



## Abstract

Peat surface CO<sub>2</sub> emission, groundwater table depth and peat temperature were monitored for two years along transects in an *Acacia* plantation on thick tropical peat (>4 m) in Sumatra, Indonesia. A total of 2300 emission measurements were taken at 144 locations. The autotrophic root respiration component of the CO<sub>2</sub> emission was separated from heterotrophic emissions caused by peat oxidation in three ways: (i) by comparing CO<sub>2</sub> emissions within and beyond the tree rooting zone, (ii) by comparing CO<sub>2</sub> emissions with and without peat trenching (i.e. cutting any roots remaining in the peat beyond the tree rooting zone), and (iii) by comparing CO<sub>2</sub> emissions before and after *Acacia* tree harvesting. On average, the contribution of root respiration to daytime CO<sub>2</sub> emission is 21 % along transects in mature tree stands. At locations 0.5 m from trees this is up to 80 % of the total emissions, but it is negligible at locations more than 1.3 m away. This means that CO<sub>2</sub> emission measurements well away from trees are free of any root respiration contribution and thus represent only peat oxidation emission. We find daytime mean annual CO<sub>2</sub> emission from peat oxidation alone of 94 t ha<sup>-1</sup> yr<sup>-1</sup> at a mean water table depth of 0.8 m, and a minimum emission value of 80 t ha<sup>-1</sup> yr<sup>-1</sup> after correction for the effect of diurnal temperature fluctuations, which resulted in a 14.5 % reduction of the daytime emission. There is a positive correlation between mean long-term water table depths and peat oxidation CO<sub>2</sub> emission. However, no such relation is found for instantaneous emission/water table depth within transects and it is clear that factors other than water table depth also affect peat oxidation and total CO<sub>2</sub> emissions. The increase in the temperature of the surface peat due to plantation development may explain over 50 % of peat oxidation emissions.

## 1 Introduction

Lowland peatlands in Southeast Asia cover 24.8 million hectares (Mha), which is 56 % of the tropical and 6 % of the global peatland area (Page et al., 2011). Their high

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carbon density gives rise to a large regional peat carbon store of 68.5 Gt, equivalent to 77% of the tropical and 11–14% of the global peat carbon store (Page et al., 2011). These peat deposits are formed and maintained by continuous organic matter inputs from tropical evergreen forests under waterlogged conditions. Since 1990, 5.1 Mha of the total 15.5 Mha of peatland in Peninsular Malaysia and the islands of Borneo and Sumatra have been deforested, drained and burned while most of the remainder has been logged intensively (Langner and Siegert, 2009; Miettinen and Liew, 2010). Over the same period, the area of unmanaged secondary peat swamp forest doubled to nearly a quarter of all peatlands, whilst industrial oil palm and pulpwood (*Acacia*) plantations expanded dramatically from 0.3 to 2.3 Mha, an increase from 2 to 15% of the total peatland area. By 2008, only 10% of the peatlands of Peninsular Malaysia, Borneo and Sumatra remained in an intact or slightly degraded condition (Miettinen and Liew, 2010). This high rate of land use change and associated increased rate of organic matter oxidation in disturbed and drainage impacted peat, has received increasing attention in recent years in both scientific and policy fora (e.g. Fargione et al., 2008; Rieley et al., 2008; Page et al., 2009; Couwenberg et al., 2010; Edwards et al., 2010; Hooijer et al., 2010; Murdiyarso et al., 2010; Koh et al., 2011). Hence, there is a strong interest in quantifying accurately carbon losses and greenhouse gas emissions from drained tropical peatlands as part of the wider debate on the impacts of tropical land use change on climate change processes.

The carbon dynamics of tropical peatland involves plant photosynthetic CO<sub>2</sub> sequestration and respiration CO<sub>2</sub> emissions (autotrophic respiration), CO<sub>2</sub> emissions from microorganisms involved in aerobic peat decomposition (heterotrophic respiration), fluvial exports of dissolved and particulate organic carbon (DOC and POC), and methane (CH<sub>4</sub>) emissions from microorganisms involved in anaerobic peat decomposition (e.g. Jauhiainen et al., 2005, 2008; Rieley et al., 2008; Moore et al., 2011). The quantities of CH<sub>4</sub> involved are small and their effect on atmospheric processes is much less than concurrent CO<sub>2</sub> emissions (Hadi et al., 2005; Jauhiainen et al., 2005, 2008, 2011). In peat swamp forest the difference between CO<sub>2</sub> sequestered and that

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lost through autotrophic and heterotrophic respiration is stored as structural carbon in tree biomass and accumulated as peat. Unfortunately, most data used to assess the scale of peat carbon losses from drainage-impacted tropical peatlands are confusing and contradictory and the literature on gaseous carbon emissions has been questioned for not quantifying separately autotrophic CO<sub>2</sub> emissions from tree roots and heterotrophic emissions from peat oxidation (cf. meta-analyses by Couwenberg et al., 2010; Hooijer et al., 2010). Two principal methods have been employed, namely closed chamber monitoring (real time) of gaseous CO<sub>2</sub> emissions from the peat surface, and measurement of the lowering of the peat surface as a result of subsidence over time combined with information on peat carbon concentration and bulk density (Couwenberg et al., 2010; Hooijer et al., 2011). Carbon loss estimates based on the latter approach have been hampered by small numbers of measurements, incomplete field information (inadequacy and inconsistency of monitoring) and a lack of reference data on peat characteristics that would enable accurate calculation of carbon loss rates before, during and after land use change. Consequently, most published estimates of carbon losses are derived from peat surface CO<sub>2</sub> emission measurements obtained using the closed-chamber method. Even for this method, however, there are fewer than ten peer-reviewed publications presenting CO<sub>2</sub> emissions data under monitored hydrological conditions (Inubushi et al., 2003; Furukawa et al., 2005; Hadi et al., 2005; Jauhiainen et al., 2005, 2008; Melling et al., 2005; Ali et al., 2006; Hirano et al., 2009), none of which has separated the contribution of CO<sub>2</sub> released in root respiration from total CO<sub>2</sub> emissions, making it impossible to determine CO<sub>2</sub> emissions arising solely from peat decomposition. Further complications are caused by poorly described methods, inconsistent data collection procedures and high variation between the size of data sets which prevents exact and meaningful comparison of results. There is, therefore, an urgent need for peat surface emissions data that quantify accurately and separately the main components of tropical peat CO<sub>2</sub> emissions and provide sufficient information on their temporal and spatial variation.

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transect consisted of either two (C, D, G, H) or four (A, B, E, F) sub-transects along which monitoring locations were situated. The sub-transects were located at 200 m intervals from each other, with the first being 100 m from the nearest canal. They were positioned between tree rows, which were ~3.5 m apart. The peat surface along all transects was almost flat, and microtopographic differences between emission monitoring locations ( $5 \pm 11$  to  $9 \pm 7$  cm) were not significant; the maximum peat surface height difference was only 31 cm between measurement locations along all 8 transects.

## 2.2 *Acacia* tree stand characteristics along transects

Stands of plantation trees along transects consisted of both 1st and 2nd rotation cycles (Table 2); one rotation being ~5 yr from planting to harvest. Monitoring transects included recently harvested sites with bare peat through to closed canopy sites with mature trees. The usual plantation tree species was *Acacia crassicaarpa*, with the exception of transect G where it was *Melaleuca* sp. Based on field observations, four plantation cycle stages were identified: (1) “unplanted” areas cleared of peat swamp forest trees and awaiting planting; (2) “open” canopy areas with 0–6 month old trees; (3) “immature” stands with a closing and closed canopy of 7–30 month old trees, and (4) “mature” closed canopy stands of 30 month to 5 yr old trees. Descriptions of tree stand characteristics during the 2 yr monitoring period are provided in Table 2. Transects D, E and F were located in “unplanted” and “immature” stands; transects G and H were in the younger end of the “immature” tree growth stage; transects A and B were in the older end of the “immature” and “mature” growth stage; and C was in the “mature” growth stage (Table 2, Fig. 2).

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## 2.3 Measurement of peat characteristics

### 2.3.1 Groundwater table depth

The depth of the water table below the peat surface was monitored monthly or quarterly, at the same locations and times as CO<sub>2</sub> emissions, in perforated PVC tubes inserted in the peat surface along the sub-transects.

### 2.3.2 Bulk density and ash contents

Peat samples for determination of bulk density and ash content were collected following the method explained in Hooijer et al. (2011).

### 2.3.3 Peat temperature

Peat temperatures were measured, using a digital thermocouple (Eutech, EcoScan) equipped with a K-type probe, at the same times and positions as the CO<sub>2</sub> emissions and water table measurements. Daytime temperature was measured above the peat surface and at depths of 5, 10, 20 and 30 cm in the peat. Towards the end of the study, temperature was also determined at depths of 40, 50 and 60 cm. Temperatures were measured close to mid-day (average time 11:33) with 50 % of the observations made between 10:28 and 13:14. In order to investigate diurnal fluctuations, temperatures in the peat profile were recorded using Thermochron<sup>®</sup> data loggers at 2-hourly intervals at five peat depths (between 5 and 60 cm) along transect B (closed canopy *Acacia*, 31–36 months old) and transect H (immature *Acacia*, 5–11 months old) during May–October 2008. The key temperature characteristics of the transects are shown in Table 3.

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## 2.4 CO<sub>2</sub> emission monitoring

CO<sub>2</sub> emissions were measured along arrays of 7 regularly-spaced (~0.5 m) gas flux monitoring locations between two adjacent living trees (Fig. 1), assuming that emissions furthest from the tree rooting zone would have a smaller autotrophic component in comparison to those nearest to trees.

Surface peat CO<sub>2</sub> emissions were measured by using a portable infrared gas analyzer EGM-4 connected to an SRC-1 respiration chamber unit (PP Systems, Hitchin, United Kingdom). In order to increase the measurement area, the standard 10 cm cover of the SRC-1 unit chamber was replaced by a 30 cm diameter one. During measurements, the chamber was placed securely over the peat surface and CO<sub>2</sub> concentrations were recorded automatically at 5-s intervals for a total incubation period of 81 s to ensure that readings were consistent and that the chambers were stable and did not leak. The CO<sub>2</sub> emission rates were calculated from the linear change of gas concentration inside the closed chamber as a function of measurement time. Readings were rejected if nonlinear concentration changes were obtained during incubation, owing to leakage or peat disturbance. Readings taken near to damaged trees (wind thrown) were not included in the data set. Measurements were made 2-weekly to monthly unless there were problems of gaining access to the transects. In total, more than 2300 CO<sub>2</sub> emission measurements were obtained at 144 individual locations forming the sub-transects and transects (Table 4, Fig. 1). For the timing of measurements during the day see Sect. 2.3.3.

## 2.5 Treatments to minimize root CO<sub>2</sub> emissions

Several measures were taken to remove or quantify autotrophic root respiration from CO<sub>2</sub> emission resulting from peat oxidation (decomposition). First, it was determined through pit observations that the bulk of the *Acacia* root system, even near “mature” trees, was restricted to within less than a metre from the tree although, in some instances, a few roots close to the peat surface extended over a longer distance in mature

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*Acacia* tree stands. Very few roots were found at monitoring locations in the middle of sub-transects, and it could therefore be assumed that at such locations (i.e.  $\geq 1.3$  m from trees on average) respiration from tree roots was negligible (see Fig. 1). Secondly, monitoring locations were kept free from any herbaceous vegetation; however it should be noted that such vegetation was scarce or absent in most locations. Thirdly, during the last 6 months of monitoring the contribution of root respiration to total  $\text{CO}_2$  emission was tested experimentally along transects B, D, G and H by regular trenching (sawing) of the peat surface down to a depth of 0.5 m around the three central monitoring locations on each sub-transect (at least  $\sim 1.3$  m from trees, Fig. 1), which was the depth within which most lateral tree root growth occurred according to our pit observations. Finally, trees were felled along several transects, before (transects E, G, H) or during (transects D, F) the monitoring period, which allowed measurements under conditions where live tree roots were guaranteed to be excluded or roots would not reach far from recently planted trees (see minimum tree age in Table 2).

Mean daytime root respiration was calculated by subtracting the mean of the  $\text{CO}_2$  emission measured at “furthest from trees” locations from that of the “nearest to trees” locations, i.e. oxidation  $\text{CO}_2$  emissions were subtracted from the total peat emission for mature *Acacia* growth stages (data is based on Table 4).

## 2.6 Statistical analyses

The SPSS<sup>TM</sup> statistical package was used for descriptive and comparative statistical analyses of the data. The main statistical test was univariate analysis of variance (one-way ANOVA), run at the 95 % confidence level.

## 3 Results

### 3.1 Peat characteristics

#### 3.1.1 Bulk density and ash content

Characteristics of the upper peat layer are similar along most transects, with ranges of 0.06–0.12 g cm<sup>-3</sup> (average 0.09 g cm<sup>-3</sup>) and 0.08–2.20 % (average 0.71 %), for bulk density and ash content, respectively (Table 1). This confirms the observation that surface peat at all locations is fibric to hemic, with a very low mineral content, indicating the ombrotrophic nature of the peat.

#### 3.1.2 Groundwater table depth

The average water table depth along all transects is about 0.8 m but there are considerable variations in time and space during the two-year monitoring period (Table 2). On average, the lowest water table during CO<sub>2</sub> flux monitoring was at C transect (mean 1.06 m, and 75 % quartile upper limit at 1.04 m). For transects A and H the water table depth mean was about 0.9 m; along the F, D, B and E transects there were shallower drainage conditions with mean water table depths of between 0.84 and 0.70 m. Transects G and H were located in a hydrology test site where water tables were maintained at distinctly different depths, i.e. the mean water table was 0.43 m at transect G and 0.92 m at transect H.

CO<sub>2</sub> emissions and water table depths measured at “nearest to trees” and “furthest from trees” locations differ significantly only along transects B and D (Table 4). The potential role of water table depth difference on CO<sub>2</sub> emission was tested by applying water table depth as a covariate in the analysis for these transects, but the impact of water table depth difference on the emissions is found to be low (Table 4).

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### 3.1.3 Peat temperature

The average daytime air temperature close to the peat surface is 33.6 °C along transects in the open and young immature *Acacia* stages (transects D, E, F, G, H) and 30.0 °C in closed canopy *Acacia* (transects A, B, C), (Table 3). At a depth of 5 cm below the peat surface, mean daytime temperatures are between 29.3 °C and 33.0 °C (mean 31.5 °C) in the open and young immature tree stands (transects D, E, F, G, H) and between 28.2 °C and 29.2 °C (mean 28.7 °C) in closed canopy tree stands (transects A, B, C). Diurnal mean (24 h) and mean daytime (11:00 to 13:00) peat temperatures at a depth of 5 cm differ by 1.3 °C to 1.6 °C along the closed canopy transect B and the open canopy transect H, respectively. The difference between daytime and diurnal peat temperature averages rapidly diminish with peat depth, to 0.3 °C at 10 cm depth. Data from both manual measurements and automated temperature loggers indicate comparable temperature differences.

### 3.2 CO<sub>2</sub> emissions

Daytime CO<sub>2</sub> emissions data are summarised in Table 4, separated into those “nearest to trees” and those “furthest from trees”, with the latter assumed to approach peat oxidation emission alone, and the former including the combined total of root and oxidation emissions. No significant differences ( $p > 0.05$ ) in CO<sub>2</sub> emission were identified before and after trenching, at the “furthest from trees” measurement locations along the B, D, G and H transects that varied from “mature” to “open” during trenching operations. This confirms that the tree roots are relatively localised around the bases of the trees. Since the data from emissions monitoring at both trenched and untreated locations did not differ, all data from the “furthest from trees” monitoring locations were combined for subsequent analyses.

The highest values for total emissions from “nearest to trees” locations were obtained along transects A, B, C, F and H, three of which (except F and H) are “mature” plantations with average tree stand ages over 31 months. The lowest total emissions were

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obtained along the recently replanted and open transects D, E and G, with average tree stand ages below 13 months.

In two of the three mature tree stands (transects A and B), mean emissions are significantly higher at the “nearest to trees” rather than the “furthest from trees” locations, at 56 % and 21 %, respectively (Table 4). In the mature tree stands (A, B and C) the emission difference is even higher (80 %, 44 % and 14 %, respectively) between individual monitoring locations at ~50 cm distance from trees (location 3 in Fig. 1) in comparison to the “furthest from trees” locations, however, it is only 28 %, 4 % and 1 % respectively at a distance of ~90 cm from trees (location 2 in Fig. 1). Along the other transects in the open and immature trees stands, the differences are in general smaller and either of the emission monitoring locations (“nearest to trees” or “furthest from trees”) could result in the higher emission (Table 4). Mean daytime root respiration, calculated as the emission difference between locations “nearest to trees” and “furthest from trees” for the 1st rotation cycle closed canopy *Acacia* transects (A, B and C) varies between 115 and 630 mg CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup> (data from Table 4). The highest average daytime root respiration at transect A is 36 % of the total emission from at monitoring locations “nearest to trees”. For transects B and C, the average root respiration emissions are about 17 % and 9 % of the emissions at locations “nearest to trees”. The overall mean root respiration for these transects is 320 mg CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup>, which is 21 % of the total emission at “nearest to trees” locations.

### 3.3 Relation between CO<sub>2</sub> emissions, groundwater table depth and tree growth stage

Analysis of datasets of instantaneous daytime CO<sub>2</sub> emissions (both for “nearest to trees” and “furthest from trees” locations) and water table depth along individual transects yields significant relations only for transects B, C, F, G and H. However these relations are very different, and for the other transects no relation is evident at all (Fig. 2).

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### 3.4 Relation between CO<sub>2</sub> emission and long-term average groundwater table depth

In order to determine a possible effect of average long-term hydrological conditions on CO<sub>2</sub> emissions, mean daytime emission rates over the two year monitoring period were tested against mean water table depths for each transect (Fig. 3, based on Table 4). Monitoring transects were also separated into two categories, i.e.  $\leq 16$  months and  $\geq 24$  months old tree growth stages in order to determine if CO<sub>2</sub> emissions differed following recent disturbance (harvesting) compared to the more stable conditions in maturing tree stands.

There is a trend of reducing CO<sub>2</sub> emission when the water table is closer to the peat surface (Fig. 3). Correlation between mean peat oxidation emission and mean water table depth, measured at locations “furthest from trees” in the  $\geq 24$  months old tree growth stages, is very high ( $R^2 = 0.99$ ). It is somewhat lower ( $R^2 = 0.53$ ) for combined open and  $\leq 16$  month old tree growth stages. The total CO<sub>2</sub> emission and mean water table depth relationship is unclear, however, in locations “nearest to trees” for which  $R^2$  values below 0.22 were obtained for the two growth stages used in the analysis (Fig. 3).

The relation between water table depth (in m) and daytime CO<sub>2</sub> emission (in  $\text{mg m}^{-2} \text{h}^{-1}$ ) for all transects is described by the following linear regressions (95 % confidence limits):

For daytime oxidation emission at “furthest from trees” locations:

$$\text{emission} = 953.35 \cdot \text{WTD} + 309.07 \quad (R^2 = 0.47, \text{SE} = 197)$$

For daytime total emission at “nearest to trees” locations:

$$\text{emission} = 989.46 \cdot \text{WTD} + 391.79 \quad (R^2 = 0.34, \text{SE} = 317)$$

Several studies suggest temperature differences in peat impact on organic matter oxidation rates by ratio  $Q_{10} = 2$  (see Sects. 4.4 and 4.6 for details). An average difference between daytime and diurnal peat temperature at 5 cm depth of 1.45 °C is found

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across the *Acacia* plantation. By applying temperature correction, based on diurnal surface peat temperature fluctuation and a  $Q_{10}$  value of 2, daytime  $\text{CO}_2$  emissions are subject to 14.5 % reduction. Presenting these temperature corrected emission values as scaled-up unit ( $\text{t ha}^{-1} \text{ yr}^{-1}$ ), the regressions for all transects are:

5 For temperature corrected oxidation emission at “furthest from trees” locations:

$$\text{emission} = 71.40 \cdot \text{WTD} + 23.15 \quad (R^2 = 0.47, \text{SE} = 197)$$

For temperature corrected total emission at “nearest to trees” locations:

$$\text{emission} = 74.11 \cdot \text{WTD} + 29.34 \quad (R^2 = 0.34, \text{SE} = 317)$$

## 4 Discussion

### 10 4.1 Separation of peat surface $\text{CO}_2$ emission sources

Several measures taken in this study have allowed us to separate  $\text{CO}_2$  emissions caused by peat oxidation from those due to root respiration. The absence of tree roots and therefore of root respiration at locations “furthest from trees” was confirmed by (i) an observed lack of tree roots in control pits, (ii) the lack of effect of the “trenching”  
15 treatment on emissions, and (iii) the absence of a systematic reduction in emissions at locations where trees were harvested during the measurement period. Moreover, the finding that mean daytime total emission values for the most mature tree stands (transects A, B and C) were indeed considerably higher (by up to 80 %, 44 % and 14 %, respectively) at “nearest to trees” rather than at “furthest from trees” locations,  
20 demonstrates that the emission measurement method does measure root respiration where it occurs, which further validates the method. We therefore conclude that it is indeed possible to measure emission that is largely or completely “root respiration free” in drained peatlands, by focusing on measurements well away from trees.

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## 4.2 The contribution of root respiration to the total CO<sub>2</sub> emission

Root respiration contributes 35–45 % to the total peat CO<sub>2</sub> flux in boreal peatlands (Nykänen et al., 1995; Silvola et al., 1996), and in non-tropical natural forest sites the contribution can be between 10 % and 90 %, depending on vegetation type and season (Hanson et al., 2000). Somewhat similar percentages are found near trees in mature tree stands in our study (transects A, B and C), where we found that root respiration accounts for an average of 21 % (36 %, 17 % and 9 %, respectively) of total emissions at “nearest to trees” locations, as compared with the oxidation emissions measured at greater distance from trees. In immature tree stands of 7–16 months age (transects E, F, G and H), however, the contribution of root respiration to total emission could not be calculated due to very different emissions from the two monitoring locations (Table 4, Fig. 2), which is probably explained by the limited extent over which roots have extended over the short time since planting. Even in relatively mature tree stands, roots were observed to hardly go beyond 1 m from trees, which may be explained by the fact that these trees were still less than 4 yr old. Their root systems, therefore, cannot be compared to those occurring in natural forest, where roots are known to extend for many metres from mature trees.

The root respiration contribution of 21 % to the total respiration emission is much lower than the previous values suggested for oil palm plantations on peatland, which range from 46 % (Melling et al., 2007), to 36 % (Murdiyarso et al., 2010) and 29 % (Hergoualc’h and Verchot, 2011). This difference may be caused by the fact that these earlier studies and reviews were based on very small numbers of measurements (at only one location in the case of Murdiyarso et al., 2010 referring to work by Melling et al., 2005), that were not specifically set up to separate root respiration from oxidation emission, i.e. these percentages proposed earlier are rough estimates of root respiration contribution rather than actual measurements.

Emission numbers from studies where the distance of the measurement location(s) from the nearest trees is unknown (e.g. Melling et al., 2005), may tentatively be

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interpreted to represent 21 % root respiration and 79 % oxidation emission: the same percentages that we find in relatively mature *Acacia* plantation. There appears to be no reason to assume that the percentage of root respiration occurring in *Acacia* plantations would differ very much from the percentage of root respiration expected in other types of plantation agriculture on peatland. In fact the extent of the bulk of the root system around mature oil palms has been observed to be less than 1 m in plantations on deep peat in Jambi, Sumatra (A. Hooijer, unpublished data), as is the case in *Acacia* plantations. Considering that oil palms are generally planted further apart than *Acacia* trees (4–6 m compared to 3.5 m between tree rows), there will be relatively more land surface where root respiration is negligible. Moreover, mature oil palm stands have oxidation emissions that are as high or higher than those from mature *Acacia* tree stands, because of similar water table depth and limited canopy cover (compared to natural conditions) combined with much higher fertilization rates (Hooijer et al., 2011). We therefore propose that the root respiration contribution estimates for *Acacia* plantations are also applicable to other peatlands that have been drained and converted to plantation agriculture.

### 4.3 Relation between CO<sub>2</sub> emission and groundwater table depth

When quantifying relations between CO<sub>2</sub> emission and groundwater table depth, it must be considered that water table depth is not in itself a control on peat oxidation. It is, however, a proxy for the soil moisture content above the water table, which is an important control on oxidation, by influencing oxygen availability in the soil pore space (Liyama and Osawa, 2010), since air-filled pore space is the inverse of moisture content. Furthermore, peat moisture content also affects the availability of water to microorganisms involved in oxidation in the peat profile.

In peatlands with high groundwater tables and no controlled drainage, the relation between water table depth and soil moisture content is strong: both go up when it rains and go down in dry periods. Jauhiainen et al. (2005, 2008) found that total CO<sub>2</sub> emissions from undrained and unregulated, drained sites on tropical peatland were

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lowest under water saturated conditions and increased as the water table fell during the dry season. In peatlands with low water tables and controlled permanent drainage, however, such as *Acacia* plantations, this relation is far weaker. Only during major rainstorms is it certain that rainfall will reach the ground water table, as much of it is stored in the unsaturated zone to replenish soil moisture deficits created in preceding dry periods; under such conditions the soil moisture content may fluctuate in time with little effect on water table depth (A. Hooijer, unpublished data). Moreover, water tables in peat follow canal water levels that are managed to meet operational needs of stable drainage depth, so they may fluctuate independently from weather conditions.

Considering the weak connection between water table depth and soil moisture content in the unsaturated peat where oxidation occurs, it is not surprising that the current study has not yielded a significant relation between instantaneous CO<sub>2</sub> emission and water table as measured on individual transects.

#### 4.4 The role of soil temperature in peat oxidation and CO<sub>2</sub> emissions

The rate of decomposition of organic matter on peatlands correlates positively with increase in temperature (Lafleur et al., 2003; Minkkinen et al., 2007; Mäkiranta et al., 2009). In the tropics, diurnal and annual temperature fluctuations are relatively modest in comparison to northern peatlands. However, there is both a general temperature increase after deforestation and also an increase in diurnal temperature fluctuation in the surface peat and hence a likely increase in the rate of peat decomposition. In this study, no significant relationship was found between mean daytime CO<sub>2</sub> emission and mean daytime peat temperature for all transects (R<sup>2</sup>-values from 0 to 0.02), probably owing to the limited variation in daytime peat temperature along each transect (Table 3). In a previous study, however, a clear CO<sub>2</sub> emission/temperature relationship for tropical peat was found through 4 yr of automated hourly monitoring of both variables in peat swamp forest (Hirano et al., 2009); this relation suggests a doubling of instantaneous in-situ peat CO<sub>2</sub> emission rates (including those from root respiration) over a temperature range of 5 °C (from 24 to 29 °C). Moreover, long-term combined field

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and laboratory studies in the subtropical peatlands of the Everglades (Florida) showed that peat oxidation expressed as peat surface subsidence doubled with a 10°C increase in temperature (Stephens and Stewart, 1977). Similarly, CO<sub>2</sub> emission rates from incubated surface samples of tropical peat from Sumatra were also found to double between 25 and 35°C (Brady, 1997). Both Brady (1997) and Hirano et al. (2009) found that the increase in temperature had a greater effect on CO<sub>2</sub> emission rate than soil moisture or water table depth. In our study, we use this relation between temperature and CO<sub>2</sub> emission to adjust CO<sub>2</sub> measurements, which apply to higher daytime temperatures, to correspond to diurnal average temperature conditions.

At a landscape-scale, the surface peat temperature in an intact peat swamp forest is lower and more constant than in deforested and developed tropical peatland (Jaya, 2007), not only because the forest floor is sheltered from direct sunlight but also because it is cooled by evaporation from the peat surface, which usually has a high water content. This cooling effect makes surface forest peat cooler than the air above it, even during the daytime. Average daytime peat temperature at a depth of 5 cm in peat swamp forest (26.5°C) in Central Kalimantan is 2.9°C below the average air (29.4°C) temperature inside the forest (Jauhiainen et al., 2008). After deforestation the amount of solar radiation reaching the peat surface increases and so does the temperature of the peat surface. In Central Kalimantan, the average daytime peat temperature at 5 cm depth is 4.4°C higher (at 29.9°C) in open degraded peatland than in nearby non-drained forest (25.5°C), while the air temperatures just above these peat surfaces are 32.4 and 26.4°C respectively, a difference of 6°C (Jauhiainen et al., 2005, 2008). Jaya (2007) reports an even greater difference in another part of Central Kalimantan, of 7.3°C between average diurnal surface peat temperature in an agricultural area (30.2°C) and in nearby relatively intact forest (22.9°C), while average daytime air temperatures are 28.8 and 33.4°C, respectively. In nearby heavily degraded forest, the average diurnal peat surface temperature and daytime air temperature are 26.7 and 30.4°C, suggesting that even partially removing the canopy cover has a profound effect on peat and air temperature. From the above, we conclude that the average

temperature of surface peat under intact tropical forest cover is around 25 °C at most, a value that we use in further calculations.

In this study, average daytime temperatures of peat and air in the *Acacia* plantation are comparable to those in degraded peatland in Kalimantan. Average peat temperature at 5 cm depth is between 29.3 and 33.3 °C (mean 31.5 °C) in open areas and from 28.2 to 29.2 °C (mean 30 °C) in closed canopy *Acacia* tree stands, and respective mean air temperatures are 33.6 and 30 °C. It must be assumed that these temperatures have increased considerably since deforestation and drainage. If we assume the same original surface peat temperature of 25 °C that was reported for Kalimantan (Jaya, 2007), in natural forest, then the temperature of the surface peat would have increased by 5.6 °C.

#### 4.5 CO<sub>2</sub> emission rates and long-term, average groundwater table

The means of the water table depths along each transect throughout the entire study period (i.e. long-term water table depth) show a strong relationship with long-term mean root respiration free CO<sub>2</sub> emissions (Fig. 3). CO<sub>2</sub> emission rates along the transects are lower at higher water table depths (i.e. when the water table is nearer to the surface). A similar CO<sub>2</sub> emission/water table depth relationship is found for the unplanted and recently planted (≤16 month old) transects and for those with older (≥24 month old) trees. The highest regression R<sup>2</sup>-value (0.99) is for the mature tree growth stage, which represents comparatively constant environmental conditions after several years have lapsed following harvesting and re-planting operations, and where the closed canopy provides relatively stable microclimatic conditions at the peat surface.

As the CO<sub>2</sub> emission means are based on 2 yr of data collected intensively from a relatively large area (Table 4), these values can be used to quantify annual emissions for the entire plantation. The overall daytime mean (±SE) peat oxidation CO<sub>2</sub> emission derived by regression (Fig. 3) is 93.9 ± 17.2 tCO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup> (1072 ± 197 mg m<sup>-2</sup> h<sup>-1</sup>) at 0.8 m water table depth. Other studies on permanently drained peat, albeit with relatively few measurements over shorter periods and without measures to quantify

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the contribution of root respiration, provide emissions of  $201 \text{ mg m}^{-2} \text{ h}^{-1}$  (water table depth 0.07 m) on a taro field (Chimner and Ewel, 2004),  $733 \text{ mg m}^{-2} \text{ h}^{-1}$  (water table depth 0.24 m) on a cassava field (Furukawa et al., 2005),  $504 \text{ mg m}^{-2} \text{ h}^{-1}$  (water table depth 0.27 m) under sago and  $693 \text{ mg m}^{-2} \text{ h}^{-1}$  (water table depth 0.60 m) under oil palm (Melling et al., 2005). Although most of these mean  $\text{CO}_2$  emissions (Chimner and Ewel, 2004; Furukawa et al., 2005; Melling et al., 2005) are outside the water table depth range in this study, an extended regression line to water table depths of 0.2 and 0.3 m (Fig. 3) would result in a comparable  $\text{CO}_2$  emission range from 502 to  $597 \text{ mg CO}_2 \text{ m}^{-2} \text{ h}^{-1}$ .

The mean daytime peat oxidation  $\text{CO}_2$  emission from this study of  $\sim 94 \text{ t CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$  at 0.8 m drainage depth (Fig. 3), is higher than reported in most other studies that have used subsidence measurements, as presented in recent meta-analyses (Couwenberg et al., 2010; Hooijer et al., 2010). One explanation for this may be that this value is based on daytime  $\text{CO}_2$  flux measurements, which may result in an overestimate if peat temperatures vary diurnally. This emission value may therefore be considered a maximum, which should be corrected for daytime temperature and emission both being above average.

### 4.6 Correcting $\text{CO}_2$ emissions for temperature effect

In this study, we calculated the potential impact of diurnal peat temperature differences on peat decomposition rates on the basis of  $Q_{10}$ -values provided from the literature for comparable environmental conditions (see Sect. 4.4). The average daytime peat decomposition  $\text{CO}_2$  emission of  $94 \text{ t ha}^{-1} \text{ yr}^{-1}$ , which covers both open and closed canopy conditions, was used as a reference. The diurnal mean temperatures of the surface peat were found to be lower in comparison to the daytime temperatures measured during gas flux monitoring. The average difference between daytime and diurnal temperatures is  $1.45^\circ\text{C}$  across both open and closed canopy conditions inside *Acacia* plantations. Assuming that a difference in peat temperature of  $1^\circ\text{C}$  will result in a

10% difference in CO<sub>2</sub> emission (Brady, 1997; Stephens and Stewart, 1977; Hirano et al., 2009), the daytime CO<sub>2</sub> emission value may therefore be reduced by up to 14.5% to account for diurnal temperature fluctuation in peat. Applying this correction to the mean daytime CO<sub>2</sub> emission value of 94 t ha<sup>-1</sup> yr<sup>-1</sup> we find an average emission value of 80 t ha<sup>-1</sup> yr<sup>-1</sup> (Fig. 3).

This temperature corrected emission value of ~80 CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup>, at an average water depth of 0.8 m, is close to the value of 76 t CO<sub>2e</sub> ha<sup>-1</sup> yr<sup>-1</sup> resulting from subsidence and bulk density measurements conducted partly in the same landscape at the same water table depth (Hooijer et al., this issue). It is also close to the values of 72 to 72.8 t CO<sub>2e</sub> ha<sup>-1</sup> yr<sup>-1</sup> suggested by Hooijer et al. (2010) and Couwenberg et al. (2010) in their meta-analyses, for a plantation water depth of 0.8 m. In two other studies, Murdiyasar et al. (2010) and Koh et al. (2011) apply a much lower CO<sub>2</sub> emission estimate (34.1 t ha<sup>-1</sup> yr<sup>-1</sup> at 0.5 m water table depth) for peat oxidation under plantation conditions. This estimate, however, is based on only two case studies (Murayama and Bakar, 1996; Melling et al., 2005) that present very limited datasets at only one or a few locations, and a poor description of measurement method and field conditions.

The above correction applies a diurnal temperature difference measured near the peat surface, at 5 cm depth, whereas we find that temperature fluctuation diminishes rapidly with depth. Our approach therefore implicitly assumes that most peat oxidation, and therefore most production of CO<sub>2</sub> gas, takes place in the upper 10 cm of the peat profile. We may assume that oxygen availability is highest at such limited depth, and it appears likely that the near-surface layer contains a relatively large amount of the most labile peat carbon compounds, so it does seem probable that the highest oxidation rate is indeed found near the peat surface. While we have no information on the distribution of CO<sub>2</sub> gas production in the peat profile, it is likely that part of it is generated at greater depth and, therefore, the temperature corrected emission value of 80 t ha<sup>-1</sup> yr<sup>-1</sup> may be seen as a minimum estimate. Support for the correction value applied, however, is provided by other studies.

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In drained forest in Kalimantan, the average of long-term diurnal CO<sub>2</sub> emission is 18% below emissions measured at 12:00 (Hirano et al., 2009). A single 24-h CO<sub>2</sub> emission monitoring by Ali et al. (2006) in Jambi also yielded a comparable diurnal emission difference of 18% in selectively logged and drained peatland, and a 13% difference in an oil palm plot on peat. These three values, with a narrow range of 13% to 18% in very different land uses in different parts of Indonesia, are close to the 14.5% reduction applied in the current study for daytime emission measurements in *Acacia* plantations.

The high sensitivity of CO<sub>2</sub> emissions to peat temperature, and the resulting relative insensitivity to water table depth, implies that bringing up water tables in plantations will not reduce carbon losses by as much as would be expected on the basis of peat surface emissions in forest systems (e.g. Jauhiainen et al., 2005, 2008) or earlier relations between water table depth and CO<sub>2</sub> emission (e.g. Couwenberg et al., 2010; Hooijer et al., 2010). The implication of this is that high CO<sub>2</sub> emission from any peatland that is converted to agriculture, whatever its water and land management, may have to be regarded as inevitable.

### 4.7 Comparing temperature and water table depth as likely main drivers of oxidation emission in tropical peatland plantations

The effect of temperature on average CO<sub>2</sub> emission from the *Acacia* plantations can be estimated by applying the same correction factor as used above, of a 1 °C temperature difference yielding a 10% difference in CO<sub>2</sub> emission, to the average increase of 5 °C after deforestation and drainage that follows from the above analysis of data from Central Kalimantan. This would indicate that up to 56% of the CO<sub>2</sub> emission in *Acacia* plantations may be caused by the change in peat temperature after plantation development alone, which would make it the most important single control. The remaining 44% of emission would then be caused by soil moisture (with water table depth as a proxy), but also by soil disturbance and fertilization. This likely dominance of temperature as a cause of oxidation in tropical peatland plantations has not been given much attention in

earlier studies reviewed by Hooijer et al. (2010) and Couwenberg et al. (2010), which have been more focused on the effect of water table depth. This may be explained by the absence of accurate time series of soil temperature in most studies.

## 5 Conclusions

This study is the largest and most detailed investigation of CO<sub>2</sub> emissions undertaken in an industrial plantation on tropical peat. It is also the first study to separate “root respiration” and “peat oxidation” CO<sub>2</sub> emissions. We conclude that this scale of study, and a consistent approach to separating emission contributions, is necessary in order to quantify “net” CO<sub>2</sub> emissions from drained peatland. We provide descriptions of a monitoring set-up that can yield such results, and that deviates significantly from set-ups applied in earlier studies.

The contribution of root respiration to CO<sub>2</sub> emission is found to be 21 % on average along transects in mature tree stands. Significant root respiration occurs very close to trees, but it is negligible at locations more than 1.3 m away from trees. This means that emission measurements well away from trees are free of root respiration and represent only oxidation emission.

We found an average minimum temperature corrected oxidation CO<sub>2</sub> emission of 80 t ha<sup>-1</sup> yr<sup>-1</sup> for the *Acacia* plantation, after reducing an average value of 94 t ha<sup>-1</sup> yr<sup>-1</sup>, as measured during the daytime, by 14.5 % to account for the lower peat temperatures that occur by night. Such a correction has not been applied before, but we think it is necessary to be able to compare the results of different emission studies. The resulting value applies at an average water table depth of 0.8 m, in peatland with a thickness greater than 4 metres, for a peat surface covered by vegetation and with limited fertilizer application only in the first year after planting.

Mean long-term water table depth along transects correlates quite well with average oxidation CO<sub>2</sub> emissions, although the results of our study indicate that temperature differences may be the most important control on peat oxidation and may in fact

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explain over 50% of emissions from drained peatlands when compared to forested, pre-clearance conditions. Even if the water table were at the surface, which is impossible in plantations, the relation found would predict that CO<sub>2</sub> emissions from peat oxidation are still 23 t ha<sup>-1</sup> yr<sup>-1</sup> or more. It is therefore evident that high CO<sub>2</sub> emissions are inevitable in any type of agriculture on tropical peatland.

There is no reason to assume these conclusions apply only to *Acacia* plantations. All agriculture on peat requires removal of forest cover and lowering of the water table, similar to the study sites. Growing non-permanent crops (like vegetables, rice) on peat results in less ground cover and higher temperatures than in *Acacia* or oil palm plantations. Most crops, including oil palm, also require much higher fertilizer inputs than *Acacia*, which will further enhance peat oxidation. Thus emissions from other types of agriculture on peat are likely to be as high or higher than those from *Acacia* plantations, at similar water depths and on similar peat types.

*Acknowledgements.* We thank APRIL (Asia Pacific Resources International Limited) for data collection and financial support, and the SDWA and TROPEASS projects for further financial support. Jack Rieley is thanked for helpful comments during paper preparation.

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## Carbon dioxide emissions from an *Acacia* plantation

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**Table 1.** Main characteristics of the peat at the CO<sub>2</sub> monitoring transects.

Transect	Peat		
	Depth (m)	BD* (g cm <sup>-3</sup> )	Ash content* (% of dw)
A	4.1–4.7	0.11 ± 0.01	0.29 ± 0.11
B	7.8–9.0	0.12 ± 0.02	2.61 ± 1.37
C, D	4.6–5.1	0.08 ± 0.03	0.15 ± 0.10
E	5.1–5.5	0.07 ± 0.01	0.08 ± 0.02
F	7.9–9.5	0.06 ± 0.01	0.51 ± 0.24
G, H	5.0–6.2	0.06 ± 0.01	0.19 ± 0.05

\* Mean ± SD at 30–50 cm horizon from the peat surface ( $n = 3 - 9$ ).

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**Table 2.** Tree stand age characteristics (months) and average water table characteristics (m from the peat surface) at the CO<sub>2</sub> monitoring transects over the two year monitoring period.

	Tree stand age (months)								Water table depth (m)							
	A	B	C	D	E	F	G, H	A	B	C	D	E	F	G*	H	
Mean	31.2	32.6	46.2	1.3	6.0	7.1	12.2	0.93	0.77	1.06	0.71	0.72	0.84	0.43	0.92	
SD	6.1	4.4	6.0	2.4	0.8	3.4	2.7	0.28	0.16	0.33	0.25	0.22	0.14	0.12	0.16	
Range	17	17	20	13	2	12	8	1.28	0.90	1.55	1.26	0.94	0.67	0.55	0.60	
Min.	24	26	40	0	5	-2	8	0.30	0.31	0.41	0.07	0.26	0.55	0.17	0.60	
Max.	41	43	60	13	7	10	16	1.58	1.21	1.96	1.20	1.20	1.22	0.72	1.20	
%ile 25	26	29	41	0	5	6	10	0.72	0.67	0.83	0.58	0.59	0.73	0.34	0.81	
%ile 50	28	33	43	0	6	9	13	0.90	0.76	1.04	0.69	0.73	0.83	0.43	0.97	
%ile 75	38	35	52	2	7	9	14	1.13	0.87	1.26	0.90	0.86	0.94	0.52	1.04	
Cycle	1st	1st	1st	2nd	2nd	2nd	2nd									

\* At G transect water table was maintained closer to surface than is normal in the plantation area.

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**Table 3.** Temperatures (mean  $\pm$  SD) of air close to the peat surface, and at depths of 5, 10, and 60 cm into the peat based on manual measurements at daytime during CO<sub>2</sub> flux monitoring and diurnally collected logger data.

Position	Temperature (°C) at transects					
	Manual measurement*				Logger data	
	Daytime				Daytime	Diurnal
	A	B	C	D	B	B
Air	30.9 $\pm$ 2.7	28.9 $\pm$ 2.1	30.2 $\pm$ 1.7	33.0 $\pm$ 3.2	29.7 $\pm$ 2.9	26.7 $\pm$ 2.9
5 cm	29.2 $\pm$ 2.3	28.2 $\pm$ 2.0	28.6 $\pm$ 1.4	30.5 $\pm$ 2.5	27.8 $\pm$ 1.6	26.5 $\pm$ 1.6
10 cm	28.9 $\pm$ 2.2	28.2 $\pm$ 1.9	28.5 $\pm$ 1.6	29.4 $\pm$ 2.1	27.1 $\pm$ 1.1	27.0 $\pm$ 1.2
60 cm	31.3 $\pm$ 2.6	29.7 $\pm$ 1.3	30.9 $\pm$ 0.9	30.6 $\pm$ 1.4	28.5 $\pm$ 0.6	28.5 $\pm$ 0.6
	E	F	G	H	H	H
Air	36.9 $\pm$ 2.3	31.0 $\pm$ 3.2	34.1 $\pm$ 3.8	33.2 $\pm$ 2.5	32.6 $\pm$ 3.7	26.9 $\pm$ 4.2
5 cm	31.9 $\pm$ 1.5	29.3 $\pm$ 2.2	33.3 $\pm$ 3.6	32.6 $\pm$ 2.6	28.9 $\pm$ 1.8	27.3 $\pm$ 2.0
10 cm	30.3 $\pm$ 1.6	28.9 $\pm$ 1.7	33.1 $\pm$ 3.5	32.3 $\pm$ 2.7	27.9 $\pm$ 1.0	28.2 $\pm$ 1.2
60 cm	31.9 $\pm$ 1.4	30.7 $\pm$ 1.1	33.5 $\pm$ 3.1	33.4 $\pm$ 2.0	29.9 $\pm$ 0.3	29.9 $\pm$ 0.4

\* Daytime mean peat temperature at 5 cm depth is 30.5°C for all transects (A–H), 28.7°C for transects A–C, and 31.5°C for transects D–H.

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**Table 4.** Mean daytime measured CO<sub>2</sub> flux in “furthest from trees” and “nearest to trees” locations and the related mean water table depths at the monitoring transects.

Transect code	Location relative to trees	N	CO <sub>2</sub> (mg m <sup>-2</sup> h <sup>-1</sup> )			Water table depth (m)			p-value	
			Mean	SE	SD	Mean	SE	SD	CO <sub>2</sub>	WD
A	Furthest	158	1128	23	292	0.92	0.02	0.27	< 0.001	ns
	Nearest	284	1758	38	649	0.94	0.02	0.28		
B*	Furthest	192	1028	26	364	0.78	0.01	0.15	< 0.001	< 0.005
	Nearest	270	1242	26	426	0.73	0.01	0.17		
C	Furthest	140	1185	43	507	1.03	0.03	0.32	ns	ns
	Nearest	222	1300	40	596	1.08	0.02	0.33		
D*	Furthest	350	903	14	253	0.69	0.01	0.25	< 0.001	< 0.01
	Nearest	71	705	38	319	0.78	0.03	0.24		
E	Furthest	34	799	67	392	0.75	0.04	0.23	ns	ns
	Nearest	44	755	67	446	0.70	0.03	0.22		
F	Furthest	74	1103	49	417	0.85	0.02	0.14	< 0.001	ns
	Nearest	154	1366	39	480	0.84	0.01	0.14		
G	Furthest	143	844	24	283	0.45	0.01	0.12	ns	ns
	Nearest	30	887	49	271	0.36	0.02	0.09		
H	Furthest	127	1584	44	496	0.93	0.01	0.16	< 0.05	ns
	Near est	29	1345	74	398	0.86	0.02	0.12		

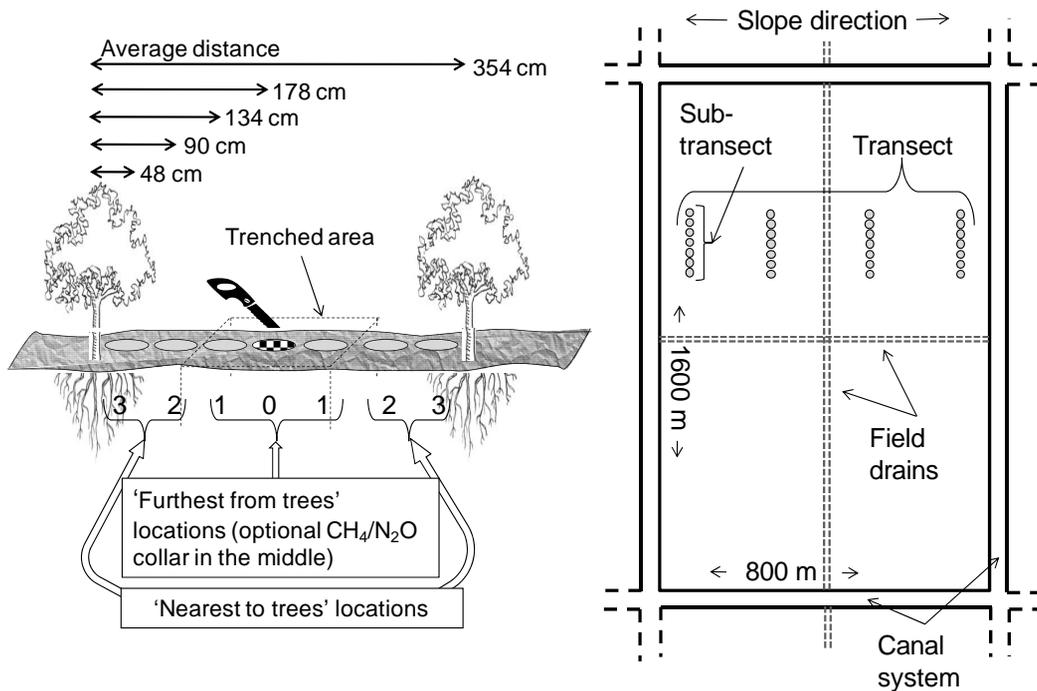
\* By accounting water table depth as covariate at B and D transects:

B	Furthest	192	1019	29	0.75	< 0.001
	Nearest	270	1248	24		
D	Furthest	350	904	14	0.70	< 0.001
	Nearest	71	702	32		



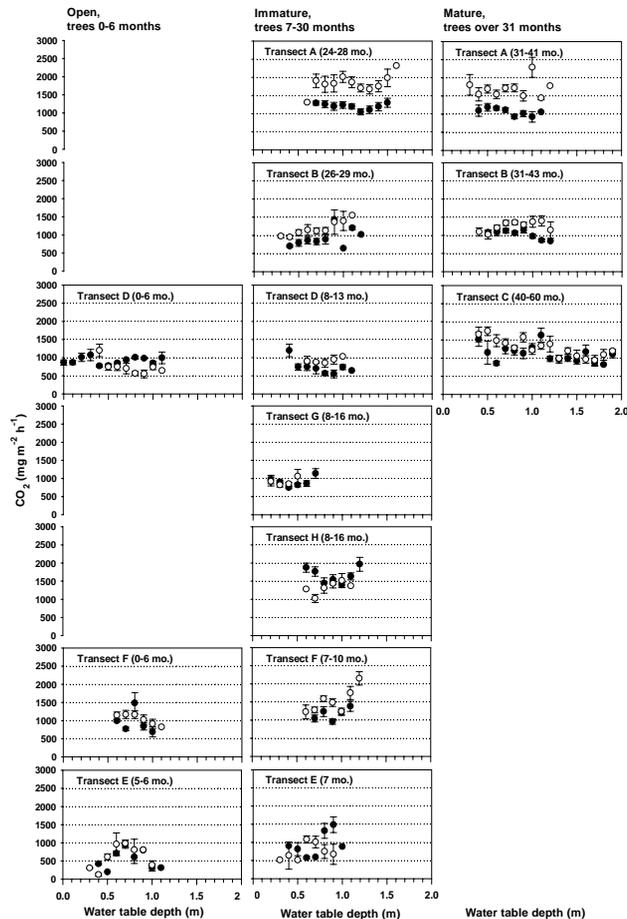
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**Fig. 1.** Outline of CO<sub>2</sub> emission monitoring location arrangement at sub-transect, and an outline of a transect in a tree growing unit.

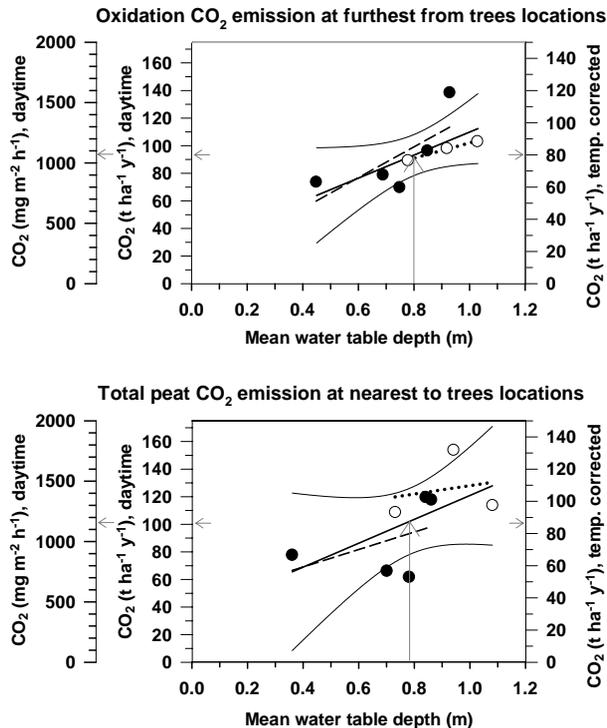
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**Fig. 2.** Instantaneous daytime  $\text{CO}_2$  fluxes (mean  $\pm$  SE) at transects representing various tree growth stages using 10 cm wide water table depth classes. Mean  $\text{CO}_2$  emissions at “furthest from trees” locations (●) and “nearest to trees” locations (○) are shown separately for each transect.

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**Fig. 3.** Regression on mean peat surface “oxidation” (upper graph) and “total” (lower graph) emissions at mean water table depths at the monitoring transects. Emission values provided in multiple units; daytime emission values ( $\text{mg m}^{-2} \text{h}^{-1}$ ,  $\text{t ha}^{-1} \text{yr}^{-1}$ ) on the left axis, and temperature corrected emissions ( $\text{t ha}^{-1} \text{yr}^{-1}$ ) on the right axis. Linear regression lines for  $\leq 16$  months old trees ( $\circ$ -symbol, dotted line),  $\geq 24$  months old acacia ( $\bullet$ -symbol, dashed line), average (solid line), and 95% confidence limits (solid curves) for the combined data of 8 transects are provided. Arrows indicate regression mean emissions and water table depths.