

1 **High heterotrophic CO₂ emissions from a Malaysian oil palm plantations during**
2 **dry-season**

3
4 Authors: Magdalena Matysek^{1, 2*, 4}, Stephanie Evers^{3,4,5}, Marshall Kana Samuel^{4,6}, Sofie Sjogersten¹

5
6 **Affiliations**

7 ¹University of Nottingham, School of Biosciences, Collage Road, Sutton Bonington, LE12 5RE,
8 Loughborough, UK

9 ²Department of Animal and Plant Sciences, Alfred Denny Building, University of Sheffield, Sheffield
10 S102TN, UK

11 ³ School of Natural Sciences and Psychology, Liverpool John Moores University, Liverpool, L3 3AF,
12 UK

13 ⁴University of Nottingham, Malaysia Campus, School of Biosciences, Jalan Broga, 43500 Semenyih,
14 Selangor Darul Ehsan, Malaysia

15 ⁵Tropical catchment Research Initiative (TROCARI)

16 ⁶Climate Change Programme, Malaysian Agricultural Research and Development Institute (MARDI)
17 Serdang, Selangor, Malaysia.

18

19

20 *Corresponding author:

21 Magdalena Matysek e-mail:[0805090m@gmail.com]

22

23 **Acknowledgements**

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

26 and Loo Yen Yi for their help in collecting water table depth values and assisting with other
27 elements of data collection during the sampling period.
28
29 Reviewed by Nick Girkin (University of Nottingham).

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 CO₂ emissions.

38 **Methods**

39 In this study we separated heterotrophic and autotrophic components of peat CO₂ 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 CO₂ 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⁻²h⁻¹ and 663.8 \pm SE 102.2 mg m⁻²h⁻¹ at the 2000 and 2006 plantations,
49 respectively. Autotrophic emissions adjacent to the palm trunks were 944 \pm SE 99.7 mg m⁻²h⁻¹ and
50 1962 \pm SE 246 mg m⁻²h⁻¹ at the 2000 and 2006 plantations, respectively. Heterotrophic CO₂ flux
51 was positively related to peat soil moisture, but not temperature. Total peat C stocks were 60 kg
52 m⁻² (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 CO₂ 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 km² globally, with more than half of the total
68 area (247 778 km²) 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 CO₂ 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 CO₂ 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 CO₂ m⁻² h⁻¹ constituting 9% to 26% of total CO₂ emissions, which compares to findings
96 from oil palm plantations in Indonesia where the autotrophic component was between 15 and
97 30 % of total CO₂ 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 ± 2.7 Mg C ha⁻¹ y⁻¹.

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 CO₂ emissions were considerably
105 higher in the more productive older plantation. Another uncertainty regarding how land use type
106 influences CO₂ 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 CO₂ fluxes as deeper peat may be more degraded and therefore produce less CO₂ due to the
109 recalcitrant nature of the remaining material. Indeed, a relationship between CO₂ 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 CO₂ emissions from
112 drained peatlands, including oil palm plantations, remains unclear.

113

114 In addition to plantation age and peat quality, the CO₂ flux from tropical peats can be influenced by
115 a range of other environmental factors. For example, Melling et al. (2005) found CO₂ 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. CO₂ 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 CO₂ 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 CO₂ 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 CO₂ effluxes from an oil palm plantation on tropical peat? (ii) How
134 do peat C stocks, soil moisture and temperature control heterotrophic and autotrophic CO₂ 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 43km² 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. 670km². Within this, approximately 48km²
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 CO₂ efflux
156 measurements and six for soil sampling. Soil samples were taken at the four CO₂ 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 CO₂ 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 CO₂ 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 CO₂ measurements across the transect were made to quantify net soil CO₂
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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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_{ds} – sample dry weight

233 M_{ash} – ash weight after combustion

234 P_{ash} – sample ash content

235 C_{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 (cm³).

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 CO₂ 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 *CO₂ 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 2nd 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 CO₂ 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 m³ m⁻³ at
298 the 2000 and 2006 plantations, respectively. Some of the variation in the peat moisture content
299 between months may be explained by the fact that the August measurements, unlike those of June
300 and July, were conducted following a rain event.

301
302 A significant interaction between the soil moisture content and site (i.e. 2000 or 2006) ($F_{(1, 44)} =$
303 4.47, $P = 0.04$) (Figure 4a) suggested that heterotrophic CO₂ emissions at the 2006 plantation were
304 moisture-limited. At the 2000 plantation, which had higher CO₂ emissions overall, there was no
305 clear link between the respiration rates and soil moisture content. The autotrophic flux did not
306 depend on the level of soil moisture ($F_{(1, 20)} = 1.04$, $P = 0.32$) (Figure 4b).

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

312 the artificially managed drainage extent. The flux did not depend on the water table level ($F_{(1,8)}=$
313 0.83 , $P= 0.390$, $r^2= 0.09$). The water table was measured in June and August and, consequently, the
314 CO_2 flux data that was used in this particular analysis came from June and August only). WTD had
315 no effect on either surface CO_2 fluxes or peat moisture content of the topsoil during the sampling
316 period ($F_{(1,8)}= 0.05$, $P= 0.82$).

317

318 Neither heterotrophic nor autotrophic respiration was influenced by soil temperature ($F_{(1,44)}= 2.75$,
319 $P= 0.11$; $F_{(1,20)}= 0.84$, $P= 0.37$). There was no interaction between soil temperature and site ($F_{(1,44)}=$
320 2.03 , $P= 0.161$). Furthermore, there was no significant relationship between pH and the spatial
321 variation in the heterotrophic CO_2 emissions averaged by month ($F_{(1, 12)}= 0.23$, $P= 0.639$) at either
322 of the sites.

323

324 *Soil organic carbon content and C stock*

325 Bulk densities were highest at the peat surface apart from at the deepest layer in the 2006
326 plantation, which was collected from the base of the remaining peat layer (Depth \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 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 CO₂ emissions from both plantations of 288 and 210 Mg CO₂ ha⁻¹ yr⁻¹ 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 CO₂ ha⁻¹ yr⁻¹ 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 CO₂ ha⁻¹ yr⁻¹ (Dariah et al.,
344 2014), 41 Mg CO₂ ha⁻¹ yr⁻¹ (Melling et al., 2007), 19.3 ± 16.6 Mg CO₂ ha⁻¹ yr⁻¹ (Agus et al., 2010), 7
345 Mg CO₂ ha⁻¹ yr⁻¹ (Melling et al., 2013). Yet while our measured CO₂ fluxes (c. 2300 mg m⁻² h⁻¹)
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 CO₂ ha⁻¹ yr⁻¹, based on Hooijer et al., (2012) subsidence assessments.
349 However, care needs to be taken when interpreting the annual fluxes as we expect CO₂ emissions
350 to be highest during the dry season so our calculated annual fluxes likely represent an
351 overestimation. The CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 CO₂ emissions. It is
407 plausible that the disconnect between heterotrophic CO₂ 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 CO₂ emissions during long periods of
410 drought.

411

412 In conclusion, we have identified high heterotrophic CO₂ 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 CO₂ emissions.

419

420

421 **References**

422

423 AGUS, F., HANDAYANI, E., VAN NOORDWIJK, M., IDRIS, K., SABIHAM, S. (2010) Root respiration
424 interferes with peat CO₂ emission measurement. In: 19th World Congress of Soil Science, Soil
425 Solutions for a Changing World. Brisbane, Australia.

426

427 BOL, R., POIRIER, N., BALESSENT, J. AND GLEIXNER, G. (2009) Molecular turnover time of soil
428 organic matter in particle-size fractions of an arable soil. Rapid Communications in Mass
429 Spectrometry, 23, 2551–2558.

430

431 CERLI, C., CELI, L., GUGGENBERGER, G. and KAISER, K. (2012) Separation of light and heavy organic
432 matter fractions in soil — Testing for proper density cut-off and dispersion level. Geoderma, 170,
433 403-416.

434

435 CHIMNER, R.A. and COOPER, D.J. (2003) Influence of water table levels on CO₂ emissions in a
436 Colorado subalpine fen: an in situ microcosm study. *Soil Biology & Biochemistry*, 35, 345–351.
437

438 CORLEY, R.H.V. and TINKER, P.B. (2003) *The Oil Palm*. Blackwell, Oxford.
439

440 COUWENBERG, J., DOMAIN, R. And JOOSTEN, H. (2010) Greenhouse gas fluxes from
441 tropical peatlands in south-east Asia. *Global Change Biology*, 16, 1715–1732.
442

443 DARIAH, A., MARWANTO, S., AGUS, F. (2014) Root- and peat-based CO₂ emissions from oil palm
444 plantations. *Mitig Adapt Strateg Glob Change*, 19, 831–843.
445

446 EPRON, D. (2009) Separating autotrophic and heterotrophic components of soil respiration: lessons
447 learned from trenching and related root-exclusion experiments. In: *Soil Carbon Dynamics: An*
448 *Integrated Methodology*, pp. 157-168. (Eds. W.L. Kutsch, M. Bahn and A. Heinemeyer) Cambridge
449 University Press, Cambridge.
450

451 FARMER, J., MATTHEWS, R., SMITH, P., LANGAN, C., HERGOUALC'H, K., VERCHOT, L. and SMITH, J.U.
452 (2014) Comparison of methods for quantifying soil carbon in tropical peats. *Geoderma*, 214-215,
453 177-183.
454

455 GRANDY, S.A. and NEFF, J.C. (2008) Molecular C dynamics downstream: The biochemical
456 decomposition sequence and its impact on soil organic matter structure and function. *Science of*
457 *the Total Environment*, 404, 297 – 307.
458

459 GRIEPENTROG, M. and SCHMIDT, M.W.I. (2013) Discrepancies in utilization of density fractionation
460 along with ultrasonic dispersion to obtain distinct pools of soil organic matter. *Journal of Plant*
461 *Nutrition and Soil Science*, 176, 500-504.

462

463 HERGOUALC'H K. and VERCHOT L.V. (2014) Greenhouse gas emission factors for land use and land-
464 use change in Southeast Asian peatlands. *Mitig Adapt Strateg Glob Change*, 19, 789–807.

465

466 HIRANO, T., JAUHAINEN, J., INOUE, T. and TAKAHASHI, H. (2009) Controls on the Carbon Balance of
467 Tropical Peatlands. *Ecosystems*, 12, 873–887.

468

469 HOOIJER, A., PAGE, S., JAUHAINEN, J., LEE, W.A., LU, X.X., IDRIS, A. and ANSHARI, G. (2012)
470 Subsidence and carbon loss in drained tropical peatlands. *Biogeoscience*, 9, 1053-1071.

471

472 HUSNAIN, H., PUTU WIGENA, I.G., DARIAH, A., MARWANTO, S., SETYANTO, P., AGUS, F. (2014) CO₂
473 emissions from tropical drained peat in Sumatra, Indonesia. *Mitig Adapt Strateg Glob Change*, 19,
474 845–862.

475

476 IPCC (2014) Summary for policymakers. In: *Climate Change 2014: Impacts, Adaptation, and*
477 *Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth*
478 *Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J.
479 Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B.
480 Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge
481 University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1-32.

482

483 JAUHIAINEN, J., KEROJOKI, O., SILVENNOINEN, H., SUWIDO, L., VASANDER, H. (2014)
484 Heterotrophic respiration in drained tropical peat is greatly affected by temperature—a passive
485 ecosystem cooling experiment. *Environmental Research Letters*, 9, 105013.
486
487 JAUHIAINEN, J., HOOIJER, A. and PAGE, S.E. (2012) Carbon dioxide emissions from an Acacia
488 plantation on peatland in Sumatra, Indonesia. *Biogeosciences*, 9, 617–630.
489
490 JAUHIAINEN, J., TAKAHASHI, H., HEIKKINEN, J.E., MARTIKAINEN, P.J. and VASSANDERS, H. (2005)
491 Carbon fluxes from a tropical peat swamp forest floor. *Global Change Biology*, 11, 1788–1797.
492
493 JOURDAN, C. and REY, H. (1997) Architecture and development of the oil-palm (*Elaeis guineensis*
494 Jacq.) root system. *Plant and Soil*, 189, 33-48.
495
496 LEIFELD, J. and FUHRER, J. (2005) The temperature response of CO₂ production from bulk soils and
497 soil fractions is related to soil organic matter quality. *Biogeochemistry*, 75, 433-453.
498
499 LO, J. and PARISH, F. (2013) Peatlands and climate change in Southeast Asia. ASEAN Peatland
500 Forests Project and Sustainable Management of Peatland Forests Project. ASEAN Secretariat and
501 Global Environment Centre, Jakarta.
502
503 LUO, Y. and ZHOU, X. (2006) *Soil Respiration and the Environment*. Academic Press, London.
504
505 MÄKIRANTA, P., LAIHO, R., FRITZE, H., HYTÖNEN, J., LAINE, J. and MINKKINEN, K. (2009) Indirect
506 regulation of heterotrophic peat soil respiration by water level via microbial community structure
507 and temperature sensitivity. *Soil Biology & Biochemistry*, 41, 695–703.

508

509 MARWANTO, S. and AGUS, F. (2014) Is CO₂ flux from oil palm plantations on peatland controlled by
510 soil moisture and/or soil and air temperatures? *Mitig Adapt Strateg Glob Change*, 19, 809–819.

511

512 MELLING, L., HATANO, R. and GOH, K. J. (2005) Soil CO₂ flux from three ecosystems in tropical
513 peatland of Sarawak, Malaysia. *Tellus*, 57B, 1-11.

514

515 MELLING, L., TAN, S.Y., GOH, K.J., HATANO, R. (2013) Soil microbial and root respirations from three
516 ecosystems in tropical peatland of Sarawak, Malaysia. *Journal of Oil Palm Research*, 25, 44-57.

517

518 MELLING, L., GOH, K.J., BEAUVAIS, C., HATANO, R. (2007) Carbon flow and budget in a young
519 mature oil palm agroecosystem on deep tropical peat. In: Rieley J.O., Banks C.J., Radjagukguk B.,
520 (Ed.) *Proceedings of the International Symposium and Workshop on Tropical Peatland*, Yogyakarta,
521 Indonesia.

522

523 PAGE, S.E., RIELEY, J.O. and BANKS, H.J. (2011a) Global and regional importance of the tropical
524 peatland carbon pool. *Global Change Biology*, 17, 798–818.

525

526 PAGE, S.E., MORRISON, R., MALINS, C., HOOIJER, A., RIELEY, J.O. and JAUHAINEN, J. (2011b) Effects
527 of peat surface greenhouse gas emissions from oil palm plantations in Southeast Asia. White Paper
528 Number 15. *Indirect Effects of Biofuel Production Series*. International Council on Clean
529 Transportation, Washington.

530

531 SWANSTON, C.W., CALDWELL, B.A., HOMANN, P.S., GANIO, L., SOLLINS, P. (2002) Carbon dynamics
532 during a long-term incubation of separate and recombined density fractions from seven forest
533 soils. *Soil Biology & Biochemistry*, 34, 1121-1130.

534
535 TONKS, A.J., APLIN, P., BERIRO, D.J., COOPER, H., EVERS, S., VANE, C.H., SJÖGERSTEN, S. (2017)
536 Impacts of conversion of tropical peat swamp forest to oil palm plantation on peat organic
537 chemistry, physical properties and carbon stocks. *Geoderma* 289, 36–45.

538
539 VANE, C.H., RAWLINS, B.G., KIM, A.W., MOSS-HAYES, V., KENDRICK, C.P. and LENG, M.J. (2013)
540 Sedimentary transport and fate of polycyclic aromatic hydrocarbons (PAH) from managed burning
541 of moorland vegetation on a blanket peat, South Yorkshire, UK. *Science of the total environment*,
542 449, 81-94.

543
544 WRIGHT, E.L., BLACK, C.R., CHEESMAN, A.W., TURNER, B.L. and SJÖGERSTEN, S. (2013) Impact of
545 simulated changes in water table depth on ex situ decomposition of leaf litter from a neotropical
546 peatland. *Wetlands*, 33, 217–226.

547

548 **Figure captions**

549 **Figure 1:** a) Net CO₂ flux (R_s), b) Autotrophic (R_a) CO₂ 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 ± SE are shown; n = 84.

552

553 **Figure 2:** Heterotrophic CO₂ fluxes at two oil palm plantations of different generations. Mean ± SE
554 are shown; n = 24.

555

556 **Figure 3:** Monthly heterotrophic and autotrophic CO₂ fluxes at the a) 2000 and c) 2006 oil palm
557 plantations. The heterotrophic flux corresponds to CO₂ 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 CO₂ flux with soil water
563 content at 2000 and 2006 plantations; significant regression lines are shown. The heterotrophic
564 flux corresponds to CO₂ 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.

571

572

573

574

575