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### Article

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1 **High heterotrophic CO<sub>2</sub> emissions from a Malaysian oil palm plantations during**  
2 **dry-season**

3  
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28  
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30 **Abstract**

31 **Background**

32 Tropical peatlands are currently being rapidly cleared and drained for the establishment of oil palm  
33 plantations, which threatens their globally significant carbon sequestration capacity. Large-scale  
34 land conversion of tropical peatlands is important in the context of greenhouse gas emission  
35 factors and sustainable land management. At present, quantification of carbon dioxide losses from  
36 tropical peatlands is limited by our understanding of the relative contribution of heterotrophic and  
37 autotrophic respiration to net peat surface CO<sub>2</sub> emissions.

38 **Methods**

39 In this study we separated heterotrophic and autotrophic components of peat CO<sub>2</sub> losses from two  
40 oil palm plantations (one established in '2000' and the other in 1978, then replanted in '2006')  
41 using chamber-based emissions sampling along a transect from the rooting to non-rooting zones  
42 on a peatland in Selangor, Peninsular Malaysia over the course of three months (June-August,  
43 2014). Collar CO<sub>2</sub> measurements were compared with soil temperature and moisture at site and  
44 also accompanied by depth profiles assessing peat C and bulk density.

45 **Results**

46 The soil respiration decreased exponentially with distance from the palm trunks with the sharpest  
47 decline found for the plantation with the younger palms. The mean heterotrophic flux was 1244.7  
48  $\pm$  SE 149.2 mg m<sup>-2</sup>h<sup>-1</sup> and 663.8  $\pm$  SE 102.2 mg m<sup>-2</sup>h<sup>-1</sup> at the 2000 and 2006 plantations,  
49 respectively. Autotrophic emissions adjacent to the palm trunks were 944  $\pm$  SE 99.7 mg m<sup>-2</sup>h<sup>-1</sup> and  
50 1962  $\pm$  SE 246 mg m<sup>-2</sup>h<sup>-1</sup> at the 2000 and 2006 plantations, respectively. Heterotrophic CO<sub>2</sub> flux  
51 was positively related to peat soil moisture, but not temperature. Total peat C stocks were 60 kg  
52 m<sup>-2</sup> (down to 1 m depth) and did not vary among plantations of different ages but SOC  
53 concentrations declined significantly with depth at both plantations but the decline was sharper in  
54 the second generation 2006 plantation.

55 **Conclusions**

56 The CO<sub>2</sub> flux values reported in this study suggest a potential for very high carbon (C) loss from  
57 drained tropical peats during the dry season. This is particularly concerning given that more  
58 intense dry periods related to climate change are predicted for SE Asia. Taken together, this study  
59 highlights the need for careful management of tropical peatlands, and the vulnerability of their  
60 carbon storage capability under conditions of drainage.

61

62

63

64

## 65 Introduction

66

67 Tropical peatlands are estimated to occupy 441 025 km<sup>2</sup> globally, with more than half of the total  
68 area (247 778 km<sup>2</sup>) being located in South-East Asia (Page et al., 2011a), and provide the largest  
69 long-term sink of terrestrial carbon (Page et al., 2011b). The substantial amount of carbon (C)  
70 present in peatlands of the region has been sequestered over millennia. Nevertheless, recent  
71 developments which lead to deforestation and drainage of wetlands, for instance for the purpose  
72 of establishment of plantations, may be rapidly turning tropical peat environments into the world's  
73 largest sources of carbon emissions (Hoijer et al., 2012, Tonks et al., 2017). The growing world  
74 demand for palm oil has driven the extensive conversion of peat into agricultural plantations, with  
75 3.1 million ha of peatlands in the region drained for the establishment of plantations, primarily of  
76 oil palm and *Acacia* (Lo and Parish, 2013). Peatlands are especially attractive as areas for plantation  
77 establishment due to the capacity for water retention of organic soils and high nutrient release  
78 from decomposing drained peat soils (Corley and Tinker, 2003). However, since oil palm trees do  
79 not grow well on waterlogged soil due to poor anchorage and anoxic conditions, the establishment  
80 of oil palm plantation requires drainage of peat. This greatly increases the risk of high levels of  
81 organic matter decomposition, as the presence of oxygen enables the activity of aerobic  
82 microorganisms (Husnain et al., 2014).

83

84 Total soil respiration ( $R_s$ ) consists of the autotrophic (root-derived;  $R_a$ ) and heterotrophic (non-root  
85 derived;  $R_h$ ) components. Heterotrophic respiration involves only the microbial decomposition of  
86 soil organic matter (SOM), whereas autotrophic respiration encompasses root growth and  
87 maintenance respiration of living roots, as well as emissions from mycorrhizal fungi (Epron, 2009).  
88 A major limitation of our ability to understand the consequences of land use change on  
89 decomposition processes and CO<sub>2</sub> losses from tropical peatlands, including oil palm plantations, is

90 the lack of separation of autotrophic and heterotrophic respiration components in the majority of  
91 studies (Couwenberg et al., 2010). Consequently, a comparison of losses of C between forests and  
92 lands utilised in agriculture is often impossible. Additionally, studies which provide estimates of  
93 CO<sub>2</sub> emissions from roots on plantations established on tropical peats are sparse. Jauhiainen et al.,  
94 (2012) estimated that autotrophic fluxes on an *Acacia* plantation on peat range between 115 and  
95 630 mg CO<sub>2</sub> m<sup>-2</sup> h<sup>-1</sup> constituting 9% to 26% of total CO<sub>2</sub> emissions, which compares to findings  
96 from oil palm plantations in Indonesia where the autotrophic component was between 15 and  
97 30 % of total CO<sub>2</sub> emissions (Dariah et al., 2014). In contrast, Melling et al. (2013) attributed 60 %  
98 of total soil respiration to autotrophic respiration based on a trenching experiment. Hergoualc'h  
99 and Verchot (2014) estimate autotrophic emissions from oil palm planted on tropical peat to be  
100 around  $0.9 \pm 2.7$  Mg C ha<sup>-1</sup> y<sup>-1</sup>.

101

102 It is possible that differences in autotrophic respiration among plantation are in part related to the  
103 age of plantations. Indeed, Dariah et al., (2014) found comparable heterotrophic respiration rates  
104 between plantations of 6 and 15 years while net and autotrophic CO<sub>2</sub> emissions were considerably  
105 higher in the more productive older plantation. Another uncertainty regarding how land use type  
106 influences CO<sub>2</sub> soil flux stems from how the lability of the peat material impacts emissions. It is  
107 plausible that surface peat consisting of less decomposed organic matter is the largest contributor  
108 to soil CO<sub>2</sub> fluxes as deeper peat may be more degraded and therefore produce less CO<sub>2</sub> due to the  
109 recalcitrant nature of the remaining material. Indeed, a relationship between CO<sub>2</sub> emissions and  
110 peat functional organic chemistry has been shown from undisturbed tropical peatlands (Wright et  
111 al., 2011). However, the variation in peat quality with depth and its role in CO<sub>2</sub> emissions from  
112 drained peatlands, including oil palm plantations, remains unclear.

113

114 In addition to plantation age and peat quality, the CO<sub>2</sub> flux from tropical peats can be influenced by  
115 a range of other environmental factors. For example, Melling et al. (2005) found CO<sub>2</sub> emissions  
116 under different land uses were regulated by different environmental factors: relative humidity in  
117 secondary forest, soil temperature for sago plantations, and water-filled pore spaces for oil palm  
118 plantations. CO<sub>2</sub> flux was also influenced by long-term water table depth on an *Acacia* plantation  
119 (Jauhiainen et al., 2012). The association between peat temperature and heterotrophic  
120 respiration is driven by an exponential increase in enzymatic activity in response to higher  
121 temperatures up to c. 45°C (Luo and Zhou, 2006). Waterlogged conditions of peatlands may limit  
122 CO<sub>2</sub> emissions by generating anaerobiosis which reduces peat oxygenation, while very dry  
123 conditions and water deficit may also restrain microbial respiration (Jauhianien et al., 2005,  
124 Marwanto and Agus, 2014). However, to date neither peat temperature nor moisture controls of  
125 CO<sub>2</sub> emissions from oil palm plantations are well understood, particularly in the context of *in situ*  
126 fluxes separated into autotrophic and heterotrophic components of emissions (Couwenberg et al.,  
127 2010).

128

129 Given the knowledge gaps around the impact of oil palm plantations on C storage and losses, this  
130 study aims to determine the relative contribution and controls of autotrophic and heterotrophic  
131 respiration in two oil palm plantations of different ages. This will be achieved by answering the  
132 following specific research questions: (i) what is the relative contribution of autotrophic and  
133 heterotrophic respiration to net CO<sub>2</sub> effluxes from an oil palm plantation on tropical peat? (ii) How  
134 do peat C stocks, soil moisture and temperature control heterotrophic and autotrophic CO<sub>2</sub> flux of  
135 tropical peatlands utilised as oil palm plantations?

136

137



138 **Methods**

139

140 *Research sites*

141

142 The study was conducted on an oil palm plantation cultivated on a peatland located in South  
143 Selangor, Peninsular Malaysia. The oil palm plantation from which samples were taken containing  
144 totalled 43km<sup>2</sup> and is within the vicinity of Kuala Lumpur International airport (2°44'25.58",  
145 101°40'29.08") and South Langat Forest Reserve. This plantation is situated on a much larger peat  
146 soil area of mixed land use in South Selangor of c. 670km<sup>2</sup>. Within this, approximately 48km<sup>2</sup>  
147 remains as peat swamp forest (albeit highly disturbed). Average annual rainfall in the area is  
148 2419mm with the dry season normally occurring from May to September (with rainfall dipping to  
149 c. 100-150 mm per month) and, to a lesser extent, also December to February. The examined sites  
150 were a first-generation oil palm plantation, established in 2000, replacing secondary forest and a  
151 second generation plantation, established in 2006 (original conversion from secondary forest in  
152 1978). Immediately prior to plantation establishment, the forest would have been cleared and  
153 ditches dug (to a depth of approximately 1.5-2 m) to drain the peatland resulting in a lower water  
154 table. These are then retained for the plantation growth. The peat depth at the time of sampling  
155 ranged between 1.5 to 2.1 m. On both plantations, four replicate sites were allocated for CO<sub>2</sub> efflux  
156 measurements and six for soil sampling. Soil samples were taken at the four CO<sub>2</sub> measurement  
157 sites plus at two extra sites. In both plantation generations, oil palm trees were positioned in the  
158 standard planting configuration, in a triangular pattern with the distance between tree trunks  
159 being approximately 9m. Each row of trees was arranged with frond piles between rows (where oil  
160 palm leaves are discarded) and open harvesting path walkways between trees. The understory  
161 surrounding frond piles consisted mostly of ferns with less aboveground biomass in general at the  
162 2006 plantation as compared with the 2000 plantation. However, the sampling areas themselves,

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

165

#### 166 *Measurement campaign*

167

168 This study was conducted over a five-month period in 2014, with soil samples taken in April and  
169 measurements of CO<sub>2</sub> flux, soil temperature and moisture conducted during the dry season, in the  
170 months of June, July and August, over the course of two to three days each month. The soil pH was  
171 measured only once, in June or July.

172

#### 173 *Soil CO<sub>2</sub> flux*

174

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

188 measured at the distances closer to the trunk, following the approach used by Jauhianen et al.,  
189 (2012) in an *Acacia* plantation on peat soil.

190

191

192 The CO<sub>2</sub> fluxes were measured with a Li-Cor LI-8100A. At sample locations, round plastic collars cut  
193 from PVC pipes of the same diameter as the Li-Cor chamber were inserted (c. 4cm deep) into the  
194 peat c. 24 hours before measurements. The Li-Cor soil flux chamber was placed onto the collars to  
195 collect the CO<sub>2</sub> flux data. The distance from the peat surface to the collar top was taken from  
196 inside the collar before each measurement and the corrections in the gas volume within the  
197 chamber were made accordingly. One measurement per collar was made every month and each of  
198 these lasted 1 minute and 30 seconds.

199

200 In parallel with each CO<sub>2</sub> flux measurement, we monitored soil temperature, moisture and water  
201 table depth. Moisture and temperature were measured at a depth of around 5-8 cm immediately  
202 adjacent to each collar with a Decagon 5TM moisture probe at the time when measurements of  
203 CO<sub>2</sub> fluxes were taken. pH values were measured for each collar with an HI 991001 pH probe  
204 (Hanna Instruments). Each measurement was taken in close proximity to a collar. The depth of the  
205 water table was obtained manually from dipwells which were located at a distance no greater than  
206 10 m from the CO<sub>2</sub> measurement points.

207

208 *Soil Organic Carbon measurement*

209

210

211

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

221

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

227

$$228 \quad p_{\text{ash}} = M_{\text{ash}}/M_{\text{ds}} \times 100$$

$$229 \quad C_{\text{org}} = (100 - p_{\text{ash}})/R_{\text{OM:C}}$$

230

231 where:

232  $M_{\text{ds}}$  – sample dry weight

233  $M_{\text{ash}}$  – ash weight after combustion

234  $P_{\text{ash}}$  – sample ash content

235  $C_{\text{org}}$  – SOC content (%)

236  $R_{\text{OM:C}}$  – conversion factor.

237

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

240

#### 241 *Bulk Density*

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

250

$$251 \text{ Bulk Density (gcm}^{-3}\text{)} = m / V$$

252 *Where;*

253 m – mass of dry soil sample (g)

254 V – volume of sample (cm<sup>3</sup>).

255

256

257

#### 258 *Statistical analysis and data presentation*

259

260 All statistical analyses were performed in GenStat version 17. General Linear Models (GLMs) were  
261 used to test if CO<sub>2</sub> fluxes (Rs, Ra and the Ra/Rs ratio), pH, soil temperature and soil moisture varied

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

270

## 271 **Results**

272

### 273 *CO<sub>2</sub> fluxes*

274 Soil respiration from the peat 2000 and 2006 plantations were  $3295 \pm SE 149$  and  $2407 \pm SE 102$   
275  $mg CO_2 m^{-2} hr^{-1}$ , respectively. At both the 2000 and the 2006 plantation  $R_s$  decreased significantly  
276 with increasing distance from the tree trunk but the decline was more pronounced at the 2006  
277 plantation (Distance  $\times$  Plantation interaction:  $F_{(6, 167)} = 3.13$ ,  $P < 0.01$ ; Figure 1 a). The decline in the  
278  $R_s$  with distance was described by highly significant exponential decay models ( $F_{(3,13)} = 16.09$ ;  $P <$   
279  $0.001$ ; Figure 1 a). When combined for the two plantations  $R_s$  were c.  $2000 mg CO_2 m^{-2} hr^{-1}$   
280 adjacent to the tree to  $900 mg CO_2 m^{-2} hr^{-1}$  at 3.5 m away from the palm (Figure 1 a). As expected  
281  $R_a$  declined away from the trunk ( $F_{(6, 167)} = 3.26$ ,  $P < 0.01$ ; Figure 1 b) and in parallel with  $R_s$  the  
282 decline was sharper at the more recently planted 2006 plantation and followed an exponential  
283 decay model ( $F_{(3,13)} = 16.60$ ;  $P < 0.001$ ; Figure 1 b). The relative contribution of  $R_a$  to  $R_s$  was 50% at  
284 0.5 m away from the trunk and declined exponentially to 25% 2 m away from the trunk with no  
285 significant difference between the 2000 and 2006 plantations ( $F_{(3,13)} = 5.12$ ;  $P < 0.05$ ; Figure 1 c).  
286 The heterotrophic  $CO_2$  losses from the 2000 first generation site were higher than from the more

287 recently replanted 2<sup>nd</sup> generation 2006 site but this difference was not statistically significant ( $F_{(1, 23)} = 0.31$ ,  $P = 0.60$ ; Figure 2).

289  
290 The soil respiration ( $F_{(2, 23)} = 3.09$ ,  $P = 0.08$ ) was lowest in August, the month with the lowest soil  
291 temperatures (Figure 3 a, b and c), while  $R_a$  ( $F_{(2, 167)} = 4.82$ ,  $P < 0.01$ ) fluxes was lowest in July which  
292 was the month with the lowest soil moisture content (Figure 3a,b and d).

293  
294 *Environmental controls of CO<sub>2</sub> emissions*

295 At the 2000 and 2006 plantations, soil moisture varied significantly between months ( $F_{(2, 165)} = 40.81$ ,  
296  $P < 0.001$ ) and so did temperature ( $F_{(2, 165)} = 32.05$ ,  $P < 0.001$ ) (Figure 3b and 3d). The average  
297 volumetric soil moisture content was similar between the two plantations: 0.20 and 0.20 m<sup>3</sup> m<sup>-3</sup> at  
298 the 2000 and 2006 plantations, respectively. Some of the variation in the peat moisture content  
299 between months may be explained by the fact that the August measurements, unlike those of June  
300 and July, were conducted following a rain event.

301  
302 A significant interaction between the soil moisture content and site (i.e. 2000 or 2006) ( $F_{(1, 44)} =$   
303 4.47,  $P = 0.04$ ) (Figure 4a) suggested that heterotrophic CO<sub>2</sub> emissions at the 2006 plantation were  
304 moisture-limited. At the 2000 plantation, which had higher CO<sub>2</sub> emissions overall, there was no  
305 clear link between the respiration rates and soil moisture content. The autotrophic flux did not  
306 depend on the level of soil moisture ( $F_{(1, 20)} = 1.04$ ,  $P = 0.32$ ) (Figure 4b).

307  
308 The water table depth (WTD) was measured at four points on the 2000 plantation and at two  
309 points on the 2006 age class. At all measurement points, WTD was well below the peat surface  
310 during the entire measurement period, varying between 70 cm and 120 cm in June and August,  
311 which reflected the dry weather conditions that were present during these two months as well as

312 the artificially managed drainage extent. The flux did not depend on the water table level ( $F_{(1,8)}=$   
313  $0.83$ ,  $P= 0.390$ ,  $r^2= 0.09$ ). The water table was measured in June and August and, consequently, the  
314  $\text{CO}_2$  flux data that was used in this particular analysis came from June and August only). WTD had  
315 no effect on either surface  $\text{CO}_2$  fluxes or peat moisture content of the topsoil during the sampling  
316 period ( $F_{(1,8)}= 0.05$ ,  $P= 0.82$ ).

317

318 Neither heterotrophic nor autotrophic respiration was influenced by soil temperature ( $F_{(1,44)}= 2.75$ ,  
319  $P= 0.11$ ;  $F_{(1,20)}= 0.84$ ,  $P= 0.37$ ). There was no interaction between soil temperature and site ( $F_{(1,44)}=$   
320  $2.03$ ,  $P= 0.161$ ). Furthermore, there was no significant relationship between pH and the spatial  
321 variation in the heterotrophic  $\text{CO}_2$  emissions averaged by month ( $F_{(1, 12)}= 0.23$ ,  $P= 0.639$ ) at either  
322 of the sites.

323

#### 324 *Soil organic carbon content and C stock*

325 Bulk densities were highest at the peat surface apart from at the deepest layer in the 2006  
326 plantation, which was collected from the base of the remaining peat layer (Depth $\times$ Plantation  
327 interaction:  $F_{(3,47)}= 4.31$ ;  $P<0.05$ ; Figure 5 a). As expected SOC concentrations declined significantly  
328 with depth at both plantations but the decline was sharper in the second generation 2006  
329 plantation (Depth $\times$ Plantation:  $F_{(3,47)}= 6.07$ ;  $P<0.05$ ; Figure 5 b). Overall SOC concentrations were  
330 higher in the 2000 than the 2006 plantation at 50 and 37%, respectively. Total peat C stocks were  
331  $60 \text{ kg m}^{-2}$  (down to 1 m depth) and did not vary significantly among the two plantations ( $F_{(1,11)}=$   
332  $0.68$ ;  $P=0.4$ ; Figure 5 c).

333

334

#### 335 **Discussion**



336 The net CO<sub>2</sub> emissions from both plantations of 288 and 210 Mg CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup> for 2000 and 2006  
337 respectively, are at the higher range of what is reported in the literature for plantations on tropical  
338 peat (Jauhianen et al., 2012; Dariah et al., 2014; Husnain et al., 2014). The high emissions are in  
339 part likely to be due to our measurements being from day time during the dry season with  
340 prevailing high temperatures. To enable comparison with other studies we used our dry season  
341 measurement to calculate annual heterotrophic fluxes from our study sites which were 109 and 58  
342 Mg CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup> for the 2000 and 2006 plantation respectively. This is on the higher side of many  
343 values previously reported for oil palm plantations on peat e.g. c. 35 Mg CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup> (Dariah et al.,  
344 2014), 41 Mg CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup> (Melling et al., 2007), 19.3 ± 16.6 Mg CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup> (Agus et al., 2010), 7  
345 Mg CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup> (Melling et al., 2013). Yet while our measured CO<sub>2</sub> fluxes (c. 2300 mg m<sup>-2</sup> h<sup>-1</sup>)  
346 represent some of the highest reported in the literature (Couwenberg et al., 2010), our annual  
347 emissions factors are comparable with those of the US Environment Protection Agency, which use  
348 an emission factor of 95 Mg CO<sub>2</sub> ha<sup>-1</sup> yr<sup>-1</sup>, based on Hooijer et al., (2012) subsidence assessments.  
349 However, care needs to be taken when interpreting the annual fluxes as we expect CO<sub>2</sub> emissions  
350 to be highest during the dry season so our calculated annual fluxes likely represent an  
351 overestimation. The CO<sub>2</sub> flux values reported in this study suggest a potential for very high C loss  
352 from drained tropical peats during the dry period. This is particularly concerning given that part of  
353 the climate projections for SE Asia is more intense dry periods (IPCC 2014) which may further  
354 increase CO<sub>2</sub> emissions from drained peatlands.

355

356 It is likely that the lower overall SOC (both at the surface and through the peat profile) in the 2006  
357 plantation was caused by long-term high heterotrophic C losses depleting the SOC (Figure 2 and  
358 5b) in line with Tonks et al., (2017). However, this did not translate into differences in C stocks  
359 between the two plantations possibly due the higher bulk densities in the second-generation 2006  
360 plantation. The more dense soil may be due to both mechanical compaction from machinery but

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

363

364

365 The high contribution of autotrophic respiration to net CO<sub>2</sub> effluxes; 24 and 72% adjacent to the  
366 trunk (0.5 m distance) at the 2000 and 2006 plantations, respectively, highlights that it is critical to  
367 account for root respiration when estimating C losses from peatlands (Figure 1). This is particularly  
368 important when comparing plantations of different ages, as the relative contribution of  
369 autotrophic CO<sub>2</sub> fluxes to net emissions varied considerably among the two plantations as well as  
370 spatially with distance from the trunk (Figure 1; Dariah et al., 2014). The sharp decline with  
371 distance from the trunk in the 2006 plantation is likely due to a less extensive root system  
372 indicating a lower overall contribution of autotrophic respiration to net emissions at the 2006  
373 plantation. The higher autotrophic flux found close to the younger palms in the 2006 plantation  
374 (i.e. 0.5 m distance) was unexpected, given that older oil palms have greater root biomass (Jourdan  
375 and Rey, 1997; Smith et al., 2012). We speculate that this might be linked to greater NPP and more  
376 active root growth in young palm plants or decomposition of old root material from the previous  
377 plantation cycle contributing to the near-palm emissions. The autotropic respiration was not  
378 related to soil moisture or temperature, even though the values of both variables varied  
379 substantially between months. This suggests that neither soil moisture nor high temperature  
380 limited root respiration.

381

382

383

384 Moisture was a stronger driver of heterotrophic CO<sub>2</sub> losses than temperature during the  
385 measurement period, however, only at the 2006 plantation. This is in line with findings from

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

396

397 The depth of the water table is considered to affect respiration rates via effects on the water  
398 content of the top soil where the SOC mineralisation rate is expected to be the highest (Hirano,  
399 2009). In contrast, in this study the water table depth did not impact on the surface peat moisture  
400 content or affect the rate of heterotrophic respiration suggesting that the relationship between the  
401 water table depth and the microbial respiration was not constant along the whole soil profile or  
402 was prevalent to a certain depth only, as has previously been found in temperate and boreal  
403 wetlands (Chimner and Cooper 2003; Mäkiranta et al., 2009). However, over long time-scales, a  
404 relationship between the water table depth and CO<sub>2</sub> emissions is more likely to be present (Hooijer  
405 et al., 2012) and the short duration of this measurement campaign might have prevented the  
406 appearance of a clear pattern between the position of the water table and CO<sub>2</sub> emissions. It is  
407 plausible that the disconnect between heterotrophic CO<sub>2</sub> emissions and the water table depth  
408 shown here, reflects the strong water table draw-down occurring during the dry season. In this  
409 case, water table depth would not a reliable predictor of CO<sub>2</sub> emissions during long periods of  
410 drought.

411

412 In conclusion, we have identified high heterotrophic CO<sub>2</sub> losses from drained tropical peatlands  
413 planted with oil palm. Such high emissions are likely to be sustained as long as the drained  
414 conditions are maintained. The low SOC in the second generation oil palm plantation suggests that  
415 repetitive plantation cycles and associated soil modification has led to C loss throughout the peat  
416 profile. Given the large C deposits in tropical peatlands and the rapid conversion of tropical  
417 peatlands to oil palm plantations, these high emissions and changed to C stocks suggests that oil  
418 palm plantations can act as hot spots of CO<sub>2</sub> emissions.

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547

548 **Figure captions**

549 **Figure 1:** a) Net CO<sub>2</sub> flux ( $R_s$ ), b) Autotrophic ( $R_a$ ) CO<sub>2</sub> flux and c) relative contribution of  $R_a$  to  $R_s$   
550 along a transect from the palm trunk to outside the canopy at the 2000 and 2006 plantations.

551 Means  $\pm$  SE are shown; n = 84.

552

553 **Figure 2:** Heterotrophic CO<sub>2</sub> fluxes at two oil palm plantations of different generations. Mean  $\pm$  SE  
554 are shown; n = 24.

555

556 **Figure 3:** Monthly heterotrophic and autotrophic CO<sub>2</sub> fluxes at the a) 2000 and c) 2006 oil palm  
557 plantations. The heterotrophic flux corresponds to CO<sub>2</sub> fluxes measured at 3.5 m distance from the  
558 trunk. The autotrophic fluxes shown are means across the 0.5 to 3.0 m measurement points.  
559 Monthly peat temperature and moisture data are shown for the b) 2000 and d) 2006 plantations.  
560 Means ± SE are shown.

561

562 **Figure 4.** Relationship between a) heterotrophic and b) autotrophic CO<sub>2</sub> flux with soil water  
563 content at 2000 and 2006 plantations; significant regression lines are shown. The heterotrophic  
564 flux corresponds to CO<sub>2</sub> fluxes measured at 3.5 m distance from the trunk. The autotrophic fluxes  
565 shown are from 0.5 m distance from the trunk.

566

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

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