High heterotrophic CO_2 emissions from a Malaysian oil palm plantations during dry-season

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Acknowledgements

We are grateful to the TROCARI (Tropical Catchment Research Initiative) team and specifically, Dr Rory Padfield, Siti Noor Fitriah Azizan, Huynh Minh Nhat, Stephané Arul Mariampillai, Tan Jia Min

and Loo Yen Yi for their help in collecting water table depth values and assisting with other elements of data collection during the sampling period.

Reviewed by Nick Girkin (University of Nottingham).

Abstract

Background

Tropical peatlands are currently being rapidly cleared and drained for the establishment of oil palm plantations, which threatens their globally significant carbon sequestration capacity. Large-scale land conversion of tropical peatlands is important in the context of greenhouse gas emission factors and sustainable land management. At present, quantification of carbon dioxide losses from tropical peatlands is limited by our understanding of the relative contribution of heterotrophic and autotrophic respiration to net peat surface CO_2 emissions.

Methods

In this study we separated heterotrophic and autotrophic components of peat CO_2 losses from two oil palm plantations (one established in '2000' and the other in 1978, then replanted in '2006') using chamber-based emissions sampling along a transect from the rooting to non-rooting zones on a peatland in Selangor, Peninsular Malaysia over the course of three months (June-August, 2014). Collar CO_2 measurements were compared with soil temperature and moisture at site and also accompanied by depth profiles assessing peat C and bulk density.

Results

The soil respiration decreased exponentially with distance from the palm trunks with the sharpest decline found for the plantation with the younger palms. The mean heterotrophic flux was 1244.7 ± SE 149.2 mg $m^{-2}h^{-1}$ and 663.8 ± SE 102.2 mg $m^{-2}h^{-1}$ at the 2000 and 2006 plantations, respectively. Autotrophic emissions adjacent to the palm trunks were 944 ± SE 99.7 mg $m^{-2}h^{-1}$ and 1962 ± SE 246 mg $m^{-2}h^{-1}$ at the 2000 and 2006 plantations, respectively. Heterotrophic CO_2 flux was positively related to peat soil moisture, but not temperature. Total peat C stocks were 60 kg m^{-2} (down to 1 m depth) and did not vary among plantations of different ages but SOC concentrations declined significantly with depth at both plantations but the decline was sharper in the second generation 2006 plantation.

Conclusions

The CO_2 flux values reported in this study suggest a potential for very high carbon (C) loss from drained tropical peats during the dry season. This is particularly concerning given that more intense dry periods related to climate change are predicted for SE Asia. Taken together, this study highlights the need for careful management of tropical peatlands, and the vulnerability of their carbon storage capability under conditions of drainage.

Introduction

Tropical peatlands are estimated to occupy 441 025 km^2 globally, with more than half of the total area (247 778 km^2) being located in South-East Asia (Page et al., 2011a), and provide the largest long-term sink of terrestrial carbon (Page et al., 2011b). The substantial amount of carbon (C) present in peatlands of the region has been sequestered over millennia. Nevertheless, recent developments which lead to deforestation and drainage of wetlands, for instance for the purpose of establishment of plantations, may be rapidly turning tropical peat environments into the world's largest sources of carbon emissions (Hoijer et al., 2012, Tonks et al., 2017). The growing world demand for palm oil has driven the extensive conversion of peat into agricultural plantations, with 3.1 million ha of peatlands in the region drained for the establishment of plantations, primarily of oil palm and *Acacia* (Lo and Parish, 2013). Peatlands are especially attractive as areas for plantation establishment due to the capacity for water retention of organic soils and high nutrient release from decomposing drained peat soils (Corley and Tinker, 2003). However, since oil palm trees do not grow well on waterlogged soil due to poor anchorage and anoxic conditions, the establishment of oil palm plantation requires drainage of peat. This greatly increases the risk of high levels of organic matter decomposition, as the presence of oxygen enables the activity of aerobic microorganisms (Husnain et al., 2014).

Total soil respiration (R_s) consists of the autotrophic (root-derived; R_a) and heterotrophic (non-root derived; R_h) components. Heterotrophic respiration involves only the microbial decomposition of soil organic matter (SOM), whereas autotrophic respiration encompasses root growth and maintenance respiration of living roots, as well as emissions from mycorrhizal fungi (Epron, 2009). A major limitation of our ability to understand the consequences of land use change on decomposition processes and CO_2 losses from tropical peatlands, including oil palm plantations, is

the lack of separation of autotrophic and heterotrophic respiration components in the majority of studies (Couwenberg et al., 2010). Consequently, a comparison of loses of C between forests and lands utilised in agriculture is often impossible. Additionally, studies which provide estimates of CO_2 emissions from roots on plantations established on tropical peats are sparse. Jauhiainen et al., (2012) estimated that autotrophic fluxes on an *Acacia* plantation on peat range between 115 and 630 mg CO_2 m^{-2} h^{-1} constituting 9% to 26% of total CO_2 emissions, which compares to findings from oil palm plantations in Indonesia where the autotrophic component was between 15 and 30 % of total CO_2 emissions (Dariah et al., 2014). In contrast, Melling et al. (2013) attributed 60 % of total soil respiration to autotrophic respiration based on a trenching experiment. Hergoualc'h and Verchot (2014) estimate autotrophic emissions from oil palm planted on tropical peat to be around 0.9 ± 2.7 Mg C ha^{-1} y^{-1}.

It is possible that differences in autotrophic respiration among plantation are in part related to the age of plantations. Indeed, Dariah et al., (2014) found comparable heterotrophic respiration rates between plantations of 6 and 15 years while net and autotropic CO_2 emissions were considerably higher in the more productive older plantation. Another uncertainty regarding how land use type influences CO_2 soil flux stems from how the lability of the peat material impacts emissions. It is plausible that surface peat consisting of less decomposed organic matter is the largest contributor to soil CO_2 fluxes as deeper peat may be more degraded and therefore produce less CO_2 due to the recalcitrant nature of the remaining material. Indeed, a relationship between CO_2 emissions and peat functional organic chemistry has been shown from undisturbed tropical peatlands (Wright et al., 2011). However, the variation in peat quality with depth and its role in CO_2 emissions from drained peatlands, including oil palm plantations, remains unclear.

In addition to plantation age and peat quality, the CO_2 flux from tropical peats can be influenced by a range of other environmental factors. For example, Melling et al. (2005) found CO_2 emissions under different land uses were regulated by different environmental factors: relative humidity in secondary forest, soil temperature for sago plantations, and water-filled pore spaces for oil palm plantations. CO_2 flux was also influenced by long-term water table depth on an *Acacia* plantation (Jauhiainnen et al., 2012). The association between peat temperature and heterotrophic respiration is driven by an exponential increase in enzymatic activity in response to higher temperatures up to *c.* 45°C (Luo and Zhou, 2006). Waterlogged conditions of peatlands may limit CO_2 emissions by generating anaerobiosis which reduces peat oxygenation, while very dry conditions and water deficit may also restrain microbial respiration (Jauhianien et al., 2005, Marwanto and Agus, 2014). However, to date neither peat temperature nor moisture controls of CO_2 emissions from oil palm plantations are well understood, particularly in the context of *in situ* fluxes separated into autotropic and heterotrophic components of emissions (Couwenberg et al., 2010).

Given the knowledge gaps around the impact of oil palm plantations on C storage and losses, this study aims to determine the relative contribution and controls of autotrophic and heterotrophic respiration in two oil palm plantations of different ages. This will be achieved by answering the following specific research questions: (i) what is the relative contribution of autotrophic and heterotrophic respiration to net CO_2 effluxes from an oil palm plantation on tropical peat? (ii) How do peat C stocks, soil moisture and temperature control heterotrophic and autotropic CO_2 flux of tropical peatlands utilised as oil palm plantations?

Methods

Research sites

The study was conducted on an oil palm plantation cultivated on a peatland located in South Selangor, Peninsular Malaysia. The oil palm plantation from which samples were taken containing totalled 43km^2 and is within the vicinity of Kuala Lumpur International airport (2°44'25.58", 101°40'29.08") and South Langat Forest Reserve. This plantation is situated on a much larger peat soil area of mixed land use in South Selangor of *c.* 670km^2. Within this, approximately 48km^2 remains as peat swamp forest (albeit highly disturbed). Average annual rainfall in the area is 2419mm with the dry season normally occurring from May to September (with rainfall dipping to *c.* 100-150 mm per month) and, to a lesser extent, also December to February. The examined sites were a first-generation oil palm plantation, established in 2000, replacing secondary forest and a second generation plantation, established in 2006 (original conversion from secondary forest in 1978). Immediately prior to plantation establishment, the forest would have been cleared and ditches dug (to a depth of approximately 1.5-2 m) to drain the peatland resulting in a lower water table. These are then retained for the plantation growth. The peat depth at the time of sampling ranged between 1.5 to 2.1 m. On both plantations, four replicate sites were allocated for CO_2 efflux measurements and six for soil sampling. Soil samples were taken at the four CO_2 measurement sites plus at two extra sites. In both plantation generations, oil palm trees were positioned in the standard planting configuration, in a triangular pattern with the distance between tree trunks being approximately 9m. Each row of trees was arranged with frond piles between rows (where oil palm leaves are discarded) and open harvesting path walkways between trees. The understorey surrounding frond piles consisted mostly of ferns with less aboveground biomass in general at the 2006 plantation as compared with the 2000 plantation. However, the sampling areas themselves,

within the harvesting path locations had bare soil, with no understory vegetation. The distance between the two plantations was approximately 1 km.

Measurement campaign

This study was conducted over a five-month period in 2014, with soil samples taken in April and measurements of CO_2 flux, soil temperature and moisture conducted during the dry season, in the months of June, July and August, over the course of two to three days each month. The soil pH was measured only once, in June or July.

Soil CO_2 flux

Within each plantation, four replicate sites *c.* 50 m apart were selected at random. At each site, a palm tree was selected at random. At each tree, seven collars were placed in a straight line at 0.5 m intervals away from the tree trunk, the first one being located 0.5 m and the last one 3.5 m away from the tree. Surface CO2 measurements across the transect were made to quantify net soil CO_2 fluxes (R_s). Since the majority of oil palm root biomass is estimated to be limited to the zone within a 2 m radius to the tree trunk, the CO_2 fluxes at the 3.5 m collar were assumed to be predominately heterotrophic (R_h) i.e. with negligible contribution of root respiration to the net soil CO_2 efflux (Dariah et al., 2014). The assumption of no roots at the 3.5 m distance was tested by digging soil pits at the study sites. This verified that there were no oil palm roots at the 3.5 distance supporting the assumption of no autotrophic contribution from oil palm to soil fluxes at this distance. Furthermore, sampling points were selected in areas with no understory vegetation to prevent roots from affecting autotrophic respiration. The autotrophic CO_2 emissions (R_a) were calculated by subtracting the flux measured at the 3.5 m collar from the soil respiration (R_s)

measured at the distances closer to the trunk, following the approach used by Jauhianen et al., (2012) in an *Acacia* plantation on peat soil.

The CO_2 fluxes were measured with a Li-Cor LI-8100A. At sample locations, round plastic collars cut from PVC pipes of the same diameter as the Li-Cor chamber were inserted (*c*. 4cm deep) into the peat *c.* 24 hours before measurements. The Li-Cor soil flux chamber was placed onto the collars to collect the CO_2 flux data. The distance from the peat surface to the collar top was taken from inside the collar before each measurement and the corrections in the gas volume within the chamber were made accordingly. One measurement per collar was made every month and each of these lasted 1 minute and 30 seconds.

In parallel with each CO_2 flux measurement, we monitored soil temperature, moisture and water table depth. Moisture and temperature were measured at a depth of around 5-8 cm immediately adjacent to each collar with a Decagon 5TM moisture probe at the time when measurements of CO_2 fluxes were taken. pH values were measured for each collar with an HI 991001 pH probe (Hanna Instruments). Each measurement was taken in close proximity to a collar. The depth of the water table was obtained manually from dipwells which were located at a distance no greater than 10 m from the CO_2 measurement points.

Soil Organic Carbon measurement

Six soil sampling points were randomly allocated at each plantation, each being within a 10 m radius from the collar transects. Soil samples were extracted with a Russian peat corer (50 cm barrel length, 5.2 cm inner diameter, Eijkelkamp, the Netherlands) at 20 cm intervals down to 1 m. The samples were collected in air-tight plastic bags and placed in a refrigerator on the day of sampling. The storage temperature was 3 to 6 °C and the samples were kept for a period of maximum one month. The samples were subsequently oven-dried at 70 °C to a constant weight and sieved through a 2 mm sieve. Since it was not possible to separate the dead and the living biomass in the peat, plant parts were not removed from the sieved samples, with the exception of large root fragments.

Soil Organic Carbon (SOC) content was measured via loss on ignition (LOI). Around 4 to 10g (depending on the sample) of dried soil was placed in a ceramic crucible, weighed and put in the furnace set at 550 °C for 4 hours, upon which the sample weight was measured again. The obtained weights of oven-dried and burnt samples were thereafter used for estimation of SOM and SOC content according to the equation 1 (Farmer et al., 2014):

$p_{ash} = M_{ash}/M_{ds} \times 100$

$C_{org} = (100-p_{ash})/R_{OM:C}$

where:

M_{ds} – sample dry weight

M_{ash} – ash weight after combustion

P_{ash} – sample ash content

C_{org}- SOC content (%)

$R_{OM:C}$ – conversion factor.

The value of 1.878 was used as the $R_{OM:C}$ factor for accurate estimation of SOC content in tropical peats as recommended by Farmer et al. (2014).

Bulk Density

Concurrently, peat dry bulk density (BD) was sampled separately. The samples were collected using fabricated aluminium soil tube samplers (3.5cm radius and 4.5cm height), with lid covers. Each sampler was pre-weighed to determine the weight without soil. For sampling, a soil pit of 100cm depth was dug and samples were taken from the pit wall wall every 20 cm. Soil in the sampler was trimmed to size then closed with lid covers prior to transfer to the laboratory refrigerator. In the laboratory, fresh weight of samples was taken before oven-drying. The BD cores were placed in the oven at 105 ^{o}C for 1-3 days until a constant weight was achieved. BD values were calculated following equation 2 (Dariah et al., 2014):

Bulk Density (gcm^{-3}) = m /V

Where;

m – mass of dry soil sample (g)

V – volume of sample (cm^3).

Statistical analysis and data presentation

All statistical analyses were performed in GenStat version 17. General Linear Models (GLMs) were used to test if CO_2 fluxes (Rs, Ra and the Ra/Rs ratio), pH, soil temperature and soil moisture varied

with distance from the trunk, months and plantations of different ages using plot as the block effect. Exponential decay functions was used to model the decline in Rs, Ra and the Ra/Rs ratio with distance from the trunk. Linear regression was used to assess of environmental conditions (soil temperature and water content, pH, water table level and SOC content) was related to autotrophic and heterotrophic CO_2 emissions. The relationship between the heterotrophic CO_2 flux and water table depth was tested using GLMs with the water table depth as the explanatory variable. The data was visually examined in GenStat for adherence to the normality assumption of GLMs.

Results

CO_2 fluxes

Soil respiration from the peat 2000 and 2006 plantations were 3295 ± SE 149 and 2407 ± SE 102 mg CO_2 m^{-2} hr^{-1}, respectively. At both the 2000 and the 2006 plantation R_s decreased significantly with increasing distance from the tree trunk but the decline was more pronounced at the 2006 plantation (Distance × Plantation interaction: $F_{(6, 167)}$= 3.13, P<0.01; Figure 1 a). The decline in the Rs with distance was described by highly significant exponential decay models ($F_{(3,13)}$ = 16.09; P < 0.001; Figure 1 a). When combined for the two plantations R_s were *c.* 2000 mg CO_2 m^{-2} hr^{-1} adjacent to the tree to 900 mg CO_2 m^{-2} hr^{-1} at 3.5 m away from the palm (Figure 1 a). As expected R_a declined away from the trunk ($F_{(6, 167)}$= 3.26, P<0.01; Figure 1 b) and in parallel with R_s the decline was sharper at the more recently planted 2006 plantation and followed an exponential decay model ($F_{(3,13)}$ = 16.60; P < 0.001; Figure 1 b). The relative contribution of R_a to R_s was 50% at 0.5 m away from the trunk and declined exponentially to 25% 2 m away from the trunk with no significant difference between the 2000 and 2006 plantations ($F_{(3,13)}$ = 5.12; P < 0.05; Figure 1 c). The heterotrophic CO_2 losses from the 2000 first generation site were higher than from the more

287 recently replanted 2nd generation 2006 site but this difference was not statistically significant ($F_{(1,}$
288 $_{23)}$= 0.31, P= 0.60; Figure 2).
289
290 The soil respiration ($F_{(2, 23)=}$ 3.09, P= 0.08) was lowest in August, the month with the lowest soil
291 temperatures (Figure 3 a, b and c), while R_a ($F_{(2,167)=}$ 4.82, P< 0.01) fluxes was lowest in July which
292 was the month with the lowest soil moisture content (Figure 3a,b and d).
293
294 *Environmental controls of CO_2 emissions*
295 At the 2000 and 2006 plantations, soil moisture varied significantly between months ($F_{(2,165)}$=40.81,
296 P<0.001) and so did temperature ($F_{(2,165)}$= 32.05, P<0.001) (Figure 3b and 3d). The average
297 volumetric soil moisture content was similar between the two plantations: 0.20 and 0.20 m^3 m^{-3} at
298 the 2000 and 2006 plantations, respectively. Some of the variation in the peat moisture content
299 between months may be explained by the fact that the August measurements, unlike those of June
300 and July, were conducted following a rain event.
301
302 A significant interaction between the soil moisture content and site (i.e. 2000 or 2006) ($F_{(1, 44)}$=
303 4.47, P= 0.04) (Figure 4a) suggested that heterotrophic CO_2 emissions at the 2006 plantation were
304 moisture-limited. At the 2000 plantation, which had higher CO_2 emissions overall, there was no
305 clear link between the respiration rates and soil moisture content. The autotrophic flux did not
306 depend on the level of soil moisture ($F_{(1, 20)}$= 1.04, P= 0.32) (Figure 4b).
307
308 The water table depth (WTD) was measured at four points on the 2000 plantation and at two
309 points on the 2006 age class. At all measurement points, WTD was well below the peat surface
310 during the entire measurement period, varying between 70 cm and 120 cm in June and August,
311 which reflected the dry weather conditions that were present during these two months as well as

312 the artificially managed drainage extent. The flux did not depend on the water table level ($F_{(1,8)}$=
313 0.83, P= 0.390, r^2= 0.09). The water table was measured in June and August and, consequently, the
314 CO_2 flux data that was used in this particular analysis came from June and August only). WTD had
315 no effect on either surface CO_2 fluxes or peat moisture content of the topsoil during the sampling
316 period ($F_{(1,8)}$= 0.05, P= 0.82).
317
318 Neither heterotrophic nor autotrophic respiration was influenced by soil temperature ($F_{(1,44)}$= 2.75,
319 P= 0.11; $F_{(1,20)}$= 0.84, P= 0.37). There was no interaction between soil temperature and site ($F_{(1,44)}$=
320 2.03, P= 0.161). Furthermore, there was no significant relationship between pH and the spatial
321 variation in the heterotrophic CO_2 emissions averaged by month ($F_{(1, 12)}$= 0.23, P= 0.639) at either
322 of the sites.
323
324 *Soil organic carbon content and C stock*
325 Bulk densities were highest at the peat surface apart from at the deepest layer in the 2006
326 plantation, which was collected from the base of the remaining peat layer (Depth×Plantation
327 interaction: $F_{(3,47)}$= 4.31; P<0.05; Figure 5 a). As expected SOC concentrations declined significantly
328 with depth at both plantations but the decline was sharper in the second generation 2006
329 plantation (Depth×Plantation: $F_{(3,47)}$= 6.07; P<0.05; Figure 5 b). Overall SOC concentrations were
330 higher in the 2000 that the 2006 plantation at 50 and 37%, respectively . Total peat C stocks were
331 60 kg m^{-2} (down to 1 m depth) and did not vary significantly among the two plantations ($F_{(1,11)}$=
332 0.68; P=0.4; Figure 5 c).
333
334
335 **Discussion**

The net CO_2 emissions from both plantations of 288 and 210 Mg CO_2 ha^{-1} yr^{-1} for 2000 and 2006 respectively, are at the higher range of what is reported in the literature for plantations on tropical peat (Jauhianen et al., 2012; Dariah et al., 2014; Husnain et al., 2014). The high emissions are in part likely to be due to our measurements being from day time during the dry season with prevailing high temperatures. To enable comparison with other studies we used our dry season measurement to calculate annual heterotrophic fluxes from our study sites which were 109 and 58 Mg CO_2 ha^{-1} yr^{-1} for the 2000 and 2006 plantation respectively. This is on the higher side of many values previously reported for oil palm plantations on peat e.g. *c.* 35 Mg CO_2 ha^{-1} yr^{-1} (Dariah et al., 2014), 41 Mg CO_2 ha^{-1} yr^{-1} (Melling et al., 2007), 19.3 ± 16.6 Mg CO_2 ha^{-1} yr^{-1} (Agus et al., 2010), 7 Mg CO_2 ha^{-1} yr^{-1} (Melling et al., 2013). Yet while our measured CO_2 fluxes (*c*. 2300 mg m^{-2} h^{-1}) represent some of the highest reported in the literature (Couwenberg et al., 2010), our annual emissions factors are comparable with those of the US Environment Protection Agency, which use an emission factor of 95 Mg CO_2 ha^{-1} yr^{-1}, based on Hooijer et al., (2012) subsidence assessments. However, care needs to be taken when interpreting the annual fluxes as we expect CO_2 emissions to be highest during the dry season so our calculated annual fluxes likely represent an overestimation. The CO_2 flux values reported in this study suggest a potential for very high C loss from drained tropical peats during the dry period. This is particularly concerning given that part of the climate projections for SE Asia is more intense dry periods (IPCC 2014) which may further increase CO_2 emissions from drained peatlands.

It is likely that the lower overall SOC (both at the surface and through the peat profile) in the 2006 plantation was caused by long-term high heterotrophic C losses depleting the SOC (Figure 2 and 5b) in line with Tonks et al., (2017). However, this did not translate into differences in C stocks between the two plantations possibly due the higher bulk densities in the second-generation 2006 plantation. The more dense soil may be due to both mechanical compation from machinery but

may also be due to enhance decomposition as great bulk densities has been found previously following conversion peat swamp forest to oil palm plantations (Tonks et al., 2017).

The high contribution of autotrophic respiration to net CO_2 effluxes; 24 and 72% adjacent to the trunk (0.5 m distance) at the 2000 and 2006 plantations, respectively, highlights that it is critical to account for root respiration when estimating C losses from peatlands (Figure 1). This is particularly important when comparing plantations of different ages, as the relative contribution of autotrophic CO_2 fluxes to net emissions varied considerably among the two plantations as well as spatially with distance from the trunk (Figure 1; Dariah et al., 2014). The sharp decline with distance from the trunk in the 2006 plantation is likely due to a less extensive root system indicating a lower overall contribution of autotrophic respiration to net emissions at the 2006 plantation. The higher autotrophic flux found close to the younger palms in the 2006 plantation (i.e. 0.5 m distance) was unexpected, given that older oil palms have greater root biomass (Jourdan and Rey, 1997; Smith et al., 2012). We speculate that this might be linked to greater NPP and more active root growth in young palm plants or decomposition of old root material from the previous plantation cycle contributing to the near-palm emissions. The autotropic respiration was not related to soil moisture or temperature, even though the values of both variables varied substantially between months. This suggests that neither soil moisture nor high temperature limited root respiration.

Moisture was a stronger driver of heterotrophic CO_2 losses than temperature during the measurement period, however, only at the 2006 plantation. This is in line with findings from

drained oil palm plantations in Indonesia (Jauhiainen et al., 2005; Marwanto and Agus 2014). Within the range of moisture contents found at the 2006 sites (around 20% volumetric moisture content), greater soil water content increased CO_2 emissions suggesting moisture limitation of decomposition. This may, in part, explain why higher temperatures did not substantially increase emissions, as in contrast to finding on Kalimantan, where peat with moisture contents of 70-80% responded strongly to higher temperatures (Jauhiainen et al., 2014). Although the average soil moisture content did not vary between the two plantations, the short duration of sampling (2-3 days each month) does not represent long-term moisture values, which are likely to be influenced by the variations in canopy coverage and evaporation rates between the old and the new tree stands.

The depth of the water table is considered to affect respiration rates via effects on the water content of the top soil where the SOC mineralisation rate is expected to be the highest (Hirano, 2009). In contrast, in this study the water table depth did not impact on the surface peat moisture content or affect the rate of heterotrophic respiration suggesting that the relationship between the water table depth and the microbial respiration was not constant along the whole soil profile or was prevalent to a certain depth only, as has previously been found in temperature and boreal wetlands (Chimner and Cooper 2003; Mäkiranta et al., 2009). However, over long time-scales, a relationship between the water table depth and CO_2 emissions is more likely to be present (Hooijer et al., 2012) and the short duration of this measurement campaign might have prevented the appearance of a clear pattern between the position of the water table and CO_2 emissions. It is plausible that the disconnect between heterotrophic CO_2 emissions and the water table depth shown here, reflects the strong water table draw-down occurring during the dry season. In this case, water table depth would not a reliable predictor of CO_2 emissions during long periods of drought.

In conclusion, we have identified high heterotrophic CO_2 losses from drained tropical peatlands planted with oil palm. Such high emissions are likely to be sustained as long as the drained conditions are maintained. The low SOC in the second generation oil palm plantation suggests that repetitive plantation cycles and associated soil modification has led to C loss throughout the peat profile. Given the large C deposits in tropical peatlands and the rapid conversion of tropical peatlands to oil palm plantations, these high emissions and changed to C stocks suggests that oil palm plantations can act as hot spots of CO_2 emissions.

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Figure captions

Figure 1: a) Net CO_2 flux (R_s), b) Autotrophic (Ra) CO_2 flux and c) relative contribution of R_a to R_s along a transect from the palm trunk to outside the canopy at the 2000 and 2006 plantations. Means ± SE are shown; n = 84.

Figure 2: Heterotrophic CO_2 fluxes at two oil palm plantations of different generations. Mean ± SE are shown; n = 24.

Figure 3: Monthly heterotrophic and autotrophic CO_2 fluxes at the a) 2000 and c) 2006 oil palm plantations. The heterotrophic flux corresponds to CO_2 fluxes measured at 3.5 m distance from the trunk. The autotrophic fluxes shown are means across the 0.5 to 3.0 m measurement points. Monthly peat temperature and moisture data are shown for the b) 2000 and d) 2006 plantations. Means ± SE are shown**.**

Figure 4. Relationship between a) heterotrophic and b) autotrophic CO_2 flux with soil water content at 2000 and 2006 plantations; significant regression lines are shown. The heterotrophic flux corresponds to CO_2 fluxes measured at 3.5 m distance from the trunk. The autotrophic fluxes shown are from 0.5 m distance from the trunk.

Figure 5: a) Soil organic carbon (SOC) content in the peat profile at the 2000 and 2006 oil palm plantations (0.5 and 3.5m subsites) from depth profiles (0-40 [n=6] and 60-100 [n=9], respectively) n= for each variable. Means ± SE are shown; and b) Carbon stock at the 2000 and 2006 oil palm plantations (0.5 and 3.5m sub-sites); n = 15 for each subsite.