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Carbon dioxide emissions from an *Acacia* plantation on peatland in Sumatra, Indonesia

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Abstract. Peat surface CO_2 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, over a 2 year period. The autotrophic root respiration component of CO_2 emission was separated from heterotrophic emission caused by peat oxidation in three ways: (i) by comparing CO_2 emissions within and beyond the tree rooting zone, (ii) by comparing CO_2 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_2 emissions before and after *Acacia* tree harvesting. On average, the contribution of autotrophic respiration to daytime CO_2 emission was 21 % along transects in mature tree stands. At locations 0.5 m from trees this was up to 80 % of the total emissions, but it was negligible at locations more than 1.3 m away. This means that CO_2 emission measurements well away from trees were free of any autotrophic respiration contribution and thus represent only heterotrophic emissions. We found daytime mean annual CO_2 emission from peat oxidation alone of 94 t ha^{-1} y^{-1} at a mean water table depth of 0.8 m, and a minimum emission value of 80 t ha^{-1} y^{-1} after correction for the effect of diurnal temperature fluctuations, which may result in a 14.5 % reduction of the daytime emission. There is a positive correlation between mean long-term water table depth and peat oxidation CO_2 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_2 emissions. The increase in the temperature of the surface peat due to plantation establishment may explain over 50 % of peat oxidation emissions. Our study sets a standard for greenhouse gas flux studies from tropical peatlands under different forms of agricultural land management. It is the first to purposefully quantify heterotrophic CO_2 emissions resulting from tropical peat decomposition by separating these from autotrophic emissions. It also provides the most scientifically- and statistically-rigorous study to date of CO_2 emissions resulting from anthropogenic modification of this globally significant carbon rich ecosystem. Our findings indicate that past studies have underestimated emissions from peatland plantations, with important implications for the scale of greenhouse gas emissions arising from land use change, particularly in the light of current, rapid agricultural conversion of peatlands in the Southeast Asian region.

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 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 remaining peat swamp forest 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 Mha 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 involve CO_2 uptake via photosynthesis and losses through autotrophic respiration of vegetation, CO_2 and CH_4 emissions from soil organic matter decomposition (heterotrophic respiration), and fluvial exports of dissolved and particulate organic carbon (DOC and POC) (e.g. Jauhiainen et al., 2005, 2008; Rieley et al., 2008; Moore et al., 2011). The quantity of methane (CH_4) emitted from anaerobic peat decomposition is small and its effect on atmospheric processes is much less than concurrent CO_2 emissions (Hadi et al., 2005; Jauhiainen et al., 2005, 2008, 2012). In peat swamp forest the difference between CO_2 sequestered and that 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_2 emissions from tree roots and heterotrophic emissions from peat oxidation (c.f. 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_2 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., 2012). 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 from subsidence. Consequently, most published estimates of carbon losses are derived from peat surface CO_2 emission measurements obtained using the closed-chamber method. Even for this method, however, there are fewer than ten peer-reviewed publications presenting CO_2 emissions data under monitored hydrological conditions in SE Asian peatlands (Inubushi et al., 2003; Furukawa et al., 2005; Hadi et al., 2005; Jauhiainen et al., 2005, 2008; Melling et al., 2005; Ali et al.,

Table 1. Main characteristics of the peat at the CO_2 monitoring transects.

| Transect | Peat | | |
	Depth (m)	BD* ($g\,cm^{-3}$)	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 ($n = 3 - 9$).

2006; Hirano et al., 2009). None of these has separated the contribution of CO_2 released in root respiration from total CO_2 emissions, making it impossible to determine CO_2 emissions arising solely from peat decomposition, i.e. heterotrophic emissions. Further complications are caused by poorly described methods, inconsistent data collection procedures and high variation in the size of data sets, all of which prevent exact and meaningful comparison of results. There is, therefore, an urgent need for tropical peat surface emissions data that quantify accurately the separate components of CO_2 emissions and provide sufficient information on their temporal and spatial variation.

The focus of this paper is on the CO_2 emissions arising from peat decomposition following conversion of peat swamp forest to industrial plantation of *Acacia* pulp wood trees. Our aim is to quantify heterotrophic CO_2 emissions across a range of conditions and obtain improved understanding of the drivers of peat oxidation. Based on daytime gas flux monitoring we assessed the effects on emissions of (i) land cover type and plantation tree growth stage and (ii) water table depth on both total (heterotrophic plus autotrophic) CO_2 emissions and emissions caused by peat oxidation alone (heterotrophic). We determined the relative contributions of autotrophic and heterotrophic emissions to total emissions. Based on our field data and values from the literature, we also investigated the effect of temperature on CO_2 emissions in tree stands at different stages of canopy closure.

2   Site characteristics and methods

2.1   Site location and sampling procedure

The study area is in an *Acacia* (pulp wood) plantation on peatland in the Kampar Peninsula, Riau Province, Sumatra, Indonesia (N0°26′ 06.9″, E101°53′ 01.4″). This part of eastern Sumatra has an average annual rainfall of around 2500 mm and average daytime air temperature around 28 °C. The Kampar Peninsula contains contiguous peat deposits of
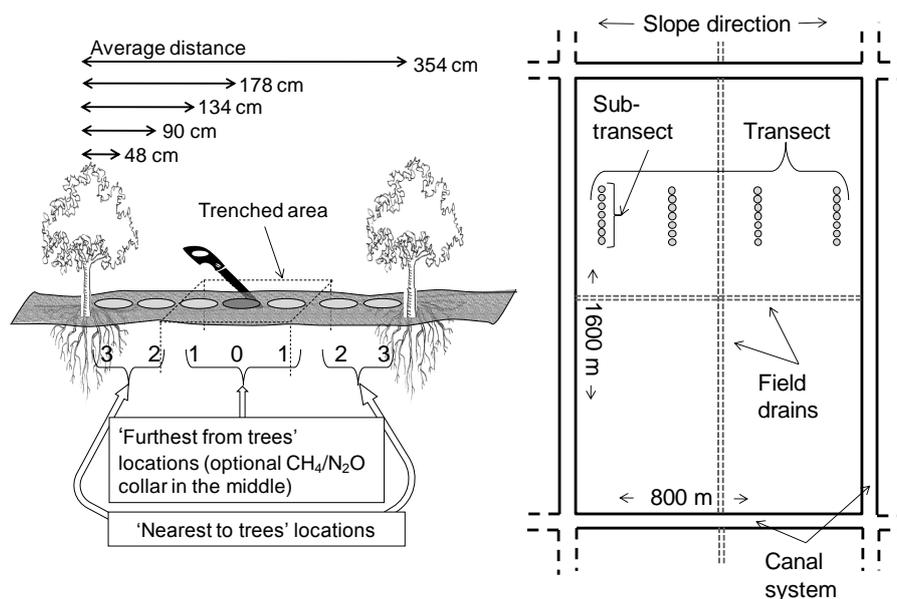
Fig. 1. Outline of CO_2 emission monitoring location arrangement at a sub-transect, and of a transect in a tree growing unit.

Table 2. Tree stand age characteristics (months) and average water table characteristics (m from the peat surface) at the CO_2 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.

around 700 000 ha. Prior to clearance of ~160 000 ha for plantation development from the year 2000 onwards, the area was peat swamp forest. The area was not affected by fire immediately prior to, during, or after land use change.

Data were collected over a 24-month period (April 2007 to April 2009) along 8 transects, A–H, located on one large peat dome on which peat thickness ranged from 4–9 m (average 6 m) (Table 1). The plantation area is drained by a rectangular system of canals at 800 m intervals (excluding field drains). The transects, 700 m long and up to 28 km apart, were located in different locations on the peat dome at low altitudes (below 11 m a.s.l.) and were positioned perpendicular to drainage canals (Fig. 1). Each 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 micro-topographic differences between emission monitoring locations (5 ± 11 cm to 9 ± 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 years from planting to harvest. Monitoring transects

Table 3. Temperatures (mean ± 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_2 flux monitoring and diurnally collected logger data.

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

included recently harvested sites with bare peat through to closed canopy sites with mature trees. The usual plantation tree species was *Acacia crassicarpa*, with the exception of transect G where it was *Melaleuca* sp. Based on field observations, three plantation cycle stages were identified: (1) "*open*" areas including recently harvested areas and young plantations with trees up to 6 months old with an open canopy; (2) "*immature*" stands with a closing or closed canopy of 7–30 month old trees, and (3) "*mature*" closed canopy stands of 30 month to 5 year old trees. Descriptions of tree stand characteristics during the 2 year monitoring period are provided in Table 2. Transects D, E and F were located in "open" 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).

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_2 emissions, in perforated PVC tubes inserted in the peat surface along the sub-transects.

2.3.2 Bulk density and ash content

Peat samples for determination of bulk density and ash content were collected following the method explained in Hooijer et al. (2012).

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_2 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® 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.

2.4 CO_2 emission monitoring

CO_2 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_2 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_2

Table 4. Mean daytime measured heterotrophic respiration CO_2 emissions (in "furthest from trees" locations) and total soil CO_2 emissions ("nearest to trees" locations) and the related mean water table depths at the monitoring transects.

Transect code	Peat surface emission type	n	CO_2 (mg m^{-2} h^{-1})			Water table depth (m)			p-value CO_2	p-value WD
			Mean	SE	SD	Mean	SE	SD		
A	Heterotrophic	158	1128	23	292	0.92	0.02	0.27	< 0.001	ns
	Total	284	1758	38	649	0.94	0.02	0.28		
B*	Heterotrophic	192	1028	26	364	0.78	0.01	0.15	< 0.001	< 0.005
	Total	270	1242	26	426	0.73	0.01	0.17		
C	Heterotrophic	140	1185	43	507	1.03	0.03	0.32	ns	ns
	Total	222	1300	40	596	1.08	0.02	0.33		
D*	Heterotrophic	350	903	14	253	0.69	0.01	0.25	< 0.001	< 0.01
	Total	71	705	38	319	0.78	0.03	0.24		
E	Heterotrophic	34	799	67	392	0.75	0.04	0.23	ns	ns
	Total	44	755	67	446	0.70	0.03	0.22		
F	Heterotrophic	74	1103	49	417	0.85	0.02	0.14	< 0.001	ns
	Total	154	1366	39	480	0.84	0.01	0.14		
G	Heterotrophic	143	844	24	283	0.45	0.01	0.12	ns	ns
	Total	30	887	49	271	0.36	0.02	0.09		
H	Heterotrophic	127	1584	44	496	0.93	0.01	0.16	< 0.05	ns
	Total	29	1345	74	398	0.86	0.02	0.12		
*By accounting water table depth as covariate at B and D transects:										
B	Heterotrophic	192	1019	29		0.75			< 0.001	
	Total	270	1248	24						
D	Heterotrophic	350	904	14		0.70			< 0.001	
	Total	71	702	32						

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_2 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_2 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_2 emissions

Soil CO_2 emission was partitioned into autotrophic root respiration and heterotrophic peat oxidation components by using several methods. First, the presence of autotrophic CO_2 emission sources was determined through pit observations,

which indicated 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 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. ≥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 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 ~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 also under conditions where live tree roots were guaranteed to be excluded (following harvesting) or, in very young plantation stands, where lateral growth of tree roots was negligible (see minimum tree age in Table 2).

Based on the measures taken in data collection outlined above and in subsequent data analysis (see Sect. 3.2), CO_2 emission data obtained from the "furthest from trees" monitoring locations were defined as "heterotrophic emissions", and this expression is used in the results and discussion. The data from the "nearest to trees" locations include emissions from both roots and organic matter decomposition and hence "total soil respiration" is used for this emission in the results and discussion. Mean daytime autotrophic respiration was calculated by subtracting the mean of the CO_2 emission measured at the "furthest from trees" locations from that of the "nearest to trees" locations, i.e. heterotrophic emission was subtracted from the total soil respiration emission for mature *Acacia* growth stages (data are based on Table 4).

2.6 Statistical analyses

The SPSS™ 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 were similar along most transects, with ranges of 0.06–0.12 g cm^{-3} (average 0.09 g cm^{-3}) and 0.08–2.20 % (average 0.71 %), for bulk density and ash content, respectively (Table 1). This confirmed our observation that surface peat at all locations was 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 was about 0.8 m but there were considerable variations in time and space during the two-year monitoring period (Table 2). On average, the lowest water table during CO_2 flux monitoring was at transect C (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_2 emissions and water table depths as measured at "nearest to trees" and "furthest from trees" locations differed significantly only along transects B and D (Table 4). The potential role of water table depth difference on CO_2 emission was tested by applying water table depth as a covariate in the analysis for these two transects, but the impact of water table depth difference on the emissions was found to be low (Table 4).

3.1.3 Peat temperature

The average daytime air temperature close to the peat surface was 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 were 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 differed 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 diminished with peat depth, to 0.3 °C at 10 cm depth. Data from both manual measurements and automated temperature loggers indicated comparable temperature differences.
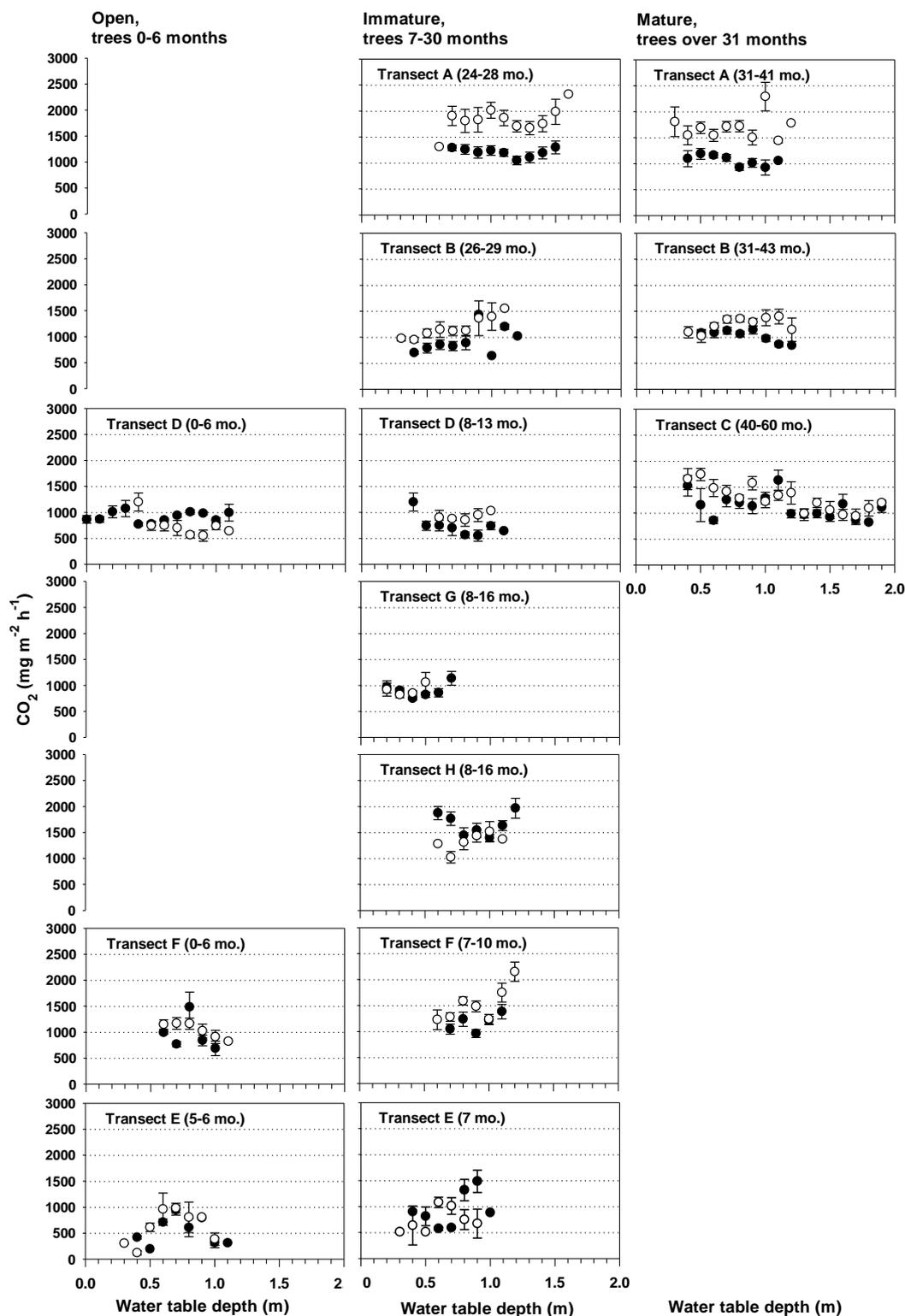
Fig. 2. Instantaneous daytime CO_2 emissions (mean $\pm$ SE) at transects representing various tree growth stages using 10 cm wide water table depth classes. Mean CO_2 emissions from heterotrophic respiration ($\bullet$) and total soil CO_2 emissions ($\circ$) are shown separately for each transect. Note that mean total CO_2 emissions especially in open and young immature growth stages have non-existent or low autotrophic respiration and thus the two flux symbols may be of variable order.
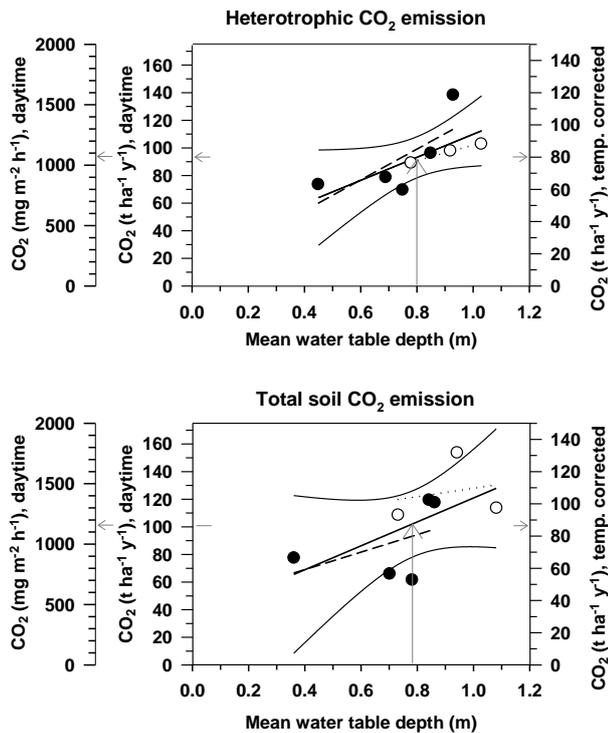
Fig. 3. Regression of mean peat surface CO_2 emission from heterotrophic respiration (upper graph) and mean total soil CO_2 emission (lower graph) at mean water table depths at the monitoring transects. Emission values provided in multiple units; daytime emission values ($mg\,m^{-2}\,h^{-1}$, $t\,ha^{-1}\,y^{-1}$) on the left axis, and temperature corrected emissions ($t\,ha^{-1}\,y^{-1}$) on the right axis. Linear regression lines for ≤ 16 months old trees ($\circ$-symbol, dotted line), ≥ 24 months old *Acacia* ($\bullet$-symbol, dashed line), average (solid line), and 95 % confidence limits (solid curves) for the combined data from 8 transects are provided. Arrows indicate regression mean emissions and water table depths.

3.2 CO_2 emissions

No significant differences ($p > 0.05$) in CO_2 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 confirmed that the tree roots were 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. Daytime CO_2 emissions data are summarised in Table 4 separated into those for total soil emissions and those for heterotrophic emissions.

The highest values for total soil respiration emissions were obtained along transects A, B, C, F and H, three of which (A, B and C) were "mature" plantations with average tree stand ages over 31 months. The lowest total emissions were ob-

tained 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 total emissions were significantly higher than the heterotrophic emissions, at 56 % and 21 % respectively (Table 4). In the mature tree stands (A, B and C) the emission difference was even higher (80 %, 44 % and 14 % respectively) between individual monitoring locations at $\sim$50 cm distance from trees (location 3 in Fig. 1). In comparison to the values for heterotrophic CO_2 emissions, however, the difference was only 28 %, 4 % and 1 % respectively at a distance of $\sim$90 cm from trees (location 2 in Fig. 1). Along the other transects in the open and immature trees stands, the differences were 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 autotrophic respiration, calculated as the emission difference between total and heterotrophic CO_2 emissions, for the 1st rotation cycle closed canopy *Acacia* transects (A, B and C) varied between 115 and 630 mg $CO_2\,m^{-2}\,h^{-1}$ (data from Table 4). The highest average daytime autotrophic respiration at transect A was 36 % of the total CO_2 emission. For transects B and C, the average autotrophic respiration emissions were about 17 % and 9 %. The overall mean autotrophic respiration for these transects was 320 mg $CO_2\,m^{-2}\,h^{-1}$, which was 21 % of the total CO_2 emission.

3.3 Relation between CO_2 emissions, groundwater table depth and tree growth stage

Analysis of datasets of instantaneous daytime CO_2 emissions (both for total and heterotrophic emissions) and water table depth along individual transects yielded significant relations only for transects B, C, F, G and H. However, these relations were very different, and for the other transects no relation was evident at all (Fig. 2). Emission readouts in some of the data sub-sets in the 10 cm wide water table depth classes were either low in number or missing, which restricted comparisons between total and heterotrophic emissions in some conditions.

3.4 Relation between CO_2 emission and long-term average groundwater table depth

In order to determine a possible effect of average long-term hydrological conditions on CO_2 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). For this analysis, monitoring transects were also separated into two categories, i.e. ≤ 16 months and ≥ 24 months old tree growth stages in order to determine if CO_2 emissions differed following recent disturbance (harvesting) compared to the more stable conditions in maturing tree stands.

There was a trend of reducing CO_2 emission when the water table was closer to the peat surface (Fig. 3). Correlation between mean heterotrophic CO_2 emission and mean water table depth, measured in the ≥ 24 month old tree growth stages, was very high ($R^2 = 0.99$). It was somewhat lower ($R^2 = 0.53$) for combined open and ≤ 16 month old tree growth stages. The total CO_2 emission and mean water table depth relationship was unclear, however, with R^2 values below 0.22 obtained for the two growth stages used in the analysis (Fig. 3).

The relation between water table depth (in m) and daytime CO_2 emission (in mg m^{-2} h^{-1}) for all transects is described by the following linear regressions (95 % confidence limits):

For daytime heterotrophic CO_2 emission:
emission = $953.35 \times$ WTD + 309.07 ($R^2 = 0.47$, SE = 197)

For daytime total CO_2 emission:
emission = $989.46 \times$ WTD + 391.79 ($R^2 = 0.34$, SE = 317)

In this study, no significant relationship (R^2 values from 0 to 0.02) was found between mean daytime heterotrophic and total CO_2 emissions and peat temperature at all transects (Tables 3, 4). Several studies suggest temperature differences in peat impact on organic matter oxidation rates by ratio $Q_{10} = 2$ (see Sect. 4.4 and 4.6 for details). An average difference between daytime and diurnal peat temperature at 5 cm depth of 1.45 °C was found across the *Acacia* plantation growth stages. By applying temperature correction, based on diurnal surface peat temperature fluctuation and a Q_{10} value of 2, daytime CO_2 emissions were subject to a 14.5 % reduction. Presenting these temperature corrected emission values as scaled-up units (t ha^{-1} y^{-1}), the regressions for all transects are:

For temperature corrected heterotrophic CO_2 emission: emission = $71.40 \times$ WTD + 23.15 ($R^2 = 0.47$, SE = 197)

For temperature corrected total CO_2 emission:
emission = $74.11 \times$ WTD + 29.34 ($R^2 = 0.34$, SE = 317)

4 Discussion

4.1 Separation of peat surface CO_2 emission sources

Several measures taken in this study allowed us to separate heterotrophic and autotrophic CO_2 emissions. The absence of tree roots and therefore of autotrophic respiration at locations "furthest from trees" was confirmed by (i) an observed lack of tree roots in control pits, (ii) a lack of effect of the

"trenching" 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 CO_2 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, demonstrated that the emission measurement method did measure autotrophic root respiration where it occurred, which further validated 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.

4.2 The contribution of autotrophic respiration to the total CO_2 emission

Autotrophic root emissions contribute 35–45 % to the total soil CO_2 emissions 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 were found near trees in mature stands in our study (transects A, B and C), where we established that autotrophic respiration accounted for an average of 21 % (36 %, 17 % and 9 %, respectively) of total CO_2 emissions. In immature tree stands of 7–16 months age (transects E, F, G and H), however, the contribution of autotrophic respiration to total CO_2 emission could not be calculated owing 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 in 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 years 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.

In recently harvested areas it is assumed that virtually all of the CO_2 emission is from heterotrophic sources since the remaining tree roots are no longer functioning. At transects D, E and H, heterotrophic emission was higher than total emission, a difference that was statistically significant for transects D and H (Table 4). Disturbance and the uneven distribution of tree harvest residues on the peat surface may have contributed to the apparent anomaly at transect D (open, immediate post harvest and early immature stages of the plantation cycle). The reason for the emission difference at transect H (immature stage) is less clear, but relatively few measurements of total CO_2 emission ($n = 29$, Table 4) were made at this site and this could have influenced this result. Analysis of instantaneous daytime CO_2 emissions and water table depth classes resulted in a relatively modest relation (Sect. 3.3, Fig. 2) and the results based on these much smaller data sub-sets cannot be directly used to explain the

general contribution of autotrophic respiration to the total CO_2 emission.

The autotrophic respiration contribution of 21 % to the total CO_2 emission in mature tree stands 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 autotrophic from heterotrophic CO_2 emissions, i.e. these percentages proposed earlier are rough estimates of the autotrophic respiration contribution rather than actual measurements. In this study, the preciseness of the oxidation and total emission measurement data used in the calculation of root respiration can be considered to be much higher because the respective relative standard errors were low, at between 2 % and 4 % for mature tree stand sites (based on data in Table 4).

CO_2 emission values from studies where the distance of the measurement location(s) from the nearest tree(s) is unknown (e.g. Melling et al., 2005), may be interpreted tentatively to represent 21 % autotrophic and 79 % heterotrophic emissions: the same percentages that we found in relatively mature *Acacia* plantation. There is no reason to believe that the percentage autotrophic respiration occurring in *Acacia* plantations differs much from the percentage expected in other types of plantation on peatland. Most of the root system of mature oil palms growing on deep peat in Jambi, Sumatra is concentrated in less than 1 m radius from the plants (A. Hooijer, unpublished data) similar to *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 peat surface where autotrophic respiration emission is negligible. Moreover, mature oil palm stands have heterotrophic CO_2 emissions that are in the same range as those from mature *Acacia* tree stands, and they have similar water table depth and limited canopy cover (compared to natural conditions) (Hooijer et al., 2012). We therefore propose that the autotrophic respiration contribution to total soil CO_2 emissions in *Acacia* plantations are also applicable to other peatlands that have been drained and converted to other types of peatland cultivation.

4.3 Relation between CO_2 emission and groundwater table depth

When quantifying relations between CO_2 emission and groundwater table depth, it must be borne in mind that water table depth *per se* does not control peat oxidation. Rather, it is a proxy for the moisture content of the peat above the water table, which has a direct effect on peat oxidation by in-

fluencing oxygen availability in the pore space (Liyama and Osawa, 2010).

In peatlands with high groundwater tables and without controlled drainage, the relation between water table depth and soil moisture content is strong: both go up when it rains and down in dry periods. Jauhiainen et al. (2005, 2008) found that total CO_2 emissions from undrained tropical peatland sites and those with unregulated drainage were 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 such as *Acacia* plantations, however, 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 above as moisture deficits created in preceding dry periods are replenished; under such conditions the peat moisture content may fluctuate over time with limited effect on water table depth (A. Hooijer, unpublished data). Moreover, peat water tables follow canal water levels that are managed to meet the operational plantation requirement of stable drainage depth, so that these can be controlled independently of 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 did not yield a significant relation between instantaneous CO_2 emission and water table as measured on individual transects. If water tables had remained close to the peat surface for longer periods during this study, then heterotrophic emissions could possibly have changed faster relative to changes in water table depth and a nonlinear relationship between CO_2 emission and water table depth might have been detected. The relationship between heterotrophic emissions from peat and water table depth has been found to be nonlinear at undrained sites and those with unregulated drainage, especially during periods when water table is close to the peat surface (e.g. Jauhiainen et al., 2005, 2008; Hirano et al., 2009). Owing to the permanent drainage required for optimal growth of *Acacia* in plantations on peat, these conditions did not occur along the study transects. However, the potential for lower emissions (and a non-linear relationship) can be seen in the data from transect G where water tables were kept permanently closer to the peat surface and heterotrophic emissions were lower than at the other transects. There are no published studies demonstrating the impact of rewetting on CO_2 emissions on previously permanently drained tropical peat with which to compare this observation.

4.4 The role of soil temperature in peat oxidation and CO_2 emissions

The rate of decomposition of organic matter in peatlands increases positively with increase in temperature (Lafleur et al., 2005; Minkkinen et al., 2007; Mäkiranta et al., 2009). In the tropics, diurnal and annual temperature fluctuations are

relatively modest compared to northern peatlands. There is, however, 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, a significant relationship was not found between mean daytime CO_2 emission and mean daytime peat temperature at any of the transects (R^2 values from 0 to 0.02), probably owing to the limited variation in daytime peat temperature along each (Table 3). For comparison, it would be important to obtain diurnal temperature data, preferably with simultaneous CO_2 emission data, across clearly different sun exposure/canopy coverage conditions. In a previous study, however, a clear CO_2 emission/temperature relationship for tropical peat was found, following 4 years of automated hourly monitoring of both variables in peat swamp forest, of a doubling of the rate of instantaneous in-situ peat CO_2 emission over a temperature range of 5 °C (from 24 °C to 29 °C) (including autotrophic respiration emissions) (Hirano et al., 2009). Moreover, long-term combined field 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_2 emission rates from incubated surface samples of tropical peat from Sumatra were also found to double between 25 °C and 35 °C (Brady, 1997). Both Brady (1997) and Hirano et al. (2009) found that increase in temperature had a greater effect on CO_2 emission rate than soil moisture or water table depth. In our study, we used this relation between temperature and CO_2 emission to adjust CO_2 measurements, obtained for higher daytime temperatures, to estimate 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. 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 °C and 26.4 °C respectively, a difference of 6 °C (Jauhiainen et al., 2005, 2008). Jaya (2007) reports an even greater difference for elsewhere in Central Kalimantan, of 7.3 °C between average diurnal surface peat temperature in an agricultural area (30.2 °C) and in adjacent, relatively intact forest (22.9 °C), while average daytime air temperatures are 33.4 °C and 28.8 °C, respectively. In nearby heavily degraded forest, the average diurnal

peat surface temperature and daytime air temperatures were 26.7 °C and 30.4 °C, suggesting that even removing part of the canopy cover has a profound effect on peat surface and air temperatures. We conclude that the average temperature of surface peat under intact tropical forest cover is around 25 °C at most, a value that we used in further calculations.

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

4.5 CO_2 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) showed a strong relationship with long-term mean heterotrophic respiration CO_2 emissions (Fig. 3). CO_2 emission rates along the transects were lower at higher water table depths (i.e. when the water table was nearer to the surface). A similar CO_2 emission/water table depth relationship was found for the unplanted and recently planted (≤ 16 month old) transects and for those with older (≥ 24 month old) trees. The highest regression R^2-value (0.99) was for the mature tree growth stage, which represented comparatively constant environmental conditions after several years had elapsed following harvesting and re-planting operations, and where the closed canopy provided relatively stable microclimatic conditions at the peat surface.

As the CO_2 emission means were based on 2 years of data collected intensively from a relatively large area (Table 4), the values could be used to quantify annual emissions for the entire plantation. The overall daytime mean ($\pm$SE) heterotrophic respiration emission derived by regression (Fig. 3) was $93.9 \pm 17.2 \, \mathrm{t} \, CO_2 \, \mathrm{ha}^{-1} \, \mathrm{y}^{-1}$ ($1072 \pm 197 \, \mathrm{mg} \, \mathrm{m}^{-2} \, \mathrm{h}^{-1}$) 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 the contribution of autotrophic respiration, have provided emissions of $201 \, \mathrm{mg} \, \mathrm{m}^{-2} \, \mathrm{h}^{-1}$ (water table depth 0.07 m) on a taro field (Chimner and Ewel, 2004), $733 \, \mathrm{mg} \, \mathrm{m}^{-2} \, \mathrm{h}^{-1}$ (water table depth 0.24 m) on a cassava field (Furukawa et al., 2005), $504 \, \mathrm{mg} \, \mathrm{m}^{-2} \, \mathrm{h}^{-1}$ (water table depth 0.27 m) under sago and $693 \, \mathrm{mg} \, \mathrm{m}^{-2} \, \mathrm{h}^{-1}$ (water table depth 0.60 m) under oil palm (Melling et al., 2005). Although most of these mean CO_2 emissions (op. cit.) were obtained at water table depths

less than those recorded in this study, an extended regression line to water table depths of 0.2 m and 0.3 m (Fig. 3) would result in a similar CO_2 emission range from 502 to 597 mg CO_2 m^{-2} h^{-1}.

The mean daytime heterotrophic respiration emission from this study of ~94 t CO_2 ha^{-1} y^{-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 CO_2 flux measurements, which may result in an overestimate because peat temperatures vary diurnally. This emission value can therefore be considered a maximum, which should be moderated for daytime temperature and emission both being above the daily average.

4.6   Correcting CO_2 emissions for temperature effect

In this study, we calculated the potential impact of diurnal peat temperature differences on heterotrophic respiration rates on the basis of Q_{10}-values provided from the literature for comparable environmental conditions (see Sect. 4.4). The average daytime heterotrophic respiration emission of 94 t CO_2 ha^{-1} y^{-1}, which covered both open and closed canopy conditions, was used as a reference. The diurnal mean temperatures of the surface peat were found to be lower than daytime temperatures measured during gas flux monitoring. The average difference between daytime and diurnal temperatures was 1.45 °C across both open and closed canopy conditions inside *Acacia* plantations. Assuming that a difference in peat temperature of 1 °C results in a 10 % difference in CO_2 emission (op. cit. in Sect. 4.4), the daytime CO_2 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_2 emission value of 94 t ha^{-1} y^{-1} we calculate an average emission value of 80 t ha^{-1} y^{-1} (Fig. 3).

This temperature corrected emission value of 80 t CO_2 ha^{-1} y^{-1}, at an average water depth of 0.8 m, is close to the value of 76 t CO_{2e} ha^{-1} y^{-1} resulting from subsidence and bulk density measurements conducted partly in the same landscape at the same water table depth (Hooijer et al., 2012). It is also close to the values of 72 to 72.8 t CO_{2e} ha^{-1} y^{-1} 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, Murdiyarso et al. (2010) and Koh et al. (2011) apply a much lower estimate (34.1 t ha^{-1} y^{-1} at 0.5 m water table depth) for heterotrophic respiration emissions 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 adjusted value (80 t CO_{2e} ha^{-1} y^{-1}) is based upon diurnal temperature difference measured near the peat surface, at 5 cm depth, whereas we found that temperature fluctuation diminished rapidly with increasing depth. Our approach therefore suggests that most peat oxidation, and therefore production of CO_2 gas, takes place in the upper 10 cm of the peat profile. We may assume therefore that oxygen availability is highest at shallowest depth where the near-surface peat layer contains a relatively larger amount of the most labile peat carbon compounds that are substrates for heterotrophic organisms. Consequently, the highest oxidation rate, i.e. heterotrophic respiration emission will take place near to the peat surface. While we have no information on the distribution of CO_2 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^{-1} y^{-1} may be seen as a minimum estimate.

In drained forest in Kalimantan, the average of long-term diurnal CO_2 emission was 18 % below emissions measured at mid-day (Hirano et al., 2009). A single 24-h CO_2 emission monitoring study by Ali et al. (2006) in Jambi also yielded a similar 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_2 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_2 emission (e.g. Couwenberg et al., 2010; Hooijer et al., 2010). The implication of this is that high CO_2 emission from any peatland that is converted to agriculture, whatever its water and land management, should be regarded as inevitable.

4.7   Comparing temperature and water table depth as likely main drivers of heterotrophic CO_2 emissions in tropical peatland plantations

The effect of temperature on average CO_2 emission arising from heterotrophic respiration in *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_2 emission, to the average increase of 5.6 °C after deforestation and drainage that follows from the above analysis of data from Central Kalimantan. This indicates that up to 56 % of the CO_2 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 controlling factor. The remaining 44 % of emission

can be attributed to reduction in soil moisture content (with water table depth as a proxy), and also to soil disturbance and fertilization. This likely dominance of temperature as a cause of oxidation in tropical peatland plantations has not been given sufficient attention in earlier studies reviewed by Hooijer et al. (2010) and Couwenberg et al. (2010), which focused on the effect of water table depth.

5   Conclusions

This study is the largest and most detailed investigation of CO_2 emissions undertaken in an industrial plantation on tropical peat. It is also the first study to separate and quantify autotrophic and heterotrophic CO_2 emissions. We conclude that the scale of this study, and its consistent approach to separating emission contributions, is necessary in order to determine "net" CO_2 emissions from drained tropical peatland. We present a monitoring system that yields reliable and checkable results, but which differs markedly from methods applied in previous studies.

The contribution of autotrophic respiration to CO_2 emission was found to be 21 % on average along transects in mature tree stands. Significantly higher autotrophic respiration occurred very close to *Acacia* trees, but was negligible at distances of more than 1.3 m from them, indicating that our emission measurements well away from trees were free of any contribution from autotrophic respiration and represented heterotrophic respiration only.

We calculated an average minimum heterotrophic respiration emission rate of $80\,t\,CO_2\,ha^{-1}\,y^{-1}$ for the *Acacia* plantation, after reducing the initial average daytime rate of $94\,t\,ha^{-1}\,y^{-1}$ by 14.5 % to account for the lower night time peat temperatures. A temperature correction has not been applied before, but we believe it is necessary in order to compare the results of different emission studies more precisely. The resulting value applies at an average water table depth of 0.8 m, in peatland with a thickness greater than 4 m, for a peat surface covered by vegetation and with limited fertilizer applied only in the first year after planting. This value ($80\,t\,CO_2\,ha^{-1}\,y^{-1}$) is supported by the results of a parallel study of carbon loss, carried out at the same location at the same time, of peat subsidence and peat characteristics (bulk density and carbon content) (Hooijer et al., 2012).

Mean long-term water table depth along transects correlates well with average heterotrophic respiration emissions, although the results of our study indicate that temperature differences may be the most important factor controlling peat oxidation and account for over 50 % of heterotrophic CO_2 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 would predict that CO_2 emissions from heterotrophic respiration are $23\,t\,ha^{-1}\,y^{-1}$ or more. It is therefore evident

that high CO_2 emissions are inevitable in any type of agricultural or plantation development on tropical peatland.

There is no reason to assume these conclusions apply only to *Acacia* plantations. All developments on tropical peatland require removal of forest cover and lowering of the water table. Growing non-permanent crops (e.g. 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 cultivation on peat are likely to be as high or higher than those from *Acacia* plantations, at similar water depths and on similar peat types.

This study sets a new standard for greenhouse gas flux studies from tropical peatlands under different forms of land management. Our findings indicate that past studies have underestimated peat surface CO_2 emissions from peatland plantations, with important implications for the scale of greenhouse gas emissions arising from land use change, particularly in the light of current, rapid agricultural conversion of peatlands in the Southeast Asian region (Miettinen and Liew, 2010).

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