

LSE

THE LONDON SCHOOL
OF ECONOMICS AND
POLITICAL SCIENCE ■

LSE Research Online

T. E. L. Smith, S. Evers, C. M. Yule, and J. Y. Gan In situ tropical peatland ire emission factors and their variability, as determined by field measurements in peninsula Malaysia

**Article (Accepted version)
(Refereed)**

Original citation:

Smith, T. E. L. and Evers, S. and Yule, C. M. and Gan, J. Y. (2018) *In situ tropical peatland ire emission factors and their variability, as determined by field measurements in peninsula Malaysia*. *Global Biogeochemical Cycles*. ISSN 0886-6236

DOI: [10.1002/2017GB005709](https://doi.org/10.1002/2017GB005709)

© 2017 [American Geophysical Union](http://www.american-geophysical.org/)

This version available at: <http://eprints.lse.ac.uk/86749/>

Available in LSE Research Online: February 2018

LSE has developed LSE Research Online so that users may access research output of the School. Copyright © and Moral Rights for the papers on this site are retained by the individual authors and/or other copyright owners. Users may download and/or print one copy of any article(s) in LSE Research Online to facilitate their private study or for non-commercial research. You may not engage in further distribution of the material or use it for any profit-making activities or any commercial gain. You may freely distribute the URL (<http://eprints.lse.ac.uk>) of the LSE Research Online website.

This document is the author's final accepted version of the journal article. There may be differences between this version and the published version. You are advised to consult the publisher's version if you wish to cite from it.

1 ***In situ* tropical peatland fire emission factors and their variability, as**
2 **determined by field measurements in Peninsula Malaysia.**

3 **T. E. L. Smith^{1,2,3}, S. Evers^{4,3,5}, C. M. Yule^{6,3}, and J. Y. Gan^{6,7}**

4 ¹Department of Geography & Environment, London School of Economics and Political
5 Science, London, United Kingdom

6 ²King's College London, Department of Geography, Strand, London, United Kingdom

7 ³Tropical Catchment Research Initiative (TROCARI), Kuala Lumpur, Malaysia

8 ⁴School of Natural Sciences & Psychology, Liverpool John Moores University, Liverpool,
9 UK

10 ⁵School of Biosciences, University of Nottingham Malaysia Campus, Semenyih, Selangor
11 Darhul Ehsan, Malaysia

12 ⁶Tropical Medicine and Biology Multidisciplinary Platform, School of Science, Monash
13 University Malaysia, Selangor, Malaysia

14 ⁷Global Environment Centre, Petaling Jaya, Selangor, Malaysia

15
16 Corresponding author: Thomas Smith (t.e.l.smith@lse.ac.uk)

17
18 **Key Points:**

- 19 • From measurements at 10 peat fires in SE Pahang and N Selangor, we present the first
20 fire emission factors for Malaysian peatlands.
- 21 • We find substantial inter-plume fire emission factor variability for key greenhouse
22 gases (e.g. methane) and reactive gases (e.g. ammonia).
- 23 • We present the first discussion of relationships between peat bulk density and
24 methane fire emission factors.
25

26 Abstract

27 Fires in tropical peatlands account for >25% of estimated total greenhouse gas emissions
28 from deforestation and degradation. Despite significant global and regional impacts, our
29 understanding of specific gaseous fire emission factors (EFs) from tropical peat burning is
30 limited to a handful of studies. Furthermore, there is substantial variability in EFs between
31 sampled fires and/or studies. For example, methane EFs vary by 91% between studies.

32 Here we present new fire EFs for the tropical peatland ecosystem; the first EFs measured for
33 Malaysian peatlands, and only the second comprehensive study of EFs in this crucial
34 environment. During August 2015 (under El Niño conditions) and July 2016, we embarked
35 on field campaigns to measure gaseous emissions at multiple peatland fires burning on
36 deforested land in Southeast Pahang (2015) and oil palm plantations in North Selangor
37 (2016), Peninsula Malaysia. Gaseous emissions were measured using open-path Fourier
38 transform infrared spectroscopy. The IR spectra were used to retrieve mole fractions of
39 twelve different gases present within the smoke (including carbon dioxide and methane), and
40 these measurements used to calculate EFs. Peat samples were taken at each burn site for
41 physicochemical analysis and to explore possible relationships between specific
42 physicochemical properties and fire EFs. Here we present the first evidence to indicate that
43 substrate bulk density affects methane fire EFs reported here. This novel explanation of inter-
44 plume, within-biome variability should be considered by those undertaking greenhouse gas
45 accounting and haze forecasting in this region, and is of importance to peatland management,
46 particularly with respect to artificial compaction.

47 1 Introduction

48 Fires in tropical peatlands account for 25% or more of the estimated total greenhouse gas
49 (GHG) emissions from global deforestation and forest degradation, amounting to
50 approximately 3% of total global anthropogenic GHG emissions [Ballhorn *et al.*, 2009;
51 IPCC, 2013; van der Werf *et al.*, 2009; van der Werf *et al.*, 2017]. In 1997 alone, El Niño-
52 related fires in Indonesia were calculated to have released 13–40% of that year’s total carbon
53 emissions from fossil fuel burning [Page *et al.*, 2002]. Beyond the global climate forcing of
54 GHGs such as CO₂, methane (CH₄), and nitrous oxide (N₂O), peatland fire emissions of
55 carbon monoxide (CO), nitrogen oxides (NO_x) and volatile organic compounds (VOCs) react
56 to form ozone (O₃). This, combined with particulate matter (PM) emissions, leads to smog
57 (referred to as ‘haze’ in SE Asia). In the southern region of SE Asia, peatland fires are
58 responsible for 90% of trans-boundary haze events [Varkkey, 2013]. Air Pollution Index
59 readings in Palangkaraya in Borneo in October 2015 reached >2000, the highest values ever
60 recorded and far above the Emergency level of >500. Exposure to haze events has been
61 shown to cause both immediate and delayed effects, increasing respiratory related mortality
62 by 19–66% [Sahani *et al.*, 2014] and resulting in over 100,000 excess deaths in Malaysia,
63 Indonesia and Singapore [Kopplitz *et al.*, 2016]. In the 2015 fires, an estimated >500,000
64 Indonesians were affected by haze-related respiratory infections [Jakarta Post, 2015].
65 Economic losses related to haze are also significant, with estimates for the 2015 fires at \$16.1
66 billion for Indonesia [CIFOR, 2015]. Despite these significant global and regional impacts,
67 very little is known of the proportional contribution of the major chemical compounds being
68 emitted *in situ* from tropical peat fires. As a result, there are no published accounts addressing
69 how GHG and reactive (haze-forming) gaseous fire emissions vary among different types of
70 tropical peatlands, precluding both accurate greenhouse gas accounting and air quality (haze)
71 forecasting in this region.

72 The Indo-Malaysian region is the global centre of tropical peat swamp forests. Over the past
73 30 years regional peat swamp forests have been increasingly subject to degradation from
74 drainage, logging and agricultural conversion – particularly to oil palms (*Elaeis guineensis*).
75 Drainage reverses the environmental conditions that lead to peat accretion, resulting in
76 oxidation, compaction and drying of peat making it highly flammable [Langner and Siegert,
77 2009; Wösten *et al.*, 2006]. Fire is often used to clear peatlands [Varkkey, 2013] and these
78 fires can continue smouldering for months both at the surface and reaching deeper
79 underground. Peatlands subjected to fire incidents have a high probability of recurrence of
80 fire [Posa *et al.*, 2011] because of the un-burnt biomass, removal of canopy shading and fire
81 prone secondary vegetation that will act to provide further fuel and ignitions [Siegert *et al.*,
82 2001]. Due to the extensive degree of land degradation in the region, peatland fires now
83 occur twice a year in the Peninsula Malaysia and Sumatra regions, during each dry season
84 [Wooster *et al.*, 2012], occurring in February–May and August–September, but may occur
85 outside of these periods (e.g. the fires in Riau, Sumatra, in June 2013; [Gaveau *et al.*, 2014]),
86 depending on human and climate factors.

87 Understanding within-biome emissions variability is an important challenge for assessing the
88 atmospheric impacts of tropical peatland fires; in a broader context, van Leeuwen and van der
89 Werf [2011] suggest that explaining emission factor (EF, grams of a compound emitted per
90 kg of dry biomass burned) variability remains one of the biggest challenges for biomass
91 burning emissions science. Despite this, our understanding of specific gaseous emissions
92 from peat burning is limited to a handful of studies where small peat samples were burned in
93 laboratories [Christian *et al.*, 2003; Stockwell *et al.*, 2014] and two field studies [Huijnen *et*
94 *al.*, 2016; Stockwell *et al.*, 2016]. With the exception of Stockwell *et al.* [2014], these studies
95 do not characterise the physicochemical properties of samples, and with the exception of
96 Stockwell *et al.* [2016], nor were specific location, fire history or sample depth stated,
97 prohibiting any explanation of the substantial variability between samples and/or studies. For
98 example Huijnen *et al.* [2016] report that 7.8 g of methane is emitted per kilogram of dry peat
99 that burns, whereas Christian *et al.* [2003] report 20.8 g, a difference of 91%, leading to
100 major implications when scaled-up to regional GHG accounting. Similar large differences in
101 the literature exist for other important emission factors (e.g. ammonia, a reactive nitrogen
102 species).

103

104 **2 Tropical peatland fire emission factors**

105 Unlike logging, the open burning of biomass directly consumes carbon stocks and rapidly
106 releases emissions (e.g. GHGs, haze-forming species, PM) to the atmosphere ‘on site’. How
107 well peat fire emissions are accounted for depends upon uncertainties in the calculation of (i)
108 The amount of peat consumed in the fire; and (ii) the emission factors used to convert the
109 estimate of fuel consumption into an estimate of the mass of gas released per unit of dry fuel
110 burned (g kg^{-1}) [Penman *et al.*, 2003]. Emission factors for CH_4 and important haze-forming
111 compounds vary massively between the few studies of gaseous emission factors [Christian *et*
112 *al.*, 2003; Stockwell *et al.*, 2014; Stockwell *et al.*, 2016]. The small number of samples in
113 these studies, combined with limited information on physicochemical peat properties beyond
114 elemental analysis, prohibits an explanation of the large differences in emissions factors
115 between studies.

116 Previous studies of peat fire gaseous emissions factors have predominantly undertaken
117 Fourier transform infrared (FTIR) spectroscopic measurements of emissions from peat

118 samples burning in a laboratory. These studies have investigated fire emissions from samples
119 of temperate peat [Stockwell *et al.*, 2014; Wilson *et al.*, 2015; Yokelson *et al.*, 1997]; boreal
120 peat [Stockwell *et al.*, 2014; Yokelson *et al.*, 1997]; and include studies of samples of tropical
121 peat from Sumatra [Christian *et al.*, 2003] and Kalimantan [Stockwell *et al.*, 2015; Stockwell
122 *et al.*, 2014].

123 Christian *et al.* [2003] report emission factors from just a single small sample of Sumatran
124 peat, while Stockwell *et al.* [2014] report emission factors from two further samples from
125 Kalimantan. Neither study reports any biological or chemical properties of the peat that might
126 help to explain the large differences in emissions factors between the two studies. Both the
127 2013 IPCC ‘Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories:
128 Wetlands’ [Hiraishi *et al.*, 2014] and the emission factors database of Akagi *et al.* [2011]
129 summarise emission factors from tropical peatland fires using only the laboratory findings of
130 Christian *et al.* [2003], with the IPCC stating that these were “derived from a very limited
131 number of studies”. Stockwell *et al.* [2014] and Stockwell *et al.* [2016] offer an update to the
132 emission factors summarised by the IPCC and Akagi *et al.* [2011] by taking an average of
133 their findings and those of Christian *et al.* [2003].

134 Despite these advances, it is difficult to assess the representativeness of emissions from
135 laboratory-scale burns [Stockwell *et al.*, 2016], particularly for peat fuels, that under
136 landscape-scale burning conditions would smoulder at the surface or underground, with less
137 access to oxygen than might be available under laboratory conditions [Rein *et al.*, 2009]. As
138 far as we are aware, the first *in situ* field measurements of gaseous fire emissions from
139 tropical peatland fires are those by Hamada *et al.* [2013], whose study of landscape-scale
140 peat fires near Palangka Raya (Kalimantan, Indonesia) in August 2009 reports emission ratios
141 of CH₄, N₂O, and CO, to CO₂. Huijnen *et al.* [2016] report emission factors for CO₂, CO, and
142 CH₄ from peatland fires measured *in situ* using a portable cavity enhanced laser absorption
143 spectrometer, also near Palangka Raya, in October 2015. The most comprehensive field
144 study to date is that of Stockwell *et al.* [2016] who reported gaseous and particulate emission
145 factors for ~90 species from measurements at 35 smoke plumes during the 2015 El Niño in
146 Central Kalimantan, Indonesia. There have been no published laboratory or *in situ* derived
147 emission factors for Malaysian peat fires.

148 van Leeuwen and van der Werf [2011] argue that future fire emissions measurement
149 campaigns would be far more beneficial to the global modelling community if measurements
150 were distributed spatially across biomes and paid more attention to fuel properties. The
151 physical properties of peat fuels (e.g. bulk density, fuel moisture) are important because they
152 will determine the combustion dynamics [Rein *et al.*, 2009]. Therefore, degradation impacts
153 (such as the lowering of the water table or artificial peat compaction) on the physical
154 properties of tropical peats (e.g. moisture content, bulk density) may influence the relative
155 abundances of CO₂ and haze-forming compounds during fires [Moreno *et al.*, 2011; Rein *et al.*,
156 *et al.*, 2009].

157 The chemical properties of fuels are important because they will determine the chemical
158 composition of fire emissions. Whilst the carbon content of vegetation and tropical peat does
159 not vary much beyond 50–56% [Christian *et al.*, 2003; Stockwell *et al.*, 2014], nitrogen
160 content of tropical peats is known to vary from 1.0–4.4% and may be heavily influenced by
161 land conversion [Andriess, 1988] and management. This will influence nitrogenous fire EFs
162 (e.g. NO_x, N₂O, NH₃, HCN) which are important for O₃ and haze formation. Direct impacts
163 of degradation include the use of fertilizers on converted peatlands (increasing peat nitrogen),
164 leading to the potential for increasing fire EFs for these nitrogen compounds.

165 Here we report new emission factors for twelve gas species measured using open-path
166 Fourier transform infrared (OP-FTIR) spectroscopy *in situ* at ten plumes from actively
167 burning tropical peatland fires in Southeast Pahang and North Selangor, Malaysia. These
168 represent the first emission factors reported for Malaysian peatlands.

169

170 **3 Methodology**

171 3.1 Site and fire descriptions

172 Tropical peatland fire emissions were measured at wildfires on peatlands along a stretch of
173 road (Federal Route 3) connecting Pekan and Lanjut in the Pekan District of the State of
174 Pahang, Malaysia in August 2015, and at oil palm plantations located about 20 km north of
175 Sekinchan, off Federal Route 5, in the Sabak Bernam District of the State of Selangor,
176 Malaysia in July 2016. Measurements at the Pahang sites were made on eight separate
177 occasions in August 2016 at three different sites between Pekan and Lanjut, within a region
178 80 km south of Kuantan. This area has a tropical wet climate (Koppen-Geiger classification:
179 Af), with no well-defined dry or wet seasons, being hot and humid throughout the year.
180 According to weather observations at Kuantan, mean annual rainfall is 2,900 mm. Peaks in
181 rainfall occur in December (564 mm) and May (202 mm). August sees a mean maximum
182 temperature of 32.3°C and mean rainfall of 174 mm. The peat soils at the Pahang sites, which
183 were located on the coastal edge of the main southeast Pahang peat dome (Figure 1), were
184 very shallow (0.2–0.8 m), typical of degraded peatlands subject to drainage, land clearance,
185 and hence oxidative loss of the peat layer over some decades. Two further sets of
186 measurements were made in July 2016 at one site in north Selangor. This area has a similar
187 climate to that of southeast Pahang. Weather observations at the nearest weather station in
188 Kuala Lumpur show a mean annual rainfall of 2,600 mm. July sees a mean maximum
189 temperature of 32°C and mean rainfall of 150 mm. The peat soils at the Selangor sites, also
190 located towards the edge of the main north Selangor dome, were deeper than those in Pahang,
191 extending to 1.5 to 2 m depth.

192 The flora of these areas is typical of deforested and degraded tropical peatlands across the
193 Malay Peninsula with many introduced, weedy species. There is a ground cover of grasses
194 and ferns as well as shrubs (particularly *Melastoma* sp. and *Mimosa* sp.) and trees such as
195 *Acacia mangium* and *Macaranga pruinosa*. *A.mangium* is a widespread introduced species
196 which can promote fire intensity and frequency due to flammable leaf litter and which
197 produces enormous numbers of seeds that remain viable for years and whose germination is
198 enhanced by fire. *M.pruinosa* is a native, secondary gap colonizer commonly found on the
199 fringes of regional peat swamp forests. Oil palm plantations are usually cleared manually and
200 treated with herbicides to remove other vegetation, leaving only a sparse ground cover of
201 grasses and ferns. We found evidence of ongoing chemical fertiliser use at the Selangor oil
202 palm plantation site (Site 4 in Figure 1), with open sacks of NPK fertiliser and pellets around
203 the base of oil palms.

204 Locations of actively burning peatland fires were identified by regular monitoring of the
205 World Resources Institute Global Forest Watch Fires website
206 (<http://fires.globalforestwatch.org/>) and NASA's Worldview website
207 (<https://worldview.earthdata.nasa.gov/>). These websites provide the near-real-time location of
208 satellite-detected fires (thermal hotspots); true-colour and false-colour imagery that can be
209 used to identify the presence of smoke plumes; as well as information on the location of

210 peatlands. Many active fires were observed in SE Pahang (Sites 1–3 in Figure 1) in July 2015
211 shortly before the ground measurement campaign; this led the research team to be based at
212 Pekan, just north of these July fire clusters. Once a possible peatland fire had been identified,
213 the research team drove in the direction of the fires until a visible confirmation of the location
214 of the fire was established. Fewer fires were observed across Peninsula Malaysia in July
215 2016, however a cluster of hotspots were detected just north of Sekinchan in N Selangor (Site
216 4 in Figure 1) in early July which led the research team to this area where a number of small
217 peatland fires were found on oil palm plantations.

218 The opportunistic nature of this campaign allowed for emissions to be measured at a number
219 of sites (Figure 1) that had different degradation characteristics, and at sites that had been
220 burning for different lengths of time. Table 1 summarises the main characteristics of the fire
221 sites and conditions studied for this paper.

222 Site 1 (SE Pahang) was visited twice, on 6 August 2015, following rain, when small areas
223 (patches of a few square metres) of the landscape were still smouldering following the large
224 fires in mid-July; and on 12 August 2015, when relatively larger areas were burning (patches
225 of $>10\text{ m}^2$). Site 1 was largely devoid of any tree vegetation and surface vegetation was
226 dominated by shrubs and leaf litter.

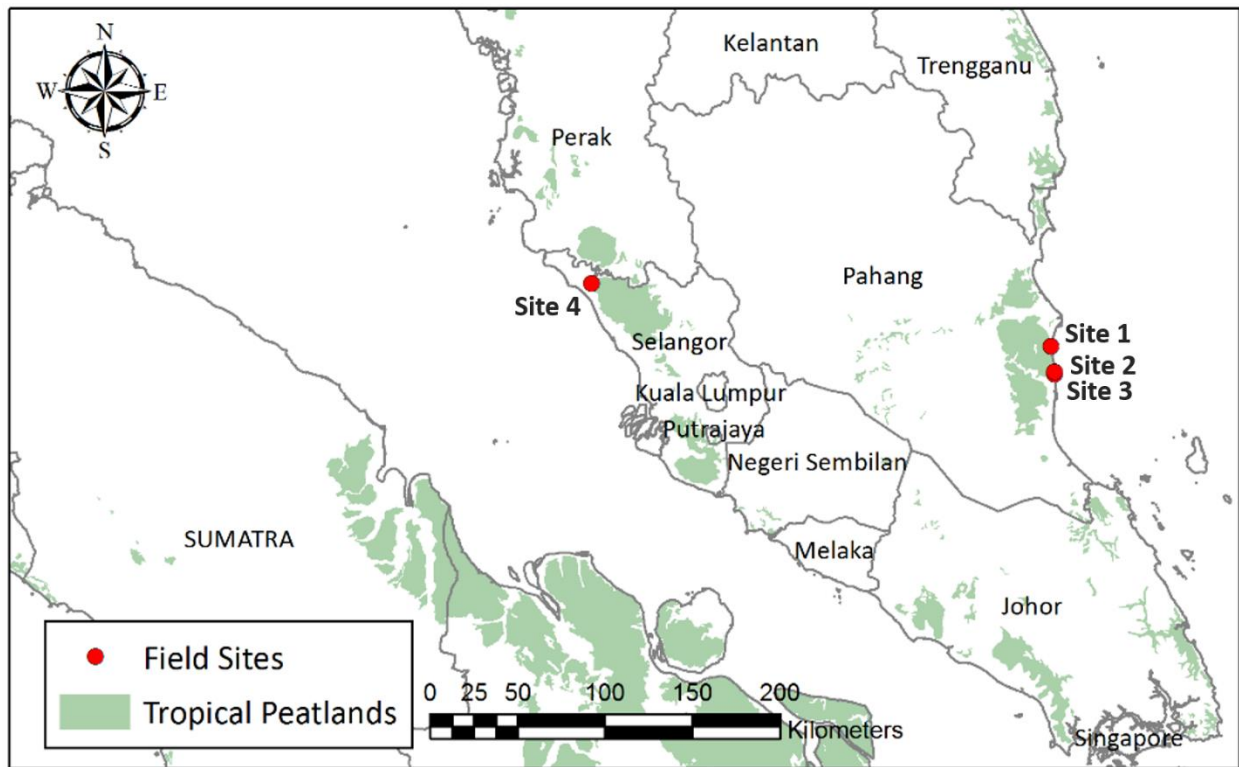
227 Site 2 (SE Pahang) was visited four times. On 17, 18, and 20 August 2015, when a large
228 landscape-scale peat fire was burning across many hectares, and on 24 August, following
229 rain, when smaller patches of the landscape fire were persisting. Site 2 had also been burning
230 since the large fires in the region in mid-July and is dominated by shrub vegetation with some
231 secondary tree growth.

232 Site 3 (SE Pahang) was visited twice, on 20 August 2015, when a large landscape-scale fire
233 was burning through the area, and on 24 August, following rain, when smaller areas of the
234 landscape ($\sim 10\text{ m}^2$) were burning. Site 3 had more secondary growth tree cover than the other
235 sites.

236 Measurements were made at Site 4 (N Selangor) on two occasions at a palm slash fire that
237 was burning into the peat on 20 July 2016, and at the same fire seven days later on 27 July
238 2016.

239

240



241

242 **Figure 1.** Map of southern Peninsular Malaysia and Sumatra, showing the location of sites
 243 measured in our two field campaigns; Sites 1–3 (Plumes P1–8) in August 2015, and Site 4
 244 (Plumes S1–2) in July 2016. The map also shows the location of Malaysian peatlands
 245 (Wetlands International, 2017) and Indonesian peatlands (Ministry of Agriculture, 2017).

246

247 **Table 1.** List of the ten plumes studied using OP-FTIR during the two Malaysian
 248 measurement campaigns in SE Pahang (P1–8) and N Selangor (S1–2), with information
 249 about the site number (Figure 1), plot location, OP-FTIR pathlength, meteorological
 250 variables, as well as peat physicochemical characteristics, including bulk density, soil
 251 moisture, nitrogen-content, and carbon-content. MCE calculated using Eqn. 5 is also
 252 presented. Standard deviations are presented in parentheses.

Plume	Site	Lat (°)	Long (°)	Path (m)	Temp (°C)	Pressure (hPa)	Bulk density (g cm ⁻³)	Soil moist (%)	N (%)	C (%)	MCE
P1	1	3.361	103.420	17	34	1008	0.63 (0.03)	24 ± 0.0	-	-	0.82
P2	1	3.361	103.420	12	36	1011	0.46 (0.20)	20 ± 1.3	0.39 (0.46)	15.2 (7.0)	0.77
P3	2	3.221	103.440	35; 29	40	1008	0.28 (0.09)	33 ± 0.1	0.69 (0.57)	20.9 (11.9)	0.83
P4	2	3.221	103.440	23; 13	38	1009	0.31 (0.10)	31 ± 0.1	0.58 (0.51)	18.3 (13.4)	0.79
P5	3	3.231	103.437	20; 12	40	1010	0.25 (0.05)	41 ± 0.6	1.75 (0.27)	43.3 (7.8)	0.79
P6	2	3.221	103.440	17	40	1010	0.38 (0.04)	29 ± 1.2	0.51 (0.21)	23.2 (15.7)	0.75
P7	3	3.231	103.437	12; 11; 10	34	1011	0.41 (0.11)	16 ± 0.3	1.76 (0.27)	41.1 (2.2)	0.78
P8	2	3.221	103.440	11; 11	34	1011	0.37 (0.10)	28 ± 0.9	1.02 (0.58)	24.3 (13.5)	0.79
S1	4	3.686	101.054	28	32	1008	0.62 (0.04)	53 ± 1.1	1.34 (0.22)	55.6 (2.6)	0.84
S2	4	3.686	101.054	18	33	1006	0.61 (0.04)	52 ± 1.2	1.34 (0.22)	55.6 (2.6)	0.84

253

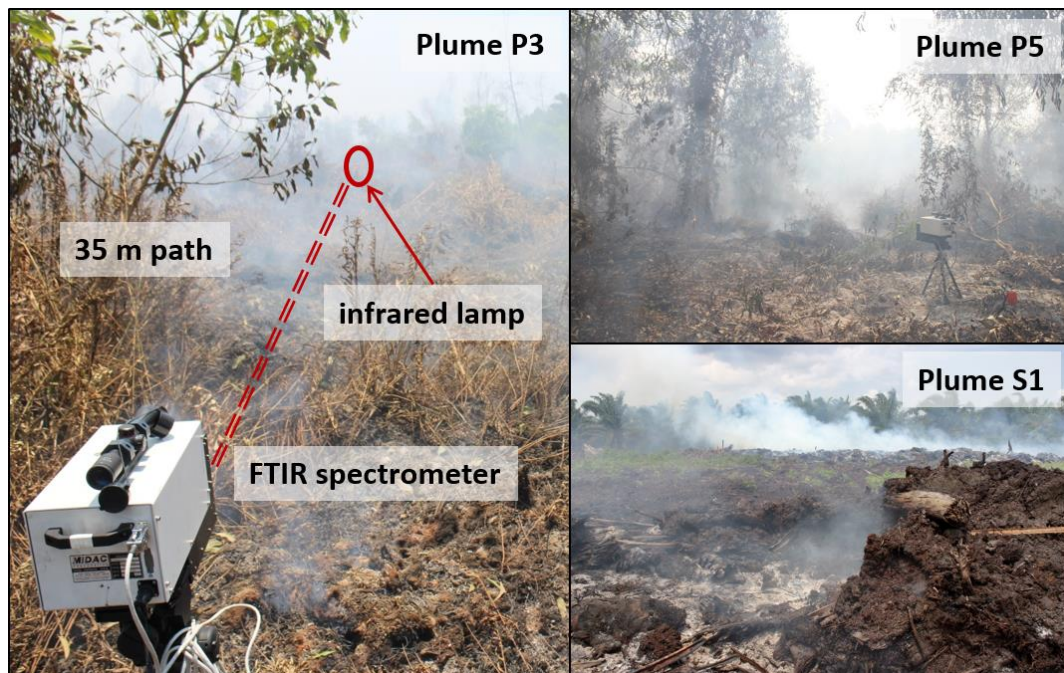
254

255 3.2 Fire emissions measurements

256 Here we use an Open-Path Fourier Transform Infrared (OP-FTIR) approach to estimate path-
 257 averaged mole fractions of twelve trace gases. The OP-FTIR system consists of a MIDAC
 258 Corporation M2000 Series FTIR spectrometer equipped with a Stirling-cooled mercury-
 259 cadmium-telluride (MCT) detector, and fitted with a MIDAC custom-built 76 mm Newtonian
 260 telescope. The spectrometer is used to view a remotely located infrared source, consisting of
 261 a 12 V silicon carbide glowbar operating at 1500 K fitted in front of a 20 cm diameter gold-
 262 plated collimator. The MIDAC system and its use to characterise biomass burning emissions
 263 via long OP-FTIR spectroscopy is detailed in *Smith et al.* [2014] and *Wooster et al.* [2011].

264 At all sites, the OP-FTIR path was positioned directly above the actively burning peat (see
 265 Figure 2). There was no evidence of flaming combustion at any of the burns, with all smoke
 266 being produced by pyrolysis and smouldering combustion. Given that there were no quick
 267 changes to burning conditions during any one deployment, spectra were collected using
 268 sixteen co-added scans to increase signal-to-noise (generating approximately one measured
 269 spectrum every 10 s). Observations of atmospheric temperature and pressure (Table 1) were
 270 made using a co-located Kestrel 5500 Weather Meter (Nielsen-Kellerman Co.).

271 Path-averaged trace gas mole fractions were retrieved from the OP-FTIR spectra using the
 272 Multiple Atmospheric Layer Transmission (MALT) program [*Griffith*, 1996], where selected
 273 spectral regions of the measured OP-FTIR spectra are fitted with synthetic spectra. A more
 274 comprehensive description of MALT can be found in *Griffith* [1996] and more details of the
 275 specific spectral regions used for the retrieval can be found in *Paton-Walsh et al.* [2014] and
 276 *Smith et al.* [2014]. An accuracy assessment of greenhouse gas mole fraction retrievals using
 277 this approach can be found in *Smith et al.* [2011], whose findings suggest that retrievals of
 278 CO₂, CH₄, and CO are accurate to within 5% of true mole fractions. *Stockwell et al.* [2016]
 279 also found retrieved mole fractions of CO₂, CH₄, and CO₂ to have an uncertainty of 3–5%.



280

281 **Figure 2.** (left) Photograph of a typical OP-FTIR setup measuring Plume P3 using a 35 m
 282 path between the FTIR spectrometer and infrared lamp (see Table 1); (right) Photographs
 283 from the sites of Plume P5 and Plume S1.

284 3.3 Calculation of emission ratios and emission factors

285 The emission ratio of species i to a reference species y is given by:

286
$$ER_{i/y} = \frac{\Delta[i]}{\Delta[y]} = \frac{[i] - [i]_{background}}{[y] - [y]_{background}} \quad (1)$$

287 where $\Delta[i]$ is the excess mole fraction of species i . Following the same method as *Paton-*
288 *Walsh et al.* [2014], here we derive emission ratios via the gradient of the linear best fit of all
289 measurements of the abundance of species i against the abundance of reference species y for
290 each fire.291 The emission factor (EF_i) refers to the mass of species i emitted per unit of dry fuel
292 consumed, expressed in units of $g\ kg^{-1}$. Here, the emission factors for all species (except CO_2
293 and CO) i are calculated via:

294
$$EF_i = ER_{i/CO} \times \frac{MM_i}{MM_{CO}} \times EF_{CO} \quad (2)$$

295 where $ER_{i/CO}$ is the emission ratio of species i to CO; MM_i is the molecular mass of species i ;
296 MM_{CO} is the molecular mass of CO ($28.01\ g\ mol^{-1}$); and EF_{CO} is the emission factor for CO.
297 The emission factor for CO_2 and CO is determined using the “summation method” [*Paton-*
298 *Walsh et al.*, 2014] where it is necessary to calculate the total excess amounts of each gas
299 species by summing the excess amounts retrieved for each spectrum (i.e. $[i] - [i]_{background}$ in
300 Eqn. 1); emission factors may then be calculated using the carbon mass balance method
301 [*Ward and Radke*, 1993]:

302
$$EF_{CO} = (F_C - F_{PMC}) \times 1000 \times \frac{MM_{CO}}{AM_C} \times \frac{\Delta_{CO}}{\sum_{i=1}^n (NC_i \times \Delta_i)} \quad (3)$$

303
$$EF_{CO_2} = (F_C - F_{PMC}) \times 1000 \times \frac{MM_{CO_2}}{AM_C} \times \frac{\Delta_{CO_2}}{\sum_{i=1}^n (NC_i \times \Delta_i)} \quad (4)$$

304 where F_C is the measured carbon mass fraction of the fuel (see Sect. 2.4); F_{PMC} is the carbon
305 mass fraction of the fuel that is emitted as particulate matter (see below); AM_C is the atomic
306 mass of carbon ($12\ g\ mol^{-1}$); NC_i is the number of carbon atoms in species i ; Δ_{CO} and Δ_i are
307 the summed excess mole fractions of CO and species i respectively. The emission factor for
308 CO_2 is calculated using the molecular mass of CO_2 ($MM_{CO_2} = 44.01\ g\ mol^{-1}$) and Δ_{CO_2} excess
309 mole fractions of CO_2 .310 The fraction of carbon emitted as particulate matter (F_{PMC}) is usually considered to be
311 negligible and ignored in the application of carbon mass balance approaches for the
312 calculation of gaseous fire emission factors (e.g. *Wooster et al.* [2011]). However, a recent *in*
313 *situ* study of PM EFs for tropical (Indonesian) peatlands [*Jayarathene et al.*, 2017] suggests
314 that PM emissions are not negligible for tropical peatland fuels and should therefore be
315 accounted for in calculations of gaseous emission factors. *Jayarathene et al.* [2017] report an
316 EF of $17.3\ g\ kg^{-1}$ for $PM_{2.5}$ with the $PM_{2.5}$ consisting of 73% carbon. We therefore assume
317 F_{PMC} of 0.0127 for Eqns. 3 and 4. EFs are directly proportional to the combined carbon mass
318 fraction in Eqns. 3 and 4, enabling easy correction of determined average EFs should this be
319 warranted by additional future PM measurements.

320

321 To enable comparison with other studies and understanding of variability between sites, we
 322 also report the modified combustion efficiency (MCE). MCE is an approximation of the
 323 combustion efficiency (the proportion of total carbon emitted as CO₂) and is given by *Hao*
 324 *and Ward* [1993] as:

$$325 \quad \text{MCE} = \frac{\Delta[\text{CO}_2]}{\Delta[\text{CO}_2] + \Delta[\text{CO}]} \quad (5)$$

326 The calculation of emission factors and MCE require knowledge of the background mole
 327 fractions of all species. Background OP-FTIR spectra were collected upwind of each of our
 328 fire sites prior to measuring the fire emissions.

329 3.4 Peat composition

330 Four substrate samples were taken from the uppermost section of the underlying unburnt
 331 substrate/peat layer, or from areas immediately adjacent to burning areas at each burn site.
 332 Samples were taken along a transect between the spectrometer and infrared lamp using a 10
 333 cm diameter and 10 cm deep brass corer. Wet and dry mass were measured to calculate bulk
 334 density and moisture content on dry basis (Table 1). Total carbon (C) and nitrogen (N)
 335 content were also determined (Table 1). For this, peat sub-samples were first oven dried at
 336 105°C for 48 hours and then ball milled for homogenisation using a Planetary Ball Mill
 337 (Retsch-PM400, Castleford, UK). Analysis of C and N used 20 mg of material enclosed in a
 338 tin capsule with measurements undertaken using a total element analyzer (Thermo Flash EA
 339 1112, CE Instruments, Wigan, UK).

340

341 4 Results and Discussion

342 4.1 Peat substrate composition

343 Given that the Pahang sites had been heavily degraded, with only a thin layer of peat
 344 remaining, the majority of the Pahang substrate samples were not pure ‘pristine’ peat, with
 345 our samples visibly containing sand or clay indicating that the peat fires had burned down to
 346 the interface with the mineral soil substrate at the Pahang sites (carbon contents ranging from
 347 15.2–43.3%), typical of degraded peats on the fringes of peat domes [*Miettinen et al.*, 2017].
 348 The samples taken at the Selangor site were clearly peat, the mean carbon content of these
 349 samples (55.6%) is close to that found for Sumatran peat (57.9%), as reported by *Stockwell et*
 350 *al.* [2014]. The nitrogen content of our samples varied significantly between 0.39% and
 351 1.76%. Nitrogen content of pristine peats is known to vary from 1.0% to 4.4% [*Andriess*,
 352 1988]. The lower nitrogen content measured here (<1%) is probably a further indicator of
 353 degradation as the main source of nutrients to the soil (peatswamp forest leaf litter) had been
 354 removed. The mean nitrogen content at the Selangor palm oil sites (1.34%) is higher than that
 355 for the abandoned Pahang sites (0.96%) and we speculate that this is due to the use of
 356 artificial fertiliser on the palm oil plantations.

357 We use a carbon fraction of 0.556 for the calculation of our peat fire emission factors (in Eqn.
 358 3), in line with samples that we determine to have been closer in composition to the overlying
 359 peat that was consumed by the fire, and also similar to the carbon fraction of 0.5793 ± 0.0252
 360 used by *Stockwell et al.* [2016], as found in the samples analysed *Stockwell et al.* [2014]. As
 361 is the case for the fraction of carbon emitted as PM_{2.5}, EFs are directly proportional to the

362 carbon mass fraction, enabling easy correction of EFs should this be warranted by additional
363 future carbon mass fraction measurements.

364 All of our sites exhibited high bulk density for tropical peat, with bulk densities ranging from
365 0.28 to 0.63 g cm⁻³; this compares with 0.09–0.11 g cm⁻³ that might be expected for pristine
366 tropical peat [Page *et al.*, 2011; Warren *et al.*, 2012]. Drainage causes loss of water from peat
367 pores and shrinkage through drying, resulting in an increase in bulk density which is
368 exacerbated by the resulting aerobic conditions causing peat degradation due to oxidation,
369 increased microbial decomposition and compaction [Könönen *et al.*, 2015]. Oil palm
370 plantation management with addition of lime and fertilizers further enhances microbial peat
371 breakdown, while artificial mechanical compaction (designed to increase root stability and
372 per volume nutrient status [Melling *et al.*, 2009], also results in further increases to bulk
373 [Evers *et al.*, 2016]. The mean bulk density at our two Selangor sites located on palm oil
374 plantations (0.62 g cm⁻³) was significantly higher than the mean bulk density at our
375 deforested but abandoned Pahang sites (0.39 g cm⁻³), probably due to extensive use of heavy
376 machinery and purposeful artificial compaction of the peat soil at the Selangor sites.

377 4.2 Trace gas emission factors and modified combustion efficiency

378 Figures 3 and 4 show example time series for each of the investigated species and their
379 corresponding emission ratio plots, respectively, for Plume P5. Our emission ratio plots show
380 a good correlation between species and mole fractions elevated far above background,
381 indicating that the plumes sampled at fires in this study were well-mixed [Stockwell *et al.*,
382 2016], and giving confidence to the individual EFs calculated for each fire (Table 2).

383 Table 2 presents the individual trace gas EFs and their associated uncertainties (in accordance
384 with Paton-Walsh *et al.* [2014]) for each of the ten plumes sampled. An EF is calculated only
385 when a trace gas species has a strong emission ratio correlation (>0.4). Table 3 presents a
386 summary of our study-averaged EFs and one standard deviation of the means for all species.
387 From measurements of ten tropical peat fire plumes, we find the major trace gas emissions by
388 mass (EF > 0.5 g kg⁻¹, as defined by Stockwell *et al.* [2016] to be: carbon dioxide (1579 ±
389 58); carbon monoxide (251 ± 39); methane (11.00 ± 6.11); ammonia (7.82 ± 4.37); acetic
390 acid (5.02 ± 1.64); hydrogen cyanide (3.79 ± 1.97); methanol (2.83 ± 0.84); ethylene (2.30 ±
391 2.79); ethane (2.17 ± 0.81); and formaldehyde (0.77 ± 0.64). We report EFs for two further
392 species that may be categorised as minor trace gas emissions by mass: formic acid (0.25 ±
393 0.04); and acetylene (0.06 ± 0.01). The modified combustion efficiency (MCE) of the fire
394 burning to produce the plumes sampled here ranged from 0.774 to 0.839 (Table 2), with an
395 average of 0.800 ± 0.031 indicating pure smouldering combustion.

396

397

398

399

400

401

402 **Table 2.** Emission factors (g kg^{-1} of dry fuel burned) for each individual plume, calculated
 403 using the standardised method outlined in *Paton-Walsh et al.* [2014]. Uncertainties were
 404 calculated in quadrature from those associated with the trace gas emission ratios and a $\pm 10\%$
 405 uncertainty in the assumed fuel carbon.

PLUME SITE	P1 1	P2 1	P3 2	P4 2	P5 3	P6 2	P7 3	P8 2	S1 4	S2 4
MCE	0.82	0.77	0.83	0.79	0.79	0.75	0.78	0.79	0.84	0.84
CO ₂	1545±154	1541±154	1662±166	1579±158	1575±157	1488±149	1535±153	1563±156	1653±165	1648±165
CO	216±34	286±46	218±35	261±42	261±42	314±50	283±45	266±43	201±32	200±32
CH ₄	26.19±4.20	6.67±1.08	5.35±0.88	7.68±1.27	8.38±1.37	9.32±1.47	8.83±1.37	8.83±1.37	14.76±2.35	14.07±2.25
C ₂ H ₂	0.06±0.01	nr	0.05±0.01	nr	nr	nr	nr	nr	nr	nr
C ₂ H ₄	10.16±1.02	1.57±0.16	1.23±0.13	1.40±0.14	1.71±0.17	1.25±0.13	1.65±0.17	1.46±0.15	0.80±0.08	1.68±0.17
C ₂ H ₆	3.88±0.62	0.90±0.15	1.66±0.26	2.24±0.36	2.02±0.32	2.83±0.46	2.07±0.32	2.05±0.32	2.56±0.41	1.44±0.22
H ₂ CO	nr	1.83±0.19	0.66±0.07	0.46±0.05	0.76±0.08	0.16±0.02	nr	nr	nr	nr
HCOOH	nr	nr	0.28±0.05	nr	0.23±0.04	nr	nr	nr	nr	nr
CH ₃ OH	2.79±0.45	3.82±0.62	1.62±0.26	1.94±0.31	2.50±0.40	2.37±0.38	2.91±0.47	3.28±0.53	2.68±0.43	4.46±0.71
CH ₃ COOH	8.91±1.43	3.66±0.59	3.65±0.59	4.14±0.66	3.78±0.61	4.46±0.71	4.14±0.66	5.65±0.90	6.20±1.00	5.61±0.90
HCN	3.43±0.55	3.26±0.52	0.34±0.06	1.96±0.31	5.99±0.96	3.26±0.52	6.24±1.00	5.92±0.95	3.71±0.22	nr
NH ₃	14.46±2.34	3.08±0.49	3.74±0.60	5.24±0.84	8.32±1.33	5.75±0.92	9.06±1.46	5.34±0.85	7.07±1.13	16.13±2.60

406

407

408

409

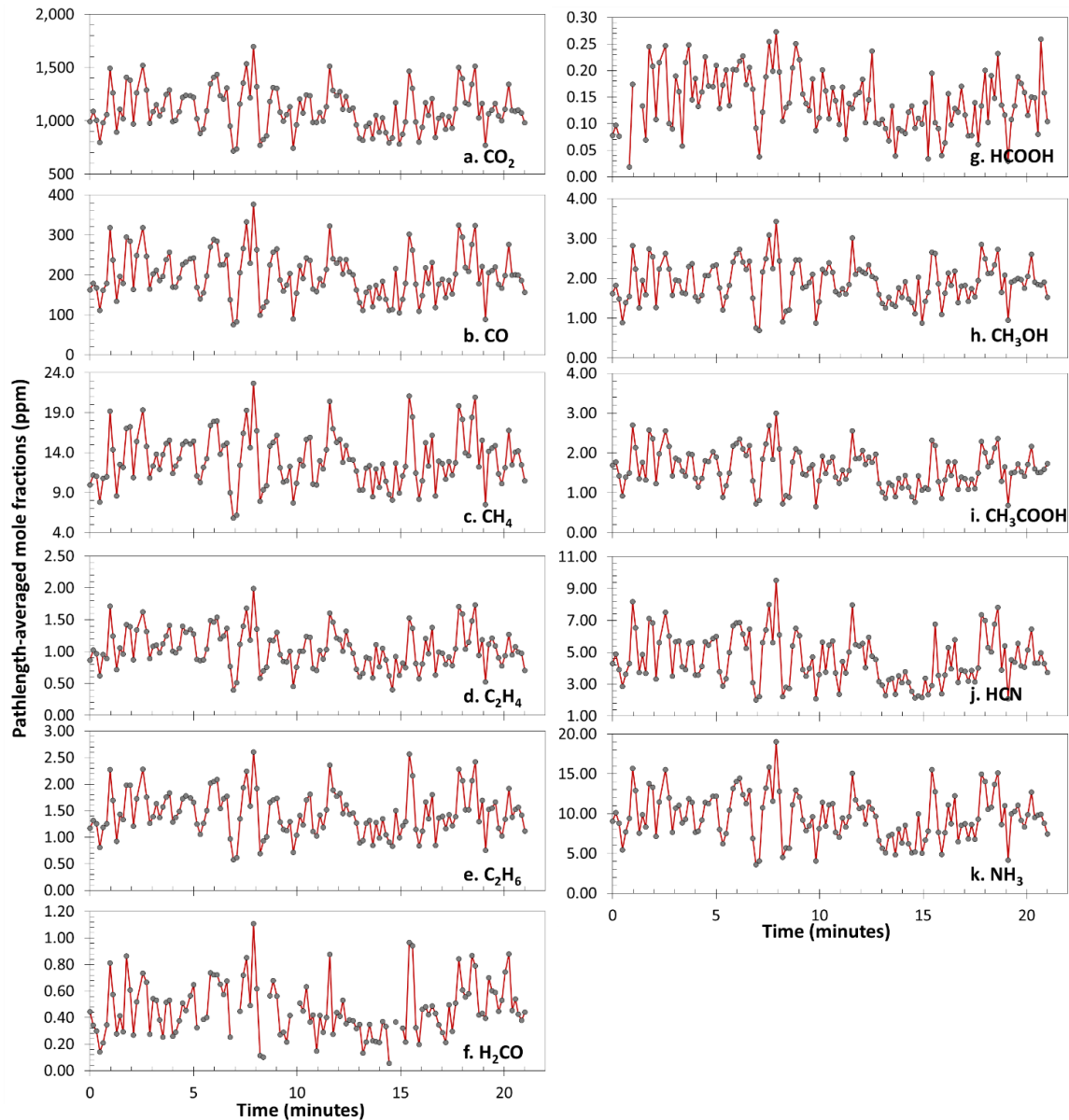
410

411 **Table 3.** Emission factors (g kg^{-1} of dry fuel burned) reported by this study of Malaysian
 412 peatlands and those for the same trace gases reported by previous *in situ* Indonesian peatland
 413 studies [*Huijnen et al.*, 2016; *Stockwell et al.*, 2016] and laboratory studies [*Christian et al.*,
 414 2003; *Stockwell et al.*, 2014]. The mean and standard deviation (in parentheses) are calculated
 415 from individual plumes (for *in situ* studies) or samples (for laboratory studies).

Trace Gas	Emission Factor (g kg^{-1} dry fuel burned)				
	Malaysian peat (<i>in situ</i>) (this study)	Kalimantan peat (<i>in situ</i>) (Stockwell et al. 2016)	Kalimantan peat (<i>in situ</i>) (Huijnen et al. 2016)	Sumatran peat (lab) (Christian et al. 2003)	Kalimantan peat (lab) (Stockwell et al. 2014)
MCE	0.800 (0.030)	0.772 (0.053)	-	0.838	0.816 (0.065)
CO ₂	1579 (58)	1564 (77)	1625 (170)	1703	1637 (204)
CO	251 (39)	291 (49)	234 (47)	210.3	233 (72)
CH ₄	11.00 (6.11)	9.51 (4.74)	7.8 (2.5)	20.8	12.8 (6.6)
C ₂ H ₂	0.06 (0.01)	0.121 (0.066)	-	0.06	0.18 (0.05)
C ₂ H ₄	2.30 (2.79)	0.961 (0.528)	-	2.57	1.39 (0.62)
C ₂ H ₆	2.17 (0.81)	1.52 (0.66)	-	-	-
H ₂ CO	0.77 (0.64)	0.867 (0.479)	-	-	1.25 (0.79)
HCOOH	0.25 (0.04)	0.180 (0.085)	-	0.79	0.55 (0.05)
CH ₃ OH	2.83 (0.84)	2.14 (1.22)	-	8.69	3.24 (1.39)
CH ₃ COOH	5.02 (1.64)	3.89 (1.65)	-	8.97	7.65 (3.65)
HCN	3.79 (1.97)	5.75 (1.60)	-	8.11	-
NH ₃	7.82 (4.37)	2.86 (1.00)	-	19.92	1.39 (0.97)

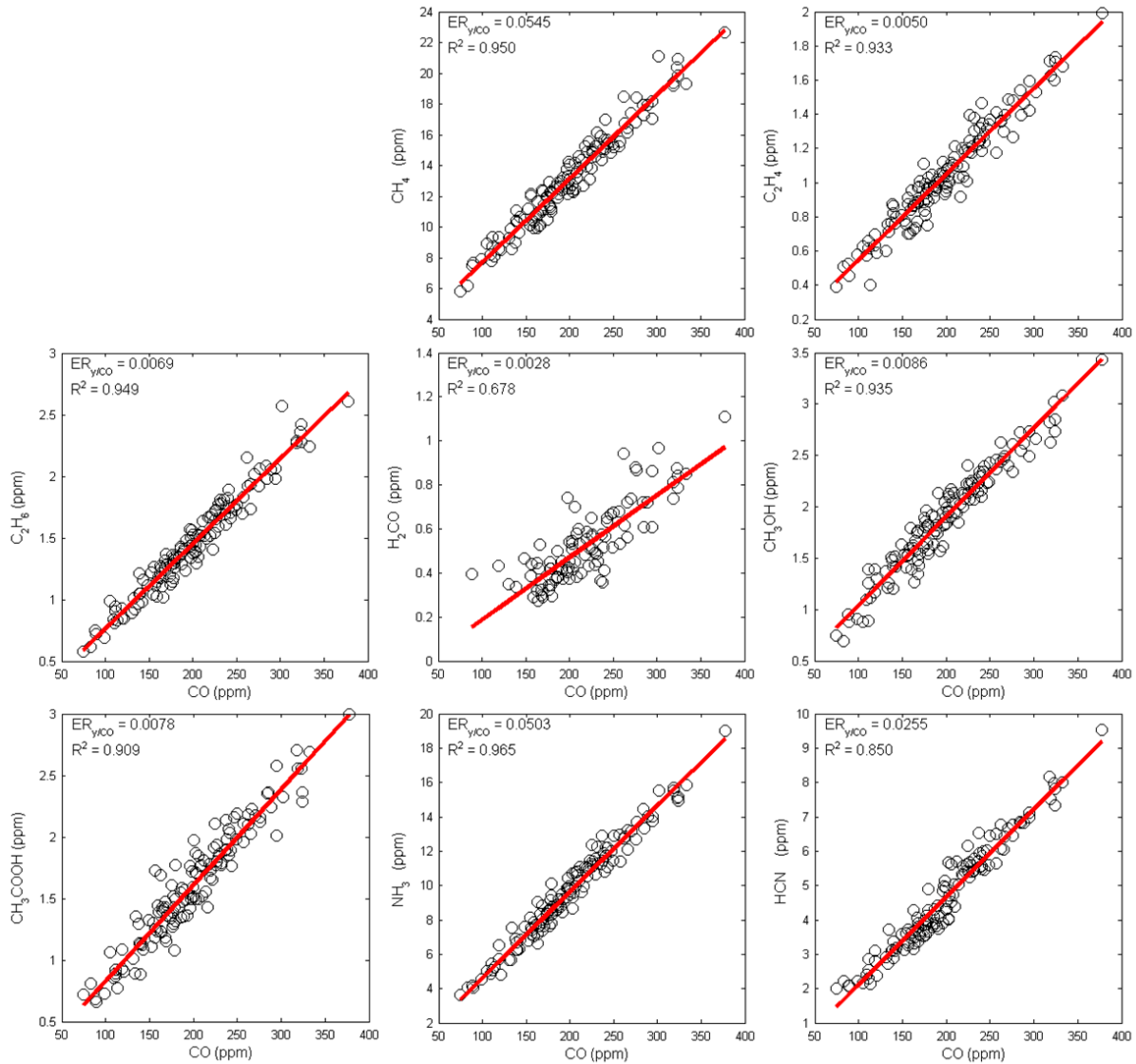
416 ^a Extratropical peat emission factors are taken from *Stockwell et al.* [2014], which are a combination of their findings with those from
 417 *Yokelson et al.* [1997]

418



419

420 **Figure 3.** Time series of path-averaged trace gas mole fractions (in ppm) for Plume P5 as
 421 measured using a 12 m path (20 August 2015) during the strong El Niño dry period of 2015.
 422 Any gaps in the time series of specific trace gases are due to periods of low signal-to-noise
 423 within the spectral window used for the retrieval of that particular species. A photograph
 424 taken during the measurements of P5 is presented in Fig. 2. Emission ratio plots for this
 425 plume are presented in Figure 4.



426

427 **Figure 4.** Example scatter plots of the measured trace gas pathlength-averaged mole fractions
 428 used to calculate emission ratios ($ER_{i/CO}$), which are in turn used to calculate emission factors
 429 through Eqn. 2. The data presented here are from Plume P5 (Figs. 2 and 3). For each of the
 430 eight trace gases shown above, the emission ratio and the R^2 is given towards the top of each
 431 plot.

432

433 4.3 Emission factor inter-plume variability and comparison with bulk density

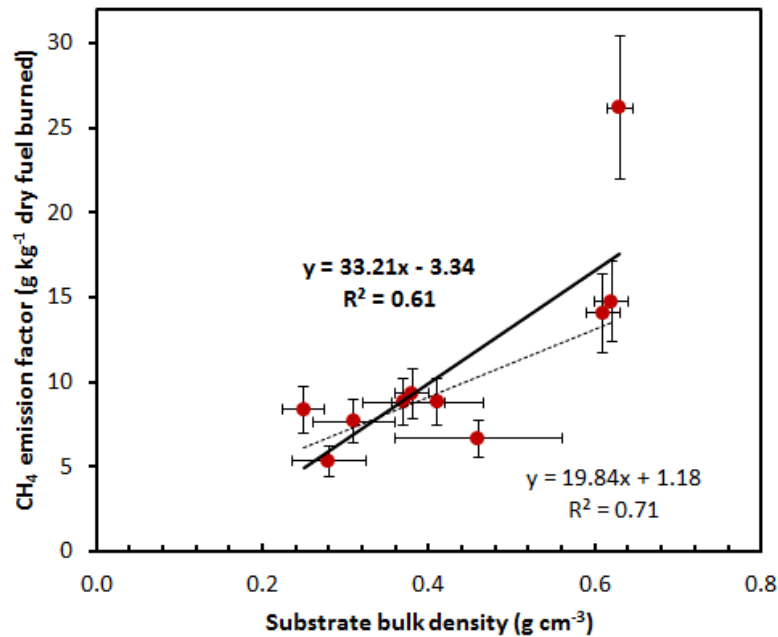
434 We found substantial inter-plume variability for EFs of a number of trace gas species (Table
 435 2). In particular, we find significant variability (percentage difference between minimum and
 436 maximum EF > 130%) for the EFs of methane (5.35–26.19 g kg⁻¹); ammonia (3.08–16.13 g
 437 kg⁻¹); and hydrogen cyanide (0.34–6.24 g kg⁻¹). The majority of the other trace gas species
 438 exhibit substantial variability with the percentage difference between minimum and
 439 maximum EFs close to 100%. Only CO₂ shows less variability (1535–1662 g kg⁻¹, a
 440 percentage difference of 7.9%), while CO shows moderate variability (200–314 g kg⁻¹, a
 441 percentage difference of 44.3%). Plume P1 is particularly anomalous, with significantly

442 elevated EFs for methane (26.19 g kg⁻¹); ammonia (14.46 g kg⁻¹); ethylene (10.16 g kg⁻¹); and
443 acetic acid (8.91 g kg⁻¹).

444 Many biomass burning studies use MCE to explain variability of non-CO₂ trace gas species
445 EFs (e.g. *Meyer et al.* [2012]) [*Stockwell et al.*, 2016]. In most biomass fires (e.g. savanna,
446 boreal forest) there is a mix of flaming and smouldering combustion, with the EFs of
447 products of flaming combustion (e.g. CO₂) tending to correlate with MCE, and the products
448 of smouldering combustion (e.g. CO) tending to anticorrelate with MCE [*Burling et al.*,
449 2011]. The plumes measured here, however, originate from smouldering combustion only,
450 and we find no dependence of our EFs on MCE. This echoes the findings of *Stockwell et al.*
451 [2016] who also find no dependence of their Indonesian peat fire EFs on MCE.

452 The three plumes with the highest EFs for methane (P1, S1, S2) all originated from sites with
453 significantly higher bulk density of the burn substrate (a mean bulk density of 0.62 g cm⁻³,
454 compared with a mean of 0.35 g cm⁻³ for our other sites). A comparison of substrate bulk
455 densities with methane emission factors (Figure 5) shows a strong positive correlation
456 between these variables ($R^2 = 0.61$, $p < 0.01$). Plume P1 is somewhat of an outlier with a
457 particularly high EF for CH₄. We decided to re-run the regression analysis without this
458 outlier; this results in a stronger relationship ($R^2 = 0.71$, $p < 0.01$). This is a novel finding that
459 suggests an important influence of the physical properties of the burn site on the resultant
460 emissions. We suggest that our results provide evidence to support the influence of bulk
461 density on burn dynamics [*Rein*, 2013; *Wijedasa et al.*, 2016], whereby a higher bulk density
462 maintains both a higher fire temperature and slower spread rate which when combined with a
463 lack of oxygen (also as a result of high bulk density), will produce more emissions through
464 non-flaming pyrolysis and glowing combustion (gasification) [*Rein*, 2013]. Methane is
465 primarily a product of glowing combustion [*Yokelson et al.*, 1997] and also a product of
466 pyrolysis [*Lobert and Warnatz*, 1993], and so we therefore propose a close link between peat
467 fire methane emission factors and site bulk density (a function of both drainage-related
468 degradation and artificial compaction). It is important to note that the bulk density at our
469 measurement sites was two-to-six times higher than that typical for pristine peats [*Page et al.*,
470 2011] and we do not recommend extending the relationship we find here to emissions from
471 fires in pristine peatlands. Further controlled experimentation is required to investigate the
472 influence of lower bulk densities on fire emissions from peat fuels.

473 Both ammonia, an important reactive nitrogen species [*Benedict et al.*, 2017]; and hydrogen
474 cyanide, a biomass burning tracer species [*Duflot et al.*, 2012] exhibit substantial inter-plume
475 variability. It is known that smoke from wildfires contains enhanced concentrations of
476 reactive nitrogen species such as ammonia [*Benedict et al.*, 2017], and the nitrogen content of
477 fuels is known to influence nitrogen species emissions during a fire [*Burling et al.*, 2010;
478 *Coggon et al.*, 2016; *Yokelson et al.*, 1996]. Further controlled experimentation is required to
479 investigate whether fertilizer addition (i.e. as was evident at our Selangor site) alters peat
480 chemical composition, and whether this in turn affects nitrogenous compound emissions
481 during fires.



482

483 **Figure 5.** Scatter plot showing the relationship between peat substrate bulk density and the
 484 methane emission factor for each of our plumes. A linear regression line of best-fit is
 485 presented using all of the data points (solid black line) as well as a best-fit line that excludes
 486 the outlier with the highest CH₄ EF (Plume P1). Both lines of best-fit have a statistically
 487 significant non-zero slope ($p < 0.01$).

488 4.4 Representativeness and comparison of emission factors to previous studies

489 Here we present the first tropical peat fire emission factors for Peninsula Malaysia. All
 490 previous studies of tropical peat emission factors have been laboratory studies of Sumatran
 491 [Christian *et al.*, 2003] or Kalimantan [Stockwell *et al.*, 2014] peat, and only one other
 492 comprehensive *in situ* study of peat fires in Kalimantan [Stockwell *et al.*, 2016]. Hamada *et al.*
 493 [2013] and Huijnen *et al.* [2016] both provide information for a limited range of species
 494 (CO₂, CO, CH₄) as measured *in situ* at peat fires in Kalimantan. These emission factors are
 495 summarised in Table 3 for comparison.

496 As noted by two other *in situ* studies [Huijnen *et al.*, 2016; Stockwell *et al.*, 2016], we also
 497 found little evidence of surface fuel combustion at our Pahang sites; the surface grasses and
 498 shrubs remained unburned although heavily dried by the heat from the fire (see Figure 2).
 499 The peat fires at our Selangor sites had clearly been ignited by a surface palm slash fire,
 500 although the fire in the palm slash had long been extinguished upon our arrival on site, with
 501 just the smouldering peat remaining. We therefore consider the EFs presented here to be of
 502 “pure” peat smoke, in line with the other studies presented in Table 3. The relative
 503 contribution of emissions from combustion of the surface layer is small compared to the
 504 emissions from burning peat [Page *et al.*, 2002], and the complexities involved in the
 505 calculation of combined surface-peat EFs is discussed at length in Stockwell *et al.* [2016].

506 An important finding from the comparison of our EFs with those from previous studies
 507 (Table 3) is the difference between our EFs and those measured in the laboratory study of
 508 Christian *et al.* [2003]. The EFs for CO₂, CH₄, and CO from Christian *et al.* [2003] were
 509 subsequently adopted by IPCC greenhouse gas guidelines [Hiraishi *et al.*, 2014]. Stockwell *et al.*

510 *al.* [2016] suggest some significant adjustments to the values used by the IPCC, with a
 511 notable decrease in CO₂ (−8%) and CH₄ (−55%) EFs, and an increase to the CO (+39%) EF.
 512 Our findings also suggest that an adjustment is needed to the IPCC values. We also find a
 513 decrease is needed for CO₂ (−5%) and CH₄ (−46%), and an increase needed for CO (+22%).
 514 Both this study and *Stockwell et al.* [2016] find significantly smaller NH₃ EFs than *Christian*
 515 *et al.* [2003], finding a decrease of 60% and 86%, respectively. The magnitude of these
 516 adjustments are similar to those suggested by the only other comprehensive *in situ* study of
 517 tropical peatland emissions [*Stockwell et al.*, 2016], lending confidence to our assertion that
 518 field-measured values are more appropriate. We suggest that any future updates to the IPCC
 519 guidelines and/or EF databases (e.g. *Akagi et al.* [2011]) use a combination of the improved
 520 field-measured EFs presented here in Table 3 and those reported in other field studies, as well
 521 as any future results from field campaigns. We find similar EFs to *Stockwell et al.* [2016] for
 522 the majority of the other gas species in Table 3 (and thus similar differences from those used
 523 by the IPCC), with the exception of ethylene (C₂H₄), which we find to have an EF closer to
 524 that found by the previous laboratory studies. We present recommended inter-study averaged
 525 EFs for tropical peatland fires in Table 4.

526
 527 **Table 4.** Recommended tropical peatland EFs for any future updates to *Akagi et al.* [2011]
 528 and/or the IPCC Greenhouse Gas Guidelines [*Hiraishi et al.*, 2014] (an asterisk indicates
 529 those species that are provided by the IPCC). The recommended EF is calculated from the
 530 mean of EFs from this study and the two other *in situ* studies [*Huijnen et al.*, 2016; *Stockwell*
 531 *et al.*, 2016]. A standard deviation is presented in parentheses where three studies are
 532 available (for CO₂, CO, CH₄), otherwise we report the range of values from the two available
 533 studies.

Trace Gas	EF (g kg ⁻¹)
CO ₂ *	1589 (32)
CO*	259 (29)
CH ₄ *	9.44 (1.6)
C ₂ H ₂	0.09 (0.06–0.12)
C ₂ H ₄	1.63 (0.96–2.30)
C ₂ H ₆	1.84 (1.52–2.17)
H ₂ CO	0.82 (0.77–0.87)
HCOOH	0.22 (0.18–0.25)
CH ₃ OH	2.49 (2.14–2.83)
CH ₃ COOH	4.46 (3.89–5.02)
HCN	4.77 (3.79–5.75)
NH ₃	5.34 (2.86–7.82)

534

535 5 Summary and conclusions

536 We present results from open-path FTIR spectroscopy measurements of emission factors for
 537 tropical peatland fires from ten fire plumes in Peninsular Malaysia. These represent the first
 538 published emission factors for fires burning in Malaysian peatlands, and only the second
 539 comprehensive set of field measurements for the tropical peatland ecosystem. We find EFs of
 540 similar magnitude to those of *Stockwell et al.* [2016] (the only other comprehensive field
 541 study of tropical peatland fire EFs) and we thus echo their suggestion that future total peat
 542 fire emissions modelling uses field-measured EFs as a more reliable alternative to the earlier
 543 laboratory studies. Mean EFs calculated from our findings, along with those of *Stockwell et*
 544 *al.* [2016] and *Huijnen et al.* [2016] (CO₂, CO, and CH₄ only) are presented in Table 4. We
 545 recommend these as the best available ecosystem-specific emission factors for tropical peat

546 fires, as determined by field measurements. Field-derived emission factors for a further ~80
 547 gas species and aerosol optical properties from Indonesian peatland fires can be found in
 548 *Stockwell et al.* [2016]

549 Further to previous studies of tropical peatland fires, we present the first evidence that may be
 550 used to explain the large inter-plume variability found by our study and others. We find
 551 substantial inter-plume variability in emission factors for methane, a potent greenhouse gas
 552 [*Hiraishi et al.*, 2014]. We find evidence, supported by a theoretical framework, which
 553 suggests much of this variability may be determined by the bulk density of the burn substrate
 554 (Figure 5). This relationship between burn substrate properties and fire emissions will need
 555 further testing through both controlled laboratory experiments and through better
 556 characterisation of fuels by *in situ* fire emissions field measurements.

557 **Acknowledgments, Samples, and Data**

558 Both the 2015 and 2016 campaigns were supported by a Royal Geographical Society Small
 559 Grant (£3,000) and by a King's College London Department of Geography Research
 560 Innovation Fund Grant (£2,000). The 2016 campaign was in-part supported by a Monash
 561 Large Strategic Grant. We would like to thank Christopher MacLellan of NERC FSF for his
 562 wide-ranging support, including the loan of the IR lamp used here. We are grateful for the
 563 much-needed field support provided by Dr Tajang Jingtut, Vicky Ting, and Christopher
 564 Roulston. We also extend thanks to Dr Bruce Main for technical and logistical support, to Dr
 565 James Millington for informing our statistical analysis; and to Dr Clare Paton-Walsh for her
 566 FTIR expertise and field support at the Selangor field sites.

567 The authors declare no financial interests. Raw mole fraction retrievals and emission ratios
 568 used to calculate emission factors may be found here: <https://doi.org/10.5281/zenodo.910770>

569 **References**

- 570 Akagi, S., R. J. Yokelson, C. Wiedinmyer, M. Alvarado, J. Reid, T. Karl, J. Crouse, and P. Wennberg (2011),
 571 Emission factors for open and domestic biomass burning for use in atmospheric models, *Atmos Chem*
 572 *Phys*, *11*(9), 4039-4072.
- 573 Andriessse, J. P. (1988), *Nature and Management of Tropical Peat Soils*, FAO (UN).
- 574 Ballhorn, U., F. Siegert, M. Mason, and S. Limin (2009), Derivation of burn scar depths and estimation of
 575 carbon emissions with LIDAR in Indonesian peatlands, *P Natl Acad Sci USA*, *106*(50), 21213-21218.
- 576 Benedict, K. B., A. J. Prenni, C. M. Carrico, A. P. Sullivan, B. A. Schichtel, and J. L. Collett (2017), Enhanced
 577 concentrations of reactive nitrogen species in wildfire smoke, *Atmospheric Environment*, *148*, 8-15.
- 578 Burling, I., R. J. Yokelson, S. Akagi, S. Urbanski, C. E. Wold, D. W. Griffith, T. J. Johnson, J. Reardon, and D.
 579 Weise (2011), Airborne and ground-based measurements of the trace gases and particles emitted by
 580 prescribed fires in the United States, *Atmos Chem Phys*, *11*(23), 12197-12216.
- 581 Burling, I., R. J. Yokelson, D. W. Griffith, T. J. Johnson, P. Veres, J. Roberts, C. Warneke, S. Urbanski, J.
 582 Reardon, and D. Weise (2010), Laboratory measurements of trace gas emissions from biomass burning of
 583 fuel types from the southeastern and southwestern United States, *Atmos Chem Phys*, *10*(22), 11115-11130.
- 584 Christian, T. J., B. Kleiss, R. J. Yokelson, R. Holzinger, P. Crutzen, W. M. Hao, B. Saharjo, and D. E. Ward
 585 (2003), Comprehensive laboratory measurements of biomass-burning emissions: 1. Emissions from
 586 Indonesian, African, and other fuels, *J. of Geophys. Res.: Atm.*, *108*(D23).
- 587 CIFOR (2015), *Clearing the smoke: The causes and consequences of Indonesia's fires*, edited.
- 588 Coggon, M. M., et al. (2016), Emissions of nitrogen-containing organic compounds from the burning of
 589 herbaceous and arboraceous biomass: Fuel composition dependence and the variability of commonly used
 590 nitrile tracers, *Geophysical Research Letters*, *43*(18), 9903-9912.
- 591 Dufлот, V., P.-F. Coheur, L. Clarisse, D. Hurtmans, Y. R'Honi, C. Wespes, Y. Ngadi, and C. Clerbaux (2012),
 592 Infrared satellite observations of HCN and C₂H₂ in biomass burning plumes, paper presented at 2012
 593 EUMETSAT Meteorological Satellite Conference.

- 594 Evers, S., C. M. Yule, R. Padfield, P. O'Reilly, and H. Varkkey (2016), Keep wetlands wet: the myth of
 595 sustainable development of tropical peatlands—implications for policies and management, *Global Change*
 596 *Biology*.
- 597 Gaveau, D. L. A., et al. (2014), Major atmospheric emissions from peat fires in Southeast Asia during non-
 598 drought years: evidence from the 2013 Sumatran fires, *Scientific Reports*, 4, 6112.
- 599 Griffith, D. W. T. (1996), Synthetic calibration and quantitative analysis of gas-phase FT-IR spectra, *Appl*
 600 *Spectrosc*, 50(1), 59-70.
- 601 Hamada, Y., U. Darung, S. H. Limin, and R. Hatano (2013), Characteristics of fire-generated gas emission
 602 observed during a large peatland fire in 2009 at Kalimantan, Indonesia, *Atmospheric Environment*, 74,
 603 177-181.
- 604 Hao, W. M., and D. E. Ward (1993), Methane production from global biomass burning, *Journal of Geophysical*
 605 *Research: Atmospheres*, 98(D11), 20657-20661.
- 606 Hiraishi, T., T. Krug, K. Tanabe, N. Srivastava, J. Baasansuren, M. Fukuda, and T. Troxler (2014), 2013
 607 supplement to the 2006 IPCC guidelines for national greenhouse gas inventories: Wetlands, *IPCC*,
 608 *Switzerland*.
- 609 Huijnen, V., M. J. Wooster, J. W. Kaiser, D. L. A. Gaveau, J. Flemming, M. Parrington, A. Inness, D.
 610 Murdiyarso, B. Main, and M. van Weele (2016), Fire carbon emissions over maritime southeast Asia in
 611 2015 largest since 1997, *Scientific Reports*, 6, 26886.
- 612 IPCC (2013), *Climate Change 2013: The Physical Science Basis.*, 1535 pp., Cambridge University Press.
- 613 Jayarathne, T., C. E. Stockwell, A. A. Gilbert, K. Daugherty, M. A. Cochrane, K. C. Ryan, E. I. Putra, B. H.
 614 Saharjo, A. D. Nurhayati, I. Albar, R. J. Yokelson, and E. A. Stone (2017), Chemical characterization of
 615 fine particulate matter emitted by peat fires in Central Kalimantan, Indonesia, during the 2015 El Niño,
 616 *Atmos. Chem. Phys. Discuss.*, <https://doi.org/10.5194/acp-2017-608>, in review.
- 617 Könönen, M., J. Jauhiainen, R. Laiho, K. Kusin, and H. Vasander (2015), Physical and chemical properties of
 618 tropical peat under stabilised land uses, *Mires Peat*, 16(8), 1-13.
- 619 Koplitz, S. N., L. J. Mickley, M. E. Marlier, J. J. Buonocore, P. S. Kim, T. Liu, M. P. Sulprizio, R. S. DeFries,
 620 D. J. Jacob, and J. Schwartz (2016), Public health impacts of the severe haze in Equatorial Asia in
 621 September–October 2015: demonstration of a new framework for informing fire management strategies to
 622 reduce downwind smoke exposure, *Environmental Research Letters*, 11(9), 094023.
- 623 Langner, A., and F. Siegert (2009), Spatiotemporal fire occurrence in Borneo over a period of 10 years, *Global*
 624 *Change Biology*, 15(1), 48-62.
- 625 Lobert, J. M., and J. Warnatz (1993), Emissions from the combustion process in vegetation, *Fire in the*
 626 *Environment*, 13, 15-37.
- 627 Melling, L., K. Chua, and K. Lim (2009), Managing Peat Soils Under Oil Palm, *Can be accessed at:*
 628 *[http://tropicalpeat.sarawak.gov.my/modules/web/pages.php?mod=download&id=Publi](http://tropicalpeat.sarawak.gov.my/modules/web/pages.php?mod=download&id=Publication&menu_id=0&sub_id=111)*
 629 *[cation&menu_id=0&sub_id, 111](http://tropicalpeat.sarawak.gov.my/modules/web/pages.php?mod=download&id=Publication&menu_id=0&sub_id=111)*.
- 630 Meyer, C. P., G. D. Cook, F. Reisen, T. E. L. Smith, M. Tattaris, J. Russell-Smith, S. W. Maier, C. P. Yates, and
 631 M. J. Wooster (2012), Direct measurements of the seasonality of emission factors from savanna fires in
 632 northern Australia, *J Geophys Res-Atmos*, 117.
- 633 Miettinen, J., A. Hooijer, R. Vernimmen, S. C. Liew, and S. E. Page (2017), From carbon sink to carbon source:
 634 extensive peat oxidation in insular Southeast Asia since 1990, *Environmental Research Letters*, 12(2),
 635 024014.
- 636 Ministry of Agriculture (2017) Indonesia peat lands. Accessed through Global Forest Watch on 5 May 2017.
 637 Available from: http://data.globalforestwatch.org/datasets/d52e0e67ad21401cbf3a2c002599cf58_10
- 638 Moreno, L., M. E. Jimenez, H. Aguilera, P. Jimenez, and A. de la Losa (2011), The 2009 Smouldering Peat Fire
 639 in Las Tablas de Daimiel National Park (Spain), *Fire Technology*, 47(2), 519-538.
- 640 Page, S. E., J. O. Rieley, and C. J. Banks (2011), Global and regional importance of the tropical peatland carbon
 641 pool, *Global Change Biology*, 17(2), 798-818.
- 642 Page, S. E., F. Siegert, J. O. Rieley, H.-D. V. Boehm, A. Jaya, and S. Limin (2002), The amount of carbon
 643 released from peat and forest fires in Indonesia during 1997, *Nature*, 420(6911), 61-65.
- 644 Paton-Walsh, C., T. E. L. Smith, E. L. Young, D. W. T. Griffith, and E. A. Guerette (2014), New emission
 645 factors for Australian vegetation fires measured using open-path Fourier transform infrared spectroscopy -
 646 Part 1: Methods and Australian temperate forest fires, *Atmos Chem Phys*, 14(20), 11313-11333.
- 647 Penman, J., M. Gytarsky, T. Hiraishi, T. Krug, D. Kruger, R. Pipatti, L. Buendia, K. Miwa, T. Ngara, and K.
 648 Tanabe (2003), *Good practice guidance for land use, land-use change and forestry*, Institute for Global
 649 Environmental Strategies.
- 650 Posa, M. R. C., L. S. Wijedasa, and R. T. Corlett (2011), Biodiversity and Conservation of Tropical Peat Swamp
 651 Forests, *Bioscience*, 61(1), 49-57.
- 652 Post, J. (2015), Haze kills 10 people, leaves 503,874 with respiratory ailments: Agency, edited.

- 653 Rein, G. (2013), Smouldering fires and natural fuels, in *Fire Phenomena in the Earth System - An*
654 *Interdisciplinary Approach to Fire Science*, edited by C. Belcher, pp. 15-34, Wiley and Sons.
- 655 Rein, G., S. Cohen, and A. Simeoni (2009), Carbon emissions from smouldering peat in shallow and strong
656 fronts, *Proceedings of the Combustion Institute*, 32(2), 2489-2496.
- 657 Sahani, M., N. A. Zainon, W. R. W. Mahiyuddin, M. T. Latif, R. Hod, M. F. Khan, N. M. Tahir, and C.-C. Chan
658 (2014), A case-crossover analysis of forest fire haze events and mortality in Malaysia, *Atmospheric*
659 *Environment*, 96, 257-265.
- 660 Siebert, F., G. Ruecker, A. Hinrichs, and A. A. Hoffmann (2001), Increased damage from fires in logged forests
661 during droughts caused by El Niño, *Nature*, 414(6862), 437-440.
- 662 Smith, T. E. L., M. J. Wooster, M. Tattaris, and D. W. T. Griffith (2011), Absolute accuracy and sensitivity
663 analysis of OP-FTIR retrievals of CO₂, CH₄ and CO over concentrations representative of "clean air" and
664 "polluted plumes", *Atmos Meas Tech*, 4(1), 97-116.
- 665 Smith, T. E. L., C. Paton-Walsh, C. P. Meyer, G. D. Cook, S. W. Maier, J. Russell-Smith, M. J. Wooster, and C.
666 P. Yates (2014), New emission factors for Australian vegetation fires measured using open-path Fourier
667 transform infrared spectroscopy - Part 2: Australian tropical savanna fires, *Atmos Chem Phys*, 14(20),
668 11335-11352.
- 669 Stockwell, C. E., P. R. Veres, J. Williams, and R. J. Yokelson (2015), Characterization of biomass burning
670 emissions from cooking fires, peat, crop residue, and other fuels with high-resolution proton-transfer-
671 reaction time-of-flight mass spectrometry, *Atmos. Chem. Phys.*, 15(2), 845-865.
- 672 Stockwell, C. E., R. J. Yokelson, S. M. Kreidenweis, A. L. Robinson, P. J. DeMott, R. C. Sullivan, J. Reardon,
673 K. C. Ryan, D. W. T. Griffith, and L. Stevens (2014), Trace gas emissions from combustion of peat, crop
674 residue, domestic biofuels, grasses, and other fuels: configuration and Fourier transform infrared (FTIR)
675 component of the fourth Fire Lab at Missoula Experiment (FLAME-4), *Atmos. Chem. Phys.*, 14(18), 9727-
676 9754.
- 677 Stockwell, C. E., T. Jayarathne, M. A. Cochrane, K. C. Ryan, E. I. Putra, B. H. Saharjo, A. D. Nurhayati, I.
678 Albar, D. R. Blake, and I. J. Simpson (2016), Field measurements of trace gases and aerosols emitted by
679 peat fires in Central Kalimantan, Indonesia, during the 2015 El Niño, *Atmos Chem Phys*, 16(18), 11711-
680 11732.
- 681 van der Werf, G. R., D. C. Morton, R. S. DeFries, J. G. J. Olivier, P. S. Kasibhatla, R. B. Jackson, G. J. Collatz,
682 and J. T. Randerson (2009), CO₂ emissions from forest loss, *Nat Geosci*, 2(11), 737-738.
- 683 van der Werf, G. R., et al. (2017), Global fire emissions estimates during 1997–2015, *Earth Syst. Sci. Data*
684 *Discuss.*, 2017, 1-43.
- 685 van Leeuwen, T. T., and G. R. van der Werf (2011), Spatial and temporal variability in the ratio of trace gases
686 emitted from biomass burning, *Atmos. Chem. Phys.*, 11(8), 3611-3629.
- 687 Varkkey, H. (2013), Patronage politics, plantation fires and transboundary haze, *Environmental Hazards*, 12(3-
688 4), 200-217.
- 689 Ward, D., and L. Radke (1993), Emissions measurements from vegetation fires: A comparative evaluation of
690 methods and results.
- 691 Warren, M., J. Kauffman, D. Murdiyarso, G. Anshari, K. Hergoualc'h, S. Kurnianto, J. Purbopuspito, E.
692 Gusmayanti, M. Afifudin, and J. Rahajoe (2012), A cost-efficient method to assess carbon stocks in
693 tropical peat soil, *Biogeosciences*, 9.
- 694 Wetlands International (2017) Malaysian peat lands. Accessed through Global Forest Watch on 5 May 2017.
695 Available from: http://data.globalforestwatch.org/datasets/d52e0e67ad21401cbf3a2c002599cf58_10
- 696 Wijedasa, L. S., J. Jauhainen, M. Könönen, M. Lampela, H. Vasander, M. C. LeBlanc, S. Evers, T. E. Smith, C.
697 M. Yule, and H. Varkkey (2016), Denial of long-term issues with agriculture on tropical peatlands will
698 have devastating consequences, *Global change biology*.
- 699 Wilson, D., S. Dixon, R. Artz, T. Smith, C. Evans, H. Owen, E. Archer, and F. Renou-Wilson (2015),
700 Derivation of greenhouse gas emission factors for peatlands managed for extraction in the Republic of
701 Ireland and the UK, *Biogeosci Disc*, 12, 7491-7535.
- 702 Wooster, M., G. Perry, and A. Zoumas (2012), Fire, drought and El Niño relationships on Borneo (Southeast
703 Asia) in the pre-MODIS era (1980–2000), *Biogeosciences*, 9(1), 317-340.
- 704 Wooster, M. J., P. H. Freeborn, S. Archibald, C. Oppenheimer, G. J. Roberts, T. E. L. Smith, N. Govender, M.
705 Burton, and I. Palumbo (2011), Field determination of biomass burning emission ratios and factors via
706 open-path FTIR spectroscopy and fire radiative power assessment: headfire, backfire and residual
707 smouldering combustion in African savannahs, *Atmos Chem Phys*, 11(22), 11591-11615.
- 708 Wösten, J. H. M., et al. (2006), Interrelationships between hydrology and ecology in fire degraded tropical peat
709 swamp forests, *Int J Water Resour D*, 22(1), 157-174.
- 710 Yokelson, R. J., D. W. Griffith, and D. E. Ward (1996), Open-path Fourier transform infrared studies of large-
711 scale laboratory biomass fires, *Journal of Geophysical Research: Atmospheres*, 101(D15), 21067-21080.

712 Yokelson, R. J., R. Susott, D. E. Ward, J. Reardon, and D. W. Griffith (1997), Emissions from smoldering
713 combustion of biomass measured by open-path Fourier transform infrared spectroscopy, *J Geophys Res:*
714 *Atmos*, *102*(D15), 18865-18877.
715
716