 2013 in the close-to-tree and far-from-tree position. Bulk density of the soil top 6 cm was measured using 3 replicates per collar at the close-to-tree and far-from-tree positions in the trenched and non-trenched plots of the fertilized and non-fertilized sections. Biomass of live fine-root of less than 2mm diameter was measured by collecting soil cores (inner diameter 8.15 cm, height 6 cm) under each respiration collar at the end of the longer-term experiment in January 2014. Alive and dead roots were separated by visual assessment. Fine root biomass was determined using the approach of Tufekcioglu et al. (1999).

4.3.6. Statistics

All of the statistical analyses were done using the statistical program R Foundation for Statistical Computing version 2.8.1 (R Development Core Team, 2008) and effects were considered to be significant at $P < 0.05$. Data were log-transformed when the residuals were not normally distributed. The statistical analysis was done in 4 steps.

1- A t-test was used to assess the environmental homogeneity between the fertilized and non-fertilized section with respect to water table depth, soil temperature, soil bulk density and CO_2 flux data monthly collected from January 2012 to January 2013.

2- Analyses of variance (ANOVA) and the corresponding Tukey post-hoc analysis was used to analyze the prevailing conditions of these variables in the different treatments and to evaluate the effectiveness of soil trenching in removing live roots (“aov” and “TukeyHSD” R Foundation for Statistical Computing).

3- The effect of fertilizer application was tested by comparing daily and hourly fluxes in the F section to that in the non-fertilized for each trenched or non-trenched treatment and each close-to-tree or far-from-tree position. For this purpose, non-parametric independent Wilcoxon tests were used.

4- A 2-way analyses of variance was used to determine the overall effect of the fertilizer on the cumulated CO_2 fluxes (response variable) and the interaction between trenching (factor 1) and fertilizer application (factor 2) (first FE and second FE separately).

The effect of rainfall on CO_2 fluxes is discussed but was not tested statistically because the data were not collected in exact concurrence with flux measurements and because a single rainfall event can influence the fluxes for several days.

4.4. Results

4.4.1. Soil properties and environmental parameters

The peat profiles contained about 20% (by volume) of recognizable plant tissue within the upper 100 cm of the soil profile and the top 10 cm layer was not saturated with water. Therefore, the peat was classified as Hemic Histosol (IUSS-Working-Group-WRB, 2006). The soil displayed a low pH and a high C content typical of ombrogenic peats (Table 4.1). It had a relatively high proportion of very light fraction plus light fraction (VLF+LF) (18.7 % ± 13.3) with a high C:N ratio (i.e. 45.5 ±6.6). The C:N ratio of the medium weight fraction plus the heaviest fraction (MWF+HF) tended to be lower (i.e. 38.8 ±1.8) than that of the VLF+LF suggesting more decomposed material in the former fraction.

Table 4.1: Average (SE, n) of soil chemical and physical properties (0-20 cm).

Variable	Value
pH_H_2O	3.61 (0.03, 80)
Total C (%)	52.7 (1.0, 3)
Total N (%)	1.3 (0.2, 3)
% of VLF+LF[b]	18.7 (13.3, 3)
C:N ratio of VLF+LF	45.5 (6.6, 3)
% of MWF+HF[c]	81.3 (19.7, 3)
C:N ratio of MWF+HF	38.3 (1.8, 3)

SE, standard errors; n, number of replicates; [b] sum of the VLF, very light fraction + LF, light fraction; [c] sum of the MWF, medium weight fraction + HF, heaviest fraction.

The t-tests between the longer-term (13 months) environmental data of the fertilized and non-fertilized sections showed that CO_2 fluxes were homogeneous across sections (P= 0.41) (Table 4.2). Although the sections were not located at the same distance from the deep secondary drainage canal, their water table depth was similar (P = 0.09). The palms in the non-fertilized and fertilized sections displayed a similar fine live-root mass (P = 0.74) and both sections were also homogeneous in terms of soil bulk density and temperature (P = 0.09 and 0.41, respectively).

Table 4.2: Comparison of environmental parameters between the non-fertilized and fertilized sections (SE, n).

Variable	Non-fertilized section	Fertilized section
Average soil CO_2 fluxes (kg CO_2–C ha^{-1} d^{-1})	107.2 (5.2, 242)	101.2 (5.2, 252)
Average water table (cm)	-77.5 (1.1, 260)	-74.6 (0.8, 260)
Average soil temperature (°C)[a]	28.5 (0.2, 259)	28.2 (0.1, 259)
Bulk density (g d.w. cm^{-3})[b,c]	0.22 (0.01, 60)	0.24 (0.01, 60)
Fine-root biomass (mg d.w. cm^{-3})	1.36 (0.60, 20)	1.11 (0.48, 20)
Water table (cm)	77.5 (1.1, 130)	74.6 (0.8, 130)

SE, standard errors; n, number of replicates.
For all these variables, the non-fertilized section and the fertilized section previous to fertilizer application were not statistically different (T-tests with α=0.05).
[a] Soil temperature taken at 10 cm depth.
[b] Bulk density from the 0-6 cm depth.
[c] d.w., dry weight

The analyses of variance used to evaluate the prevailing conditions of the environmental variables measured in the trenched and non-trenched plots, close and far from the palm showed no significant differences in soil temperature at 10 cm depth (P=0.42) (Table 4.3). Conversely, statistical differences between these four treatments were found in CO_2 flux, peat bulk density and fine-root biomass ($P < 0.01$ in all cases). The largest CO_2 flux was found in the non-trenched close to the tree plots and the smallest in the trenched plots (for both close-to-tree and far-from-tree positions). Non-trenched far-from-tree plots had intermediate CO_2 fluxes. The bulkiest soil was found in the non-trenched far-from-tree position and the lightest in the close-to-tree position (for both trenched and non-trenched plots). Trenched far-from-tree plots had intermediate bulk density. The soil porosity results were analogous to the bulk density results. The largest fine-root biomass was in the non-trenched close-to-tree plots and all the other treatments were not statistically different in term of fine-roots (Table 4.3). During the first FE, average air temperature and total precipitation (from day -1 to 16) amounted to 28.9 ± 0.4°C and 282.6 mm, respectively. Heavy rain occurred between days 2 and 5 (cumulative rainfall, 151.2 mm; Fig. 4.3a, b). During the second FE (Fig. 4.3c, d), from day -1 to 14 the average temperature was 27.7 ± 0.2°C and the total precipitation 128.6 mm. Between day 2 and 3 during the 24 h sampling, the temperature was the highest between 12 p.m. and 4 p.m. (36.7-40.6°C) and the lowest between 4 a.m. and 7 a.m. (22.4-21.6°C). A light rain occurred between 10 p.m. and 3 a.m. (cumulative rainfall, 8.6 mm; Fig. 4.4). Throughout the first FE, the soil temperature remained stable around 27.5°C and the water table varied between -61.6 and -77.8 cm depth (Table 4.4). During the second FE, soil temperature and water table fluctuated more than during the first FE with almost a 5°C and nearly 20 cm differences, respectively between the lowest and highest recorded values. Maximum and minimum soil temperatures were measured at 5 p.m. and 9 a.m., respectively (Table 4.5).

Table 4.3: Average soil, alive fine root biomass and climatic conditions in the treatments (SE, n).

Treatment[a]	Average fluxes (kg CO_2–C ha^{-1} d^{-1})	Average soil temperature (°C)[c]	Bulk density (g d.w. cm^{-3})[d]	Porosity (%)	Fine-root biomass (Mg d.w ha^{-1})
NT-CT	126.4 (7.3, 122) α[b]	28.6 (0.3, 130) α	0.20 (0.01, 30) γ	86.8 (1.1, 30) γ	2.47 (0.64, 10) α
NT-FT	108.7 (8.6, 124) αβ	28.4 (0.2, 128) α	0.27 (0.01, 30) α	82.0 (1.7, 30) α	0.28 (0.13, 10) β
T-CT	86.9 (5.1, 125) β	28.1 (0.2, 130) α	0.20 (0.01, 30) γ	86.6 (1.2, 30) γ	0.13 (0.07, 10) β
T-FT	94.9 (7.4, 123) β	28.2 (0.2 130) α	0.23 (0.01, 30) β	84.3 (1.6, 30) β	0.07 (0.06, 10) β

SE, standard errors; n, number of replicates.

[a] Treatments: NT, non-trenched; T, trenched; CT, collar located at 1 m distance from the palm trunk; FT, collar located at 2.5 m distance from the trunk.

[b] Values in the same column followed by a different Greek letter (α, β, γ) are significantly different from each other at α =0.05.

[c] Soil temperature taken at 10 cm depth.

[d] Bulk density from the 0-6 cm depth.

Table 4.4: Average (SE) of environmental features measured simultaneously with soil CO_2 flux during the first and second fertilization events (FE).

	Days before/after fertilizer application												
	-24	-14	-1	0	1	2	3	4	5	6	7	14	16
First FE													
Soil temperature	27.6		27.7	27.3	27.8	27.9				27.2	26.6		27.5
(°C)	(0.1)		(0.1)	(0.1)	(0.1)	(0.1)				(0.1)	(0.1)		(0.1)
Water table depth	-70.1		-75.9	-77.8	-76.9	-74.3				-61.6	-62.7		-65.0
(cm)	(1.4)		(1.3)	(1.5)	(1.3)	(1.9)				(1.5)	(1.4)		(1.3)
Heterotrophic	99		111	80	131	58				67	74		105
respiration (%)	(20)		(19)	(11)	(28)	(31)				(15)	(27)		(45)
Second FE													
Soil temperature		27.7	27.7	27.7	27.7	28.1	27.0	27.2	30.1	29.7	31.7	31.0	
(°C)		(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.2)	(0.1)	(0.3)	(0.2)	(0.2)	(0.3)	
Water table depth		-78.6	-91.6	-87.8	-90.0	-86.1	-87.9	-82.6	-81.8	-82.3	-71.8	-78.7	
(cm)		(1.5)	(2.0)	(1.8)	(1.8)	(1.5)	(1.4)	(2.1)	(2.5)	(2.0)	(1.8)	(2.8)	
Heterotrophic		60	50	58	38	44	48	70	56	45	52	73	
respiration (%)		(13)	(14)	(10)	(9)	(15)	(19)	(29)	(19)	(18)	(16)	(56)	

For soil temperature n=40, for water table depth n=20 and for % of heterotrophic respiration n=5. The % of heterotrophic respiration was calculated at a distance of 1 m from the palm exclusively.

Table 4.5: Average (SE) of environmental features from 8 a.m. on February 4th to 9 a.m. February 5th during the second FE.

	Time								
	8a.m.	11a.m.	2p.m.	5p.m.	8p.m.	0a.m.	3a.m.	6a.m.	9a.m.
Soil temperature	28.3	28.4	28.8	29.1	29.0	29.0	28.9	27.5	26.2
(°C)	(0.1)	(0.2)	(0.2)	(0.2)	(0.1)	(0.2)	(0.2)	(0.2)	(0.2)
Rainfall (mm)	0	0	0	0	2.6	5.8	0.2	0	0

For soil temperature n=24.

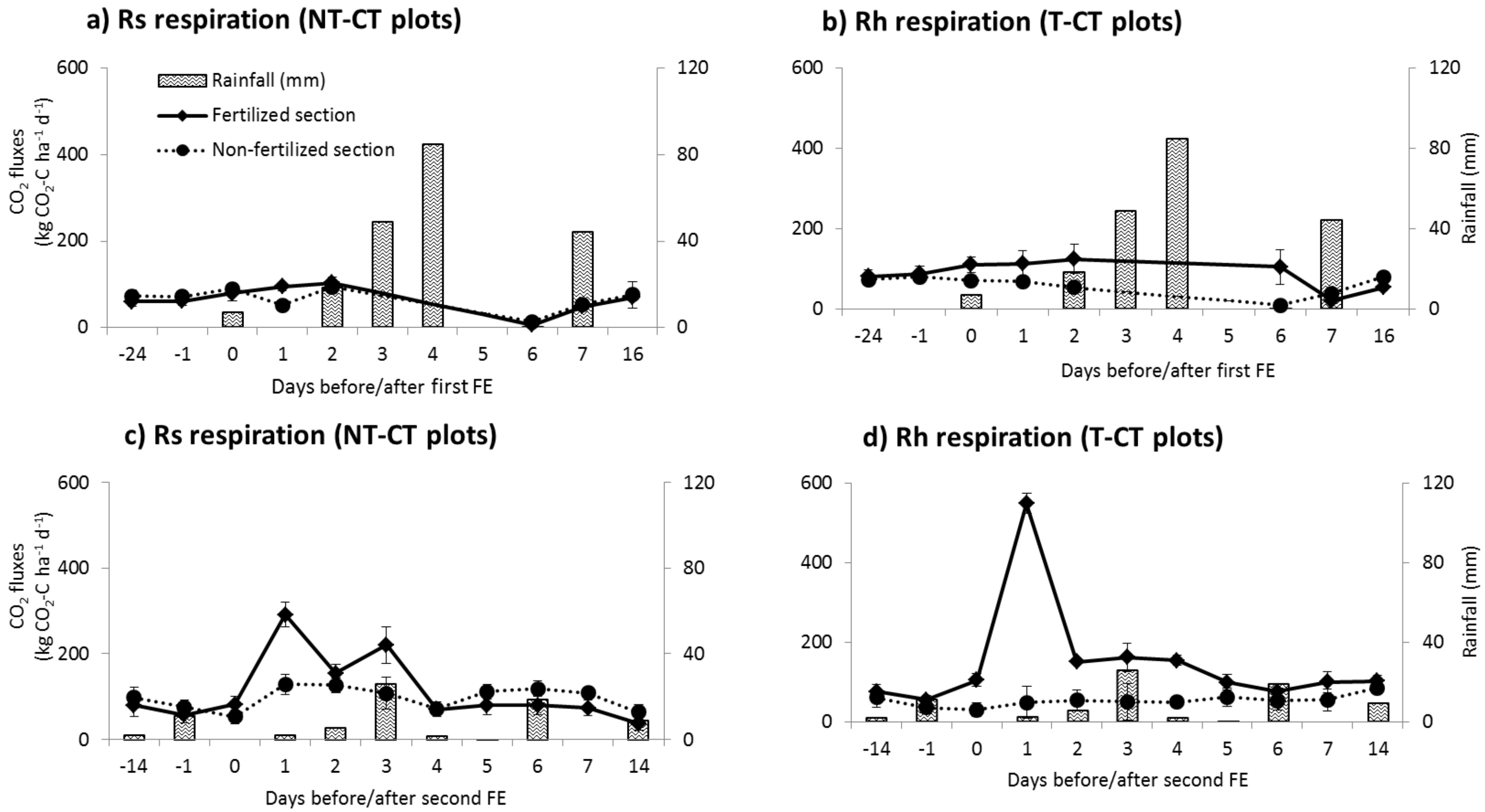

Fig. 4.3: Average daily soil CO_2 fluxes before and after fertilizer application in: a) first FE NT-CT, the non-trenched plots close to the palm; b) first FE T-CT, the trenched plots close to the palm; c) second FE NT-CT, non-trenched plots close to the palm; d) second FE T-CT, trenched plots close to the palm. Error bars indicate the standard error associated with the average, n=5.

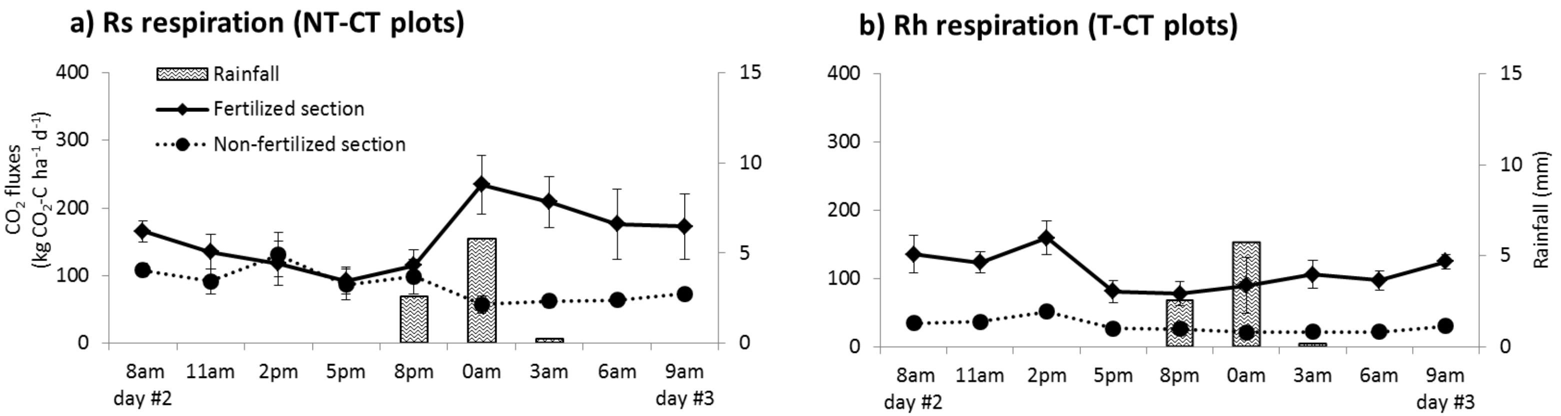

Fig. 4.4: Average hourly soil CO_2 fluxes between day 2 and 3 during the second FE in: a) NT-CT, non-trenched plots close to the palm; b) T-CT, trenched plots close to the palm. Error bars indicate the standard error associated with the average, n=3.

The average contribution of Rh to Rs close to the palm was 91 (±9) % and 54 (±3) % for the first and second FE, respectively (Table 4.4). On 3 occasions during the first FE the percentage Rh to Rs was greater than 100% which is likely to be due to the small number of replicates (n=5) and relatively large variance. The longer-term experiment monitoring CO_2 emissions produced an average of 69% (±8.9) of Rh close to the palm.

4.4.2. Daily and hourly dynamic of soil CO_2 fluxes

The statistical Wilcoxon tests showed that during the first FE, the fertilized—non-trenched—close-to-tree plots had a significantly higher flux than the non-fertilized—non-trenched—close-to-tree plots one day after fertilizer application only (P = 0.03). On that date the Rs in the fertilized plots was 41.3 kg CO_2-C ha^{-1} d^{-1} higher than the Rs in the non-fertilized plots representing an increase of 82% (Fig. 4.3a). The fluxes were higher in the fertilized—trenched—close-to-tree plots than in the non-fertilized—trenched—close-to-tree ones on days 0 (immediately after fertilizer application), 1, 2 and 6. On these dates the Rh in the fertilized plots was 50.8, 55.8, 98.0 and 98.7 kg CO_2-C ha^{-1} d^{-1} higher than the Rh in the non-fertilized plots, respectively. Due to equipment failure, one replicate only was available for the non-fertilized plots on day 2 and 6 and statistical significance could not be determined for these days (Fig. 4.3b).

During the second FE, the Rs was significantly higher in the fertilized section than in the non-fertilized one on day 1 (P< 0.01) and 3 (P = 0.04) after fertilizer application. Differences in fluxes between sections amounted to 176.6 and 127.5 kg CO_2-C ha^{-1} d^{-1} representing increases of 153% and 138%, respectively (Fig. 4.3c). The Rh was significantly higher in the fertilized section than in the non-fertilized one on days 0 (P< 0.01), 1 (P< 0.01), 2 (P< 0.01), 3 (P< 0.01) and 4 (P< 0.01) after fertilizer application. Differences in Rh rates between sections amounted to 75.1, 500.9, 96.2, 111.4 and 104.6 kg CO_2-C ha^{-1} d^{-1} equivalent to increases of 245%, 1026%, 174%, 217% and 208%, respectively (Fig. 4.3d).

During the diurnal measurement, the Rs was significantly higher in the fertilized than in the non-fertilized plots at 8 a.m. ($P= 0.03$), 0 a.m. ($P= 0.01$), 3 a.m. ($P > 0.01$) and 6 a.m. ($P= 0.04$) (Fig. 4.4a). The Rh was significantly higher in the fertilized plots than in the non-fertilized ones at all times between 8 a.m. and 9 a.m. except at 0 a.m. ($P = 0.21$) (Fig. 4.4b). We do not present here the detailed daily or hourly dynamics in the far-from-tree position where no fertilizer was applied. The 7 days cumulative emissions from this position are shown in Table 4.6.

Table 4.6: Cumulative soil CO_2 emission (Ccum, kg CO_2-C ha^{-1} (7 days)$^{-1}$) from day 0 to 7.

		First FE (35 kg N ha^{-1})[a]			Second FE (70 kg N ha^{-1})		
Component of soil respiration[b]	Spatial position[c]	Not fertilized	Fertilized	% increase	Not fertilized	Fertilized	% increase
Rs (NT)	Close to tree (CT)	395.1 (54.1)[d]	275.9 (29.5)	-30.1	745.1 (37.5)	658.0 (49.2)	-11.6
	Far from tree (FT)	304.4 (63.0)	357.5 (52.4)	17.4	285.2 (18.9)	214.5 (19.4)	-24.8
	Plot scale	313.0 (47.5)	349.8 (47.2)	11.8	328.4 (17.4)	256.2 (18.1)	-22.0
Rh (T)	Close to tree (CT)	284.1 (10.6)	595.6 (125.6)	109.7	364.7 (32.7)	979.5 (115.7)	168.7
	Far from tree (FT)	360.1 (7.9)	703.6 (63.7)	95.4	256.0 (20.9)	301.3 (22.8)	17.7
	Plot scale	352.9 (7.2)	693.4 (58.6)	96.5	266.2 (19.1)	365.0 (23.5)	37.1

[a] First FE, first fertilizer application event; second FE, second fertilizer application event.
[b] NT, non-trenched; T, trenched; Rs, total soil respiration; Rh, heterotrophic respiration.
[c] CT, collar located at 1 m distance from the palm trunk; FT, collar located at 2.5 m distance from the trunk (FT collars were outside the fertilized area in all cases). Plot scale calculated as 9.4% Ccum CT + 90.6% Ccum FT.
[d] Numbers are means followed by standard errors (n=5).

Table 4.7: Sensitivity of soil CO_2 emission to added N.

	First FE (35 kg N ha^{-1})[a]			Second FE (70 kg N ha^{-1})		
Component of soil respiration[b]	N-induced CO_2 emissions[c]	Sensitivity CO_2 to N addition[d]	Priming effect[e]	N-induced CO_2 emissions	Sensitivity CO_2 to N addition	Priming effect
Rs (NT)	36.9 (4.5)[f]	1.1 (0.1)	11.8 (1.0)	-72.2 (5.2)	-1.0 (0.1)	-22.0 (3.0)
Rh (T)	340.5 (58.2)	9.7 (1.7)	96.5 (81.1)	98.9 (13.8)	1.4 (0.2)	37.1 (7.2)

[a] First FE, first fertilizer application event; second FE, second fertilizer application event.
[b] NT, non-trenched; T, trenched; Rs, total soil respiration; Rh, heterotrophic respiration.
[c] N-induced CO_2 emissions (kg CO_2-C ha^{-1} (7 days)$^{-1}$) calculated as plot scale Ccum Fertilized – plot scale Ccum Not fertilized.
[d] Sensitivity CO_2 to N addition calculated as (plot scale Ccum Fertilized – plot scale Ccum Not fertilized)/N fertilization rate.
[e] Priming effect calculated as 100 × (plot scale Ccum Fertilized – plot scale Ccum Not fertilized)/ plot scale Ccum Not fertilized.
[f] Numbers are means followed by standard errors (n=5).

4.4.3. Cumulative carbon dioxide fluxes and response to nitrogen addition

The CO_2 fluxes were not normally distributed during either fertilizer application event. Log transformation effectively normalized the residual data for the second FE but not for the first. The cumulative CO_2 fluxes at each close-to-tree and far-from-tree positions in each non-trenched and trenched plots of the non-fertilized and fertilized sections are presented in Table 4.6. The 7 day cumulated emissions during the first FE in the fertilized collars (fertilized—close-to-tree) amounted to 275.9 (±29.5) and 595.6 (±125.6) kg CO_2-C ha^{-1} for Rs and Rh, respectively. The corresponding values during the second FE were 658.0 (±49.2) and 979.5 (±115.7) kg CO_2-C ha^{-1} for Rs and Rh, respectively. Cumulative emissions at the plot scale (i.e. considering that the close-to-tree position represents 9.4% of the plot area) were higher overall in the fertilized than in the non-fertilized plots except for Rs during the second FE.

At plot scale, the % of increase in CO_2 fluxes during the first FE was 11.8 and 96.5 % for Rs and Rh, respectively. During the second FE the % of decrease or increase was -22.0 and 37.1 for Rs and Rh, respectively. The effect of fertilizer application on Rh was higher during the first FE than that during the second one. This is mainly due to higher CO_2 emission rates in the far-from-tree position after the first FE than after the second FE. The 2-way analyses of variance showed that over the second FE, in the absence of fertilizer, Rs and Rh were similar whereas when fertilizer was applied Rh was higher than Rs; the interaction between trenches and fertilizer was significant ($P<0.01$). This trend was also observed over the first FE but no analyses of variance were made due to non-normal distribution of the residuals.

The Rh was 340.5 (±58.2) and 98.9 (±13.8) kg C ha^{-1} greater in the fertilized than in the non-fertilized plots over the 7 day period during the first and second FE, respectively. For the Rs, during the same period, the difference between the fertilized and non-fertilized plot was 36.9 (±4.5) and -72.2 (±5.2) kg C ha^{-1}, respectively (Table 4.6). During the first FE the sensitivity of CO_2 emissions to N addition (i.e. g of CO_2-C emitted per g of N fertilizer applied) and the priming effect were larger for Rh than for Rs ($P < 0.01$ in both cases). The sensitivity of CO_2 emissions to N addition and the priming effect for Rh were smaller during the second FE than during the first FE (Table 4.7).

4.5. Discussion

4.5.1. Carbon dioxide fluxes in response to nitrogen addition

To date there is no consensus in the literature about the direction and timing of N addition effect on soil emissions of CO_2 (Lemke et al., 2010; Minasny et al., 2012; Paustian et al., 1997). Urea application is known to release CO_2 since C is a main component of it. The IPCC guidelines (IPCC, 2006), for instance, suggest the use of an emission factor from urea fertilizer application in forestry and agriculture of 0.2 g CO_2–C g^{-1} urea. This value does not consider any potential increase in SOM decomposition due to N addition as it is actually equivalent to the C content of urea. It corresponds in this study to the 159 and 318 kg C ha^{-1} that were withdrawn from the 7 days cumulative emissions during the first FE and second FE. Once this outer source of C is removed from cumulative CO_2 emissions an increase or a decrease in Rh or Rs can be attributed to a positive or negative priming effect.

Contrasting results have been found on the direction of the effect of N fertilizers on Rs, especially in mineral soils. A few studies have found a decrease in emissions due to N fertilizer application (Ding et al., 2007; Huth et al., 2010), several have found an increase (Conde et al., 2005; Hamer et al., 2009; Iqbal et al., 2009; Khalil et al., 2007; Milkha et al. 2001) and some have found limited or no effect (Grandy et al. 2013; Louro et al., 2013;

Rowlings et al. 2013). These contradictory findings are likely to be due to the intrinsic fertility of the soil and soil organic C content, the timing and method of fertilizer application especially with respect to plant demand, and the experimental design used. In these studies, soils with typical low C content (e.g. Regosol and Luvisols) tended to have no effect or decreased CO_2 emissions after fertilizer application, while soils with high C content (Chernozems, Gleysols and some Cambisols) tended to show increased CO_2 emissions. On boreal peats, N fertilizer application either increased CO_2 emissions (Kivimäki et al., 2013; McGreevy and Farrell, 1984; Shaver et al., 2006) or had no effect (Shaver et al., 2006), but no study mentioned decreased emissions. Only three studies (Jauhiainen et al., 2014; Sakata et al., 2015; Watanabe et al., 2009) were carried out on tropical peatlands. Sakata et al. (2015) and Watanabe et al. (2009) did not find a significant effect of N fertilizer applications on peat mineralization and Jauhiainen et al. (2014) found an increase in agricultural land but a decrease in degraded land.

Our experimental design followed the common practice applied in OP plantations of fertilizing a small area around the palm trunk where roots are more likely to actively take up the fertilizer. The pulses of CO_2 emissions measured either in Rs or in Rh (Fig. 4.3) were therefore concentrated in these small areas which represent only 9.4% of the surface of the field. Nevertheless the impact of these fertilizer-induced emission hotspots was still important at the field scale. Our results showed that cumulated Rh emissions were greater following fertilizer application than in the absence of a fertilizer application (Table 4.6), which confirms that peat mineralization was stimulated by N fertilizer application. On the other hand, cumulated Rs emissions were only slightly increased with fertilizer application in far-from-tree collars during the first FE, and did not increase during the second FE. In these non-trenched plots, palm roots are likely to have absorbed the extra

NH_4^+ coming from theapplied urea before heterotrophic organisms could be stimulated. In addition, because after fertilizer application there was sufficient N in the soil for plant growth, the growth rate of the roots was consequently reduced to conserve C allocation (Beidler et al., 2015; Garnett et al., 2009; Zhang and Forde, 2000).

Concerning the timing of priming effect, our results show that the fertilizer effect lasted only for a few days with an emission peak soon after application. This is in agreement with several other studies on mineral soils and boreal peats (Choi et al., 2007; Hamer et al., 2009; Hergoualc'h et al., 2008; Khalil et al., 2007; Milkha et al., 2001) that found peak CO_2 emissions only during the few days, immediately following N fertilizer application. More precise assessment of CO_2 emission as affected by N fertilizer application should therefore consider more intense measurements in the 24 hours immediately following application and daily monitoring after that for a week.

Given the short term nature of the priming effect, the 340.5 and 98.9 kg CO_2-C ha^{-1} (7 days)$^{-1}$ increases in Rh in the fertilized plots as compared to non-fertilized plots, after the first and second FE, respectively (Table 4.7) will not have any significant effect on annual peat C budgets. Indeed this increases represent about four and one day of average daily emissions, respectively (i.e. 86.9 ±5.1 and 94.9 ±7.4 kg CO_2–C ha^{-1} d^{-1}, close and far from palm respectively; Table 4.3). The even smaller increase in Rs outside of the root zone (53.1 kg CO_2-C ha^{-1} (7 days)$^{-1}$) after the first FE represents only half of average daily emission rate at this spatial position (108.7 ±8.6 kg CO_2–C ha^{-1} d^{-1} far from palm; Table 4.3) and won't be detectable on an annual scale.

4.5.2. Sensitivity of carbon dioxide emissions to nitrogen fertilizer

Choi et al. (2011) reported sensitivity of Rh to N addition between 0.23 and 1.12 g CO_2-C g^{-1} N applied from lab incubation with a loamy soil containing 14 g C kg^{-1}. Because our site had a large amount of organic C (527 g kg^{-1}) and a high C:N ratio (Table 4.1), larger sensitivity values were expected. Indeed the sensitivity we measured (9.7 and 1.4 g CO_2-C g^{-1} N (7 $days)^{-1}$ for Rh during the first FE and second FE, respectively were on average eight time higher than the values measured by Choi et al. (2011). Priming effects are defined as clear short-term changes in the turnover of SOM, which release large amounts of C, N and other nutrients, caused by comparatively moderate treatments (Kuzyakov et al. 2000). Hamer et al. (2009) obtained priming effect values of 13% and 27% in tropical cambisols with, respectively, 12.2 and 7.8 g C kg^{-1} soil, fertilized with urea following 4 days of CO_2 measurements in root-free samples. Larger effects were expected from the soils studied here due to their larger soil C content along with a sizable proportion of VLF+LF (18.7 %) and N limitation. Comeau et al. (2013b) found that the VLF+LF are highly labile and an easily mineralizable soil fraction. The priming effects on Rh measured here (96.5% and 37.1% for first FE and second FE, Table 4.7) were indeed much larger than those from Hamer et al. (2009).

4.5.3. The components of carbon dioxide fluxes and the trenching method

With respect to atmospheric impacts, only peat mineralization or the heterotrophic component of soil respiration actively contributes to climate change. The emissions from root respiration are from recently fixed carbon and will later be reabsorbed through photosynthesis. Here we used the root trenching method to separate Rs from Rh. We recognize the limitations of this approach including a potential alteration of moisture, the decomposition of freshly excised roots and a possible decrease in peat decomposition rates due to the lack of rhizosphere N and P exudates which can promote peat mineralization (Hanson et al., 2000; Kuzyakov, 2006). To avoid dead root decomposition interferences, the experiment started six months after trenching. The longer-term CO_2

flux monitoring in the different treatments shows that the trenched plots are overall a good proxy for Rh in these plots (Table 4.3).

During both FE, we found that, in the absence of fertilizer application, Rs was higher than Rh (i.e. 352.9 (7.2) to 313.0 (47.5) and 328.4 (17.4) to 266.2 (19.1) kg CO_2-C ha^{-1} $(7\ days)^{-1}$ for non-trenched to trenched in the first and second FE, respectively), as expected because Rs is the sum of autotrophic and heterotrophic respiration. By contrast, following fertilizer application, Rh was higher than Rs (i.e. 349.8 (47.2) to 693.4 (58.6) and 256.2 (18.1) to 365.0 (23.5) kg CO_2-C ha^{-1} $(7\ days)^{-1}$ for non-trenched to trenched in the first and second FE, respectively) (Table 4.6). Higher emissions in the trenched compared to the non-trenched treatments following fertilizer application may be explained by decreased N uptake due to the lack of a vegetation sink for mineral N and stimulation of SOM mineralization by the excess inorganic N remaining in the soil (Cheng and Coleman, 1990; Kuzyakov et al., 2000). We therefore recommend that future studies use the trenching method and monitor soil gross N mineralization, nitrification and total inorganic-N content concomitantly with soil respiration measurements. A more appropriate way of monitoring the response of Rh to N addition "in situ", overcoming the absence of root activity associated with the trenching method, would be to use isotopic methods; however these have not yet proved to be fully successful when implemented in tropical peatlands (Farmer 2013).

4.5.4. Carbon dioxide fluxes and environmental variables

The precipitations during the first and second FE might have produced some urea leaching. The heavy rainfalls between days 2 and 7 of the first FE may explain the small decrease in CO_2 fluxes on days 6 and 7 for several chambers (both fertilized and non-fertilized). Even if the peat was highly porous, the intensity of the rain was such that in many places the soil became saturated, likely decreasing aerobic respiration. The light rain that fell between days 2 and 3 (11 p.m. to 1 a.m.) of the second FE (Fig. 4.4) was most likely to low to have caused leaching of soluble N. However, due to the high solubility of urea in water, the humidity brought by this drizzle may have helped the palm roots to absorb the extra NH_4^+ present in the soil and stimulate their respiration. By contrast, only a small increase in Rh following fertilizer application was measured after this rainfall event. While rainfall is certainly a parameter affecting soil respiration, either Rs or Rh, finding simple relationships between both variables is rare due to the lag between rainfall events and plants or microorganisms response as well as the interactions of the parameters affected.

4.5.5. Sensitivity of carbon dioxide emissions to nitrogen fertilizer

Choi et al. (2011) reported sensitivity of CO_2 emissions to N addition between 0.23 and 1.12 g CO_2-C g^{-1} N applied from lab incubation with a loamy soil containing 14 g C kg^{-1}. Because our site had a large amount of organic C (527 g kg^{-1}) and a high C:N ratio (Table 4.1), larger sensitivity values were expected. The sensitivity we measured (9.7 and 1.1 g CO_2-C g^{-1} N (7 days)$^{-1}$ for Rh during the first and second FE, respectively) were higher than the maximum values measured by Choi et al. (2011). Priming effects are defined as clear short-term changes in the turnover of SOM, which release large amounts of C, N and other nutrients, caused by comparatively moderate treatments (Kuzyakov et al. 2000). Hamer et al. (2009) obtained priming effect values of 13% and 27% in tropical cambisols with, respectively, 12.2 and 7.8 g C kg^{-1} soil, fertilized with urea following 4 days of CO_2 measurements in root-free samples. Larger effects were expected from the soils studied here due to their larger soil C content along with a sizable proportion of VLF+LF (18.7 %) and N limitation. Indeed Comeau et al. (2013b) found that the VLF+LF are highly labile and easily mineralizable soil fraction. The priming effects on Rh measured here (96.5% and 37.1% for first FE and second FE, Table 4.7) were indeed much larger than those from Hamer et al. (2009).

4.6. Conclusion

The management of oil palm plantations on peatlands, especially the application of N fertilizer, has implications on the C budget that to date remain unassessed. This research evaluated total and heterotrophic soil CO_2 emissions after two doses of N fertilizer and confirmed the short timing of emission enhancement which occurred in the few days following fertilizer application. One recommendation for further studies on the topic would therefore be to intensively monitor CO_2 fluxes immediately after N fertilizer application. Following fertilizer application, the net CO_2 flux enhancement was larger for heterotrophic soil respiration than for total soil respiration. This higher fertilizer effect in heterotrophic soil respiration as compared to total soil respiration may be explained by the lack of a vegetation sink for mineral N and stimulation of SOM mineralization by excess inorganic N remaining in the trenched plots. In addition, in the none-trenched plots after N fertilizer application palm roots might have reduced their growth rates because they detected a sufficient amount of N in the soil which would have decreased autotrophic and total respiration rates.

This research was limited to the priming effect of N fertilizer application on soil CO_2 emissions. However, decades of fertilizer application may alter pH, microbial community composition and other peat characteristics which in turn would affect the different components of soil respiration. The implementation of long-term studies would therefore be required but remain challenging in practice. This research is a case study on a typical but single industrial oil palm plantation which displays high CO_2 emissions compared to other plantations on peatlands (Carlson et al., 2015; Comeau et al., 2013a). Different environmental conditions, peat characteristics and depth, agricultural practices (e.g. fertilizer other than urea, *E. guineensis* variety, etc.) and palm age could display a different response of soil respiration to N addition. Furthermore, our experiment was located on a representative but limited area and more chamber measurements inside and outside the fertilized area would be advisable. Further studies that test the influence of the above factors would allow a more comprehensive understanding of N fertilization impacts on peat decomposition in oil palm plantations.

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4.7. References

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