Smith, T, Evers, SL, Yule, C and Gan, J

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

http://researchonline.ljmu.ac.uk/id/eprint/7763/

Article

Citation (please note it is advisable to refer to the publisher's version if you intend to cite from this work)

Smith, T, Evers, SL, Yule, C and Gan, J (2017) In situ tropical peatland fire emission factors and their variability, as determined by field measurements in Peninsula Malaysia. Global Biogeochemical Cycles. ISSN 0886-6236

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

T. E. L. Smith[1,2,3], S. Evers[4,3,5], C. M. Yule[6,3], and J. Y. Gan[6,7]

[1]Department of Geography & Environment, London School of Economics and Political Science, London, United Kingdom
[2]King's College London, Department of Geography, Strand, London, United Kingdom
[3]Tropical Catchment Research Initiative (TROCARI), Kuala Lumpur, Malaysia
[4]School of Natural Sciences & Psychology, Liverpool John Moores University, Liverpool, UK
[5]School of Biosciences, University of Nottingham Malaysia Campus, Semenyih, Selangor Darhul Ehsan, Malaysia
[6]Tropical Medicine and Biology Multidisciplinary Platform, School of Science, Monash University Malaysia, Selangor, Malaysia
[7]Global Environment Centre, Petaling Jaya, Selangor, Malaysia

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

Key Points:

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

Abstract

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

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

1 Introduction

Fires in tropical peatlands account for 25% or more of the estimated total greenhouse gas (GHG) emissions from global deforestation and forest degradation, amounting to approximately 3% of total global anthropogenic GHG emissions [*Ballhorn et al.*, 2009; *IPCC*, 2013; *van der Werf et al.*, 2009; *van der Werf et al.*, 2017]. In 1997 alone, El Niño-related fires in Indonesia were calculated to have released 13–40% of that year’s total carbon emissions from fossil fuel burning [*Page et al.*, 2002]. Beyond the global climate forcing of GHGs such as CO_2, methane (CH_4), and nitrous oxide (N_2O), peatland fire emissions of carbon monoxide (CO), nitrogen oxides (NO_x) and volatile organic compounds (VOCs) react to form ozone (O_3). This, combined with particulate matter (PM) emissions, leads to smog (referred to as ‘haze’ in SE Asia). In the southern region of SE Asia, peatland fires are responsible for 90% of trans-boundary haze events [*Varkkey*, 2013]. Air Pollution Index readings in Palangkaraya in Borneo in October 2015 reached >2000, the highest values ever recorded and far above the Emergency level of >500. Exposure to haze events has been shown to cause both immediate and delayed effects, increasing respiratory related mortality by 19–66% [*Sahani et al.*, 2014] and resulting in over 100,000 excess deaths in Malaysia, Indonesia and Singapore [*Koplitz et al.*, 2016]. In the 2015 fires, an estimated >500,000 Indonesians were affected by haze-related respiratory infections [Jakarta *Post*, 2015]. Economic losses related to haze are also significant, with estimates for the 2015 fires at $16.1 billion for Indonesia [*CIFOR*, 2015]. Despite these significant global and regional impacts, very little is known of the proportional contribution of the major chemical compounds being emitted *in situ* from tropical peat fires. As a result, there are no published accounts addressing how GHG and reactive (haze-forming) gaseous fire emissions vary among different types of tropical peatlands, precluding both accurate greenhouse gas accounting and air quality (haze) forecasting in this region.

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

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

2 Tropical peatland fire emission factors

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

Previous studies of peat fire gaseous emissions factors have predominantly undertaken Fourier transform infrared (FTIR) spectroscopic measurements of emissions from peat samples burning in a laboratory. These studies have investigated fire emissions from samples of temperate peat [*Stockwell et al.*, 2014; *Wilson et al.*, 2015; *Yokelson et al.*, 1997]; boreal peat [*Stockwell et al.*, 2014; *Yokelson et al.*, 1997]; and include studies of samples of tropical peat from Sumatra [*Christian et al.*, 2003] and Kalimantan [*Stockwell et al.*, 2015; *Stockwell et al.*, 2014].

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

Despite these advances, it is difficult to assess the representativeness of emissions from laboratory-scale burns [*Stockwell et al.*, 2016], particularly for peat fuels, that under landscape-scale burning conditions would smoulder at the surface or underground, with less access to oxygen than might be available under laboratory conditions [*Rein et al.*, 2009]. As far as we are aware, the first *in situ* field measurements of gaseous fire emissions from tropical peatland fires are those by *Hamada et al.* [2013], whose study of landscape-scale peat fires near Palangka Raya (Kalimantan, Indonesia) in August 2009 reports emission ratios of CH_4, N_2O, and CO, to CO_2. *Huijnen et al.* [2016] report emission factors for CO_2, CO, and CH_4 from peatland fires measured *in situ* using a portable cavity enhanced laser absorption spectrometer, also near Palangka Raya, in October 2015. The most comprehensive field study to date is that of *Stockwell et al.* [2016] who reported gaseous and particulate emission factors for ~90 species from measurements at 35 smoke plumes during the 2015 El Niño in Central Kalimantan, Indonesia. There have been no published laboratory or *in situ* derived emission factors for Malaysian peat fires.

van Leeuwen and van der Werf [2011] argue that future fire emissions measurement campaigns would be far more beneficial to the global modelling community if measurements were distributed spatially across biomes and paid more attention to fuel properties. The physical properties of peat fuels (e.g. bulk density, fuel moisture) are important because they will determine the combustion dynamics [*Rein et al.*, 2009]. Therefore, degradation impacts (such as the lowering of the water table or artificial peat compaction) on the physical properties of tropical peats (e.g. moisture content, bulk density) may influence the relative abundances of CO_2 and haze-forming compounds during fires [*Moreno et al.*, 2011; *Rein et al.*, 2009].

The chemical properties of fuels are important because they will determine the chemical composition of fire emissions. Whilst the carbon content of vegetation and tropical peat does not vary much beyond 50–56% [*Christian et al.*, 2003; *Stockwell et al.*, 2014], nitrogen content of tropical peats is known to vary from 1.0–4.4% and may be heavily influenced by land conversion [*Andriesse*, 1988] and management. This will influence nitrogenous fire EFs (e.g. NO_X, N_2O, NH_3, HCN) which are important for O_3 and haze formation. Direct impacts of degradation include the use of fertilizers on converted peatlands (increasing peat nitrogen), leading to the potential for increasing fire EFs for these nitrogen compounds.

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

3 Methodology

3.1 Site and fire descriptions

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

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

Locations of actively burning peatland fires were identified by regular monitoring of the World Resources Institute Global Forest Watch Fires website (http://fires.globalforestwatch.org/) and NASA’s Worldview website (https://worldview.earthdata.nasa.gov/). These websites provide the near-real-time location of satellite-detected fires (thermal hotspots); true-colour and false-colour imagery that can be used to identify the presence of smoke plumes; as well as information on the location of peatlands. Many active fires were observed in SE Pahang (Sites 1–3 in Figure 1) in July 2015 shortly before the ground measurement campaign; this led the research team to be based at Pekan, just north of these July fire clusters. Once a possible peatland fire had been identified, the research team drove in the direction of the fires until a visible confirmation of the location of the fire was established. Fewer fires were observed across Peninsula Malaysia in July 2016, however a cluster of hotspots were detected just north of Sekinchan in N Selangor (Site 4 in Figure 1) in early July which led the research team to this area where a number of small peatland fires were found on oil palm plantations.

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

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

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

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

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

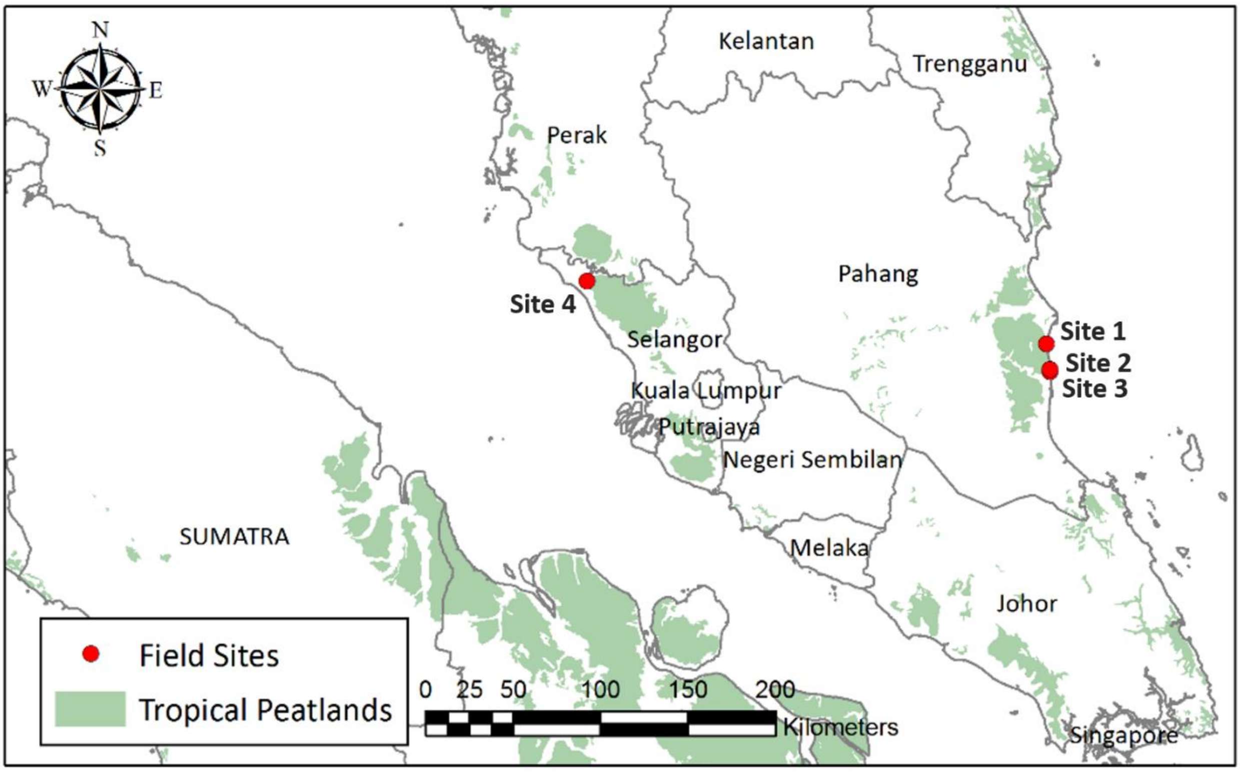

Figure 1. Map of southern Peninsula Malaysia and Sumatra, showing the location of sites measured in our two field campaigns; Sites 1–3 (Plumes P1–8) in August 2015, and Site 4 (Plumes S1–2) in July 2016. The map also shows the location of Malaysian peatlands (Wetlands International, 2017) and Indonesian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

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

3.2 Fire emissions measurements

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

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

Path-averaged trace gas mole fractions were retrieved from the OP-FTIR spectra using the Multiple Atmospheric Layer Transmission (MALT) program [*Griffith*, 1996], where selected spectral regions of the measured OP-FTIR spectra are fitted with synthetic spectra. A more comprehensive description of MALT can be found in *Griffith* [1996] and more details of the specific spectral regions used for the retrieval can be found in *Paton-Walsh et al.* [2014] and *Smith et al.* [2014]. An accuracy assessment of greenhouse gas mole fraction retrievals using this approach can be found in *Smith et al.* [2011], whose findings suggest that retrievals of CO_2, CH_4, and CO are accurate to within 5% of true mole fractions. *Stockwell et al.* [2016] also found retrieved mole fractions of CO_2, CH_4, and CO_2 to have an uncertainty of 3–5%.

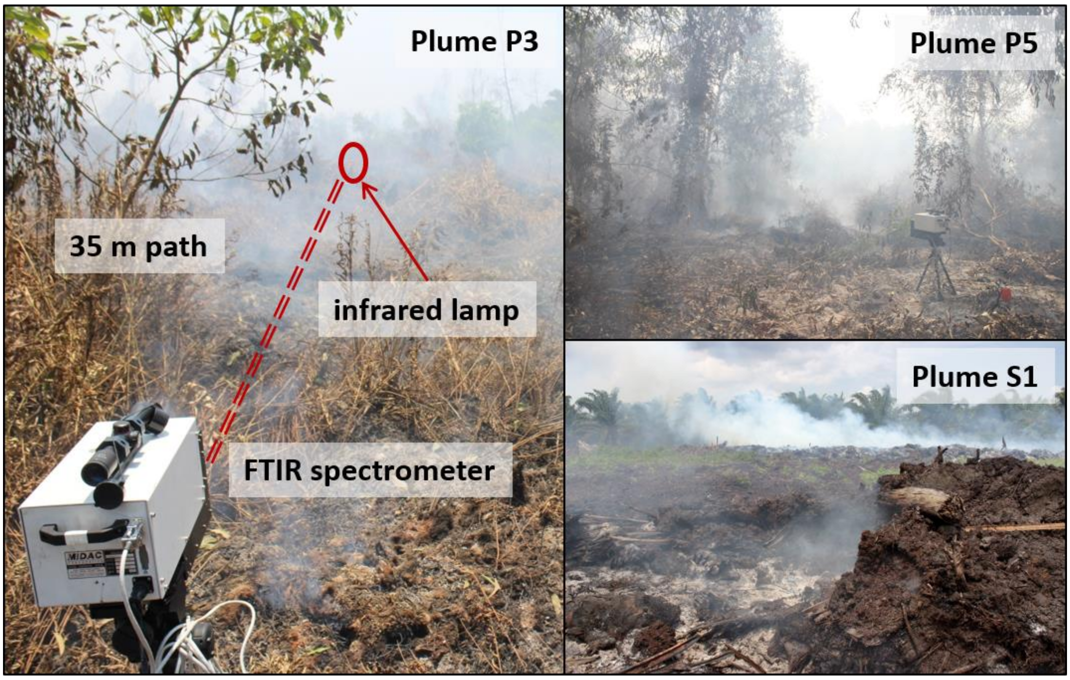

Figure 2. (left) Photograph of a typical OP-FTIR setup measuring Plume P3 using a 35 m path between the FTIR spectrometer and infrared lamp (see Table 1); (right) Photographs from the sites of Plume P5 and Plume S1.

3.3 Calculation of emission ratios and emission factors

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

$$\mathrm{ER}_{i/y} = \frac{\Delta[i]}{\Delta[y]} = \frac{[i] - [i]_{background}}{[y] - [y]_{background}} \tag{1}$$

where $\Delta[i]$ is the excess mole fraction of species *i*. Following the same method as *Paton-Walsh et al.* [2014], here we derive emission ratios via the gradient of the linear best fit of all measurements of the abundance of species *i* against the abundance of reference species *y* for each fire.

The emission factor (EF_i) refers to the mass of species *i* emitted per unit of dry fuel consumed, expressed in units of g kg^{-1}. Here, the emission factors for all species (except CO_2 and CO) *i* are calculated via:

$$\mathrm{EF}_i = \mathrm{ER}_{i/\mathrm{CO}} \times \frac{\mathrm{MM}_i}{\mathrm{MM}_{\mathrm{CO}}} \times \mathrm{EF}_{\mathrm{CO}} \tag{2}$$

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

$$\mathrm{EF}_{\mathrm{CO}} = (F_{\mathrm{C}} - F_{\mathrm{PMC}}) \times 1000 \times \frac{\mathrm{MM}_{\mathrm{CO}}}{\mathrm{AM}_{\mathrm{C}}} \times \frac{\Delta_{\mathrm{CO}}}{\sum_{i=1}^{n}(\mathrm{NC}_i \times \Delta_i)} \tag{3}$$

$$\mathrm{EF}_{\mathrm{CO2}} = (F_{\mathrm{C}} - F_{\mathrm{PMC}}) \times 1000 \times \frac{\mathrm{MM}_{\mathrm{CO2}}}{\mathrm{AM}_{\mathrm{C}}} \times \frac{\Delta_{\mathrm{CO2}}}{\sum_{i=1}^{n}(\mathrm{NC}_i \times \Delta_i)} \tag{4}$$

where F_{C} is the measured carbon mass fraction of the fuel (see Sect. 2.4); F_{PMC} is the carbon mass fraction of the fuel that is emitted as particulate matter (see below); AM_{C} is the atomic mass of carbon (12 g mol^{-1}); NC_i is the number of carbon atoms in species *i*; Δ_{CO} and Δ_i are the summed excess mole fractions of CO and species *i* respectively. The emission factor for CO_2 is calculated using the molecular mass of CO_2 ($\mathrm{MM}_{\mathrm{CO2}}$ = 44.01 g mol^{-1}) and Δ_{CO2} excess mole fractions of CO_2.

The fraction of carbon emitted as particulate matter (F_{PMC}) is usually considered to be negligible and ignored in the application of carbon mass balance approaches for the calculation of gaseous fire emission factors (e.g. *Wooster et al.* [2011]). However, a recent *in situ* study of PM EFs for tropical (Indonesian) peatlands [*Jayarathene et al.*, 2017] suggests that PM emissions are not negligible for tropical peatland fuels and should therefore be accounted for in calculations of gaseous emission factors. *Jayarathene et al.* [2017] report an EF of 17.3 g kg^{-1} for $PM_{2.5}$ with the $PM_{2.5}$ consisting of 73% carbon. We therefore assume F_{PMC} of 0.0127 for Eqns. 3 and 4. EFs are directly proportional to the combined carbon mass fraction in Eqns. 3 and 4, enabling easy correction of determined average EFs should this be warranted by additional future PM measurements.

To enable comparison with other studies and understanding of variability between sites, we also report the modified combustion efficiency (MCE). MCE is an approximation of the combustion efficiency (the proportion of total carbon emitted as CO_2) and is given by *Hao and Ward* [1993] as:

$$\mathrm{MCE} = \frac{\Delta[\mathrm{CO_2}]}{\Delta[\mathrm{CO_2}] + \Delta[\mathrm{CO}]} \tag{5}$$

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

3.4 Peat composition

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

4 Results and Discussion

4.1 Peat substrate composition

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

We use a carbon fraction of 0.556 for the calculation of our peat fire emission factors (in Eqn. 3), in line with samples that we determine to have been closer in composition to the overlying peat that was consumed by the fire, and also similar to the carbon fraction of 0.5793 ± 0.0252 used by *Stockwell et al.* [2016], as found in the samples analysed *Stockwell et al.* [2014]. As is the case for the fraction of carbon emitted as PM,, EFs are directly proportional to the carbon mass fraction, enabling easy correction of EFs should this be warranted by additional future carbon mass fraction measurements.

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

4.2 Trace gas emission factors and modified combustion efficiency

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

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

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

PLUME	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**S1**	**S2**
SITE	**1**	**1**	**2**	**2**	**3**	**2**	**3**	**2**	**4**	**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_2H_2	0.06±0.01	nr	0.05±0.01	nr	nr	nr	nr	nr	nr	nr
C_2H_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_2H_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_2CO	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_3OH	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_3COOH	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

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

Trace Gas	**Emission Factor (g kg^{-1} dry fuel burned)**				
	Malaysian peat (*in situ*) (this study)	Kalimantan peat (*in situ*) (Stockwell et al. 2016)	Kalimantan peat (*in situ*) (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_2H_2	0.06 (0.01)	0.121 (0.066)	-	0.06	0.18 (0.05)
C_2H_4	2.30 (2.79)	0.961 (0.528)	-	2.57	1.39 (0.62)
C_2H_6	2.17 (0.81)	1.52 (0.66)	-	-	-
H_2CO	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_3OH	2.83 (0.84)	2.14 (1.22)	-	8.69	3.24 (1.39)
CH_3COOH	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)

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

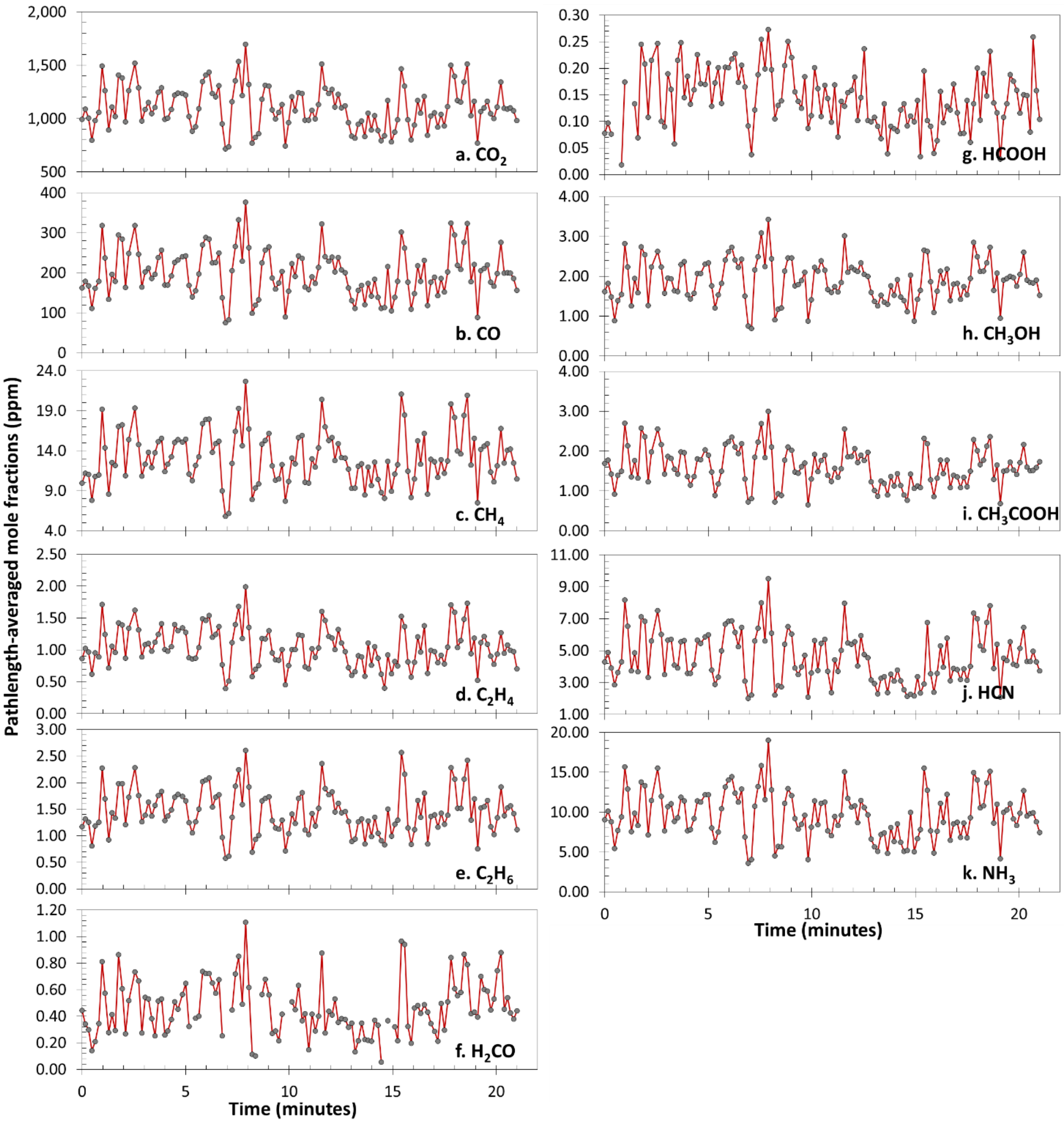

Figure 3. Time series of path-averaged trace gas mole fractions (in ppm) for Plume P5 as measured using a 12 m path (20 August 2015) during the strong El Niño dry period of 2015. Any gaps in the time series of specific trace gases are due to periods of low signal-to-noise within the spectral window used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

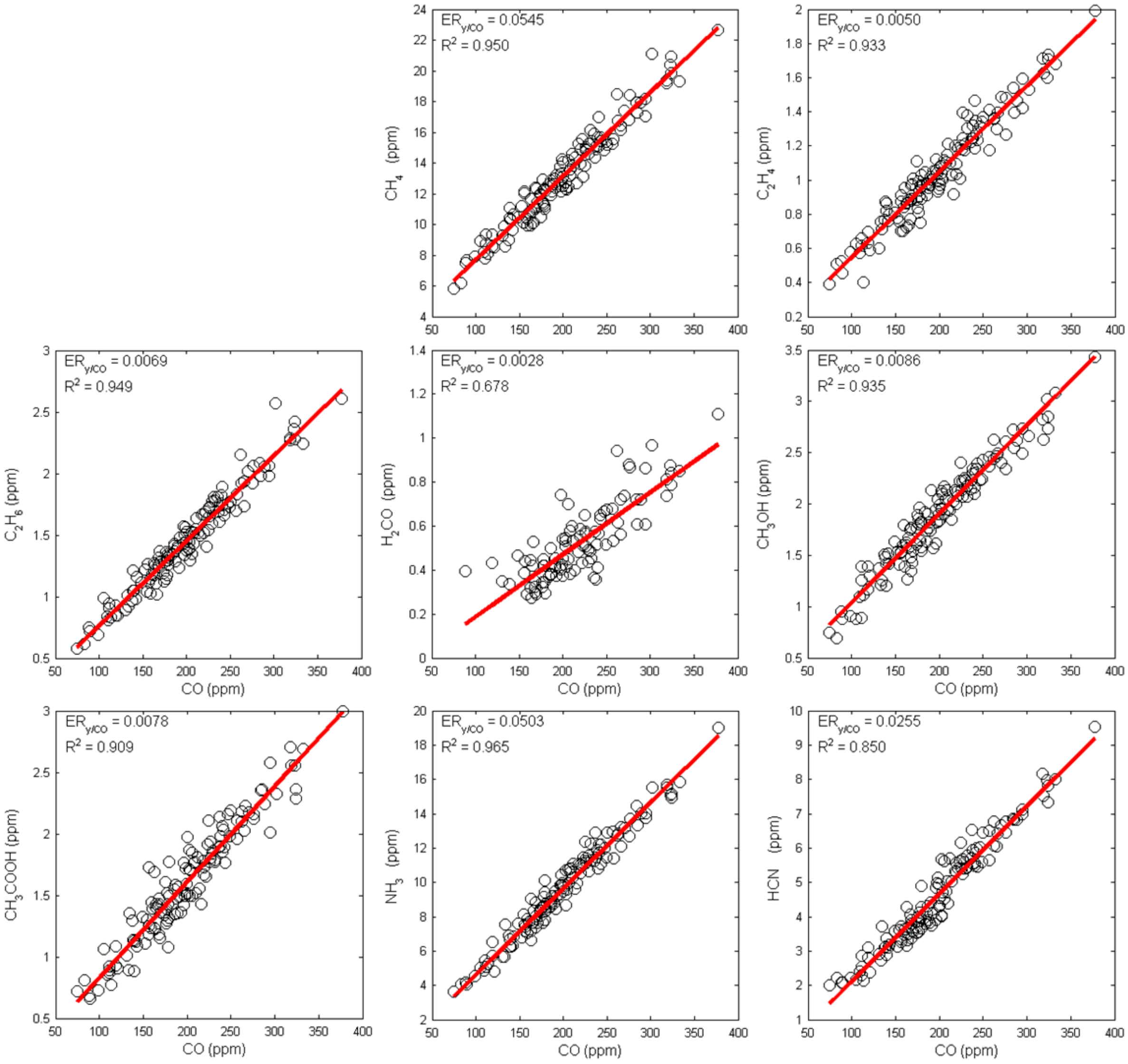

Figure 4. Example scatter plots of the measured trace gas pathlength-averaged mole fractions used to calculate emission ratios ($ER_{i/CO}$), which are in turn used to calculate emission factors through Eqn. 2. The data presented here are from Plume P5 (Figs. 2 and 3). For each of the eight trace gases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

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

We found substantial inter-plume variability for EFs of a number of trace gas species (Table 2). In particular, we find significant variability (percentage difference between minimum and maximum EF > 130%) for the EFs of methane (5.35–26.19 g kg^{-1}); ammonia (3.08–16.13 g kg^{-1}); and hydrogen cyanide (0.34–6.24 g kg^{-1}). The majority of the other trace gas species exhibit substantial variability with the percentage difference between minimum and maximum EFs close to 100%. Only CO_2 shows less variability (1535–1662 g kg^{-1}, a percentage difference of 7.9%), while CO shows moderate variability (200–314 g kg^{-1}, a percentage difference of 44.3%). Plume P1 is particularly anomalous, with significantly elevated EFs for methane (26.19 g kg^{-1}); ammonia (14.46 g kg^{-1}); ethylene (10.16 g kg^{-1}); and acetic acid (8.91 g kg^{-1}).

Many biomass burning studies use MCE to explain variability of non-CO_2 trace gas species EFs (e.g. *Meyer et al.* [2012]) [*Stockwell et al.*, 2016]. In most biomass fires (e.g. savanna, boreal forest) there is a mix of flaming and smouldering combustion, with the EFs of products of flaming combustion (e.g. CO_2) tending to correlate with MCE, and the products of smouldering combustion (e.g. CO) tending to anticorrelate with MCE [*Burling et al.*, 2011]. The plumes measured here, however, originate from smouldering combustion only, and we find no dependence of our EFs on MCE. This echoes the findings of *Stockwell et al.* [2016] who also find no dependence of their Indonesian peat fire EFs on MCE.

The three plumes with the highest EFs for methane (P1, S1, S2) all originated from sites with significantly higher bulk density of the burn substrate (a mean bulk density of 0.62 g cm^{-3}, compared with a mean of 0.35 g cm^{-3} for our other sites). A comparison of substrate bulk densities with methane emission factors (Figure 5) shows a strong positive correlation between these variables ($R^2 = 0.61$, $p<0.01$). Plume P1 is somewhat of an outlier with a particularly high EF for CH_4. We decided to re-run the regression analysis without this outlier; this results in a stronger relationship ($R^2 = 0.71$, $p<0.01$). This is a novel finding that suggests an important influence of the physical properties of the burn site on the resultant emissions. We suggest that our results provide evidence to support the influence of bulk density on burn dynamics [*Rein*, 2013; *Wijedasa et al.*, 2016], whereby a higher bulk density maintains both a higher fire temperature and slower spread rate which when combined with a lack of oxygen (also as a result of high bulk density), will produce more emissions through non-flaming pyrolysis and glowing combustion (gasification) [*Rein*, 2013]. Methane is primarily a product of glowing combustion [*Yokelson et al.*, 1997] and also a product of pyrolysis [*Lobert and Warnatz*, 1993], and so we therefore propose a close link between peat fire methane emission factors and site bulk density (a function of both drainage-related degradation and artificial compaction). It is important to note that the bulk density at our measurement sites was two-to-six times higher than that typical for pristine peats [*Page et al.*, 2011] and we do not recommend extending the relationship we find here to emissions from fires in pristine peatlands. Further controlled experimentation is required to investigate the influence of lower bulk densities on fire emissions from peat fuels.

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

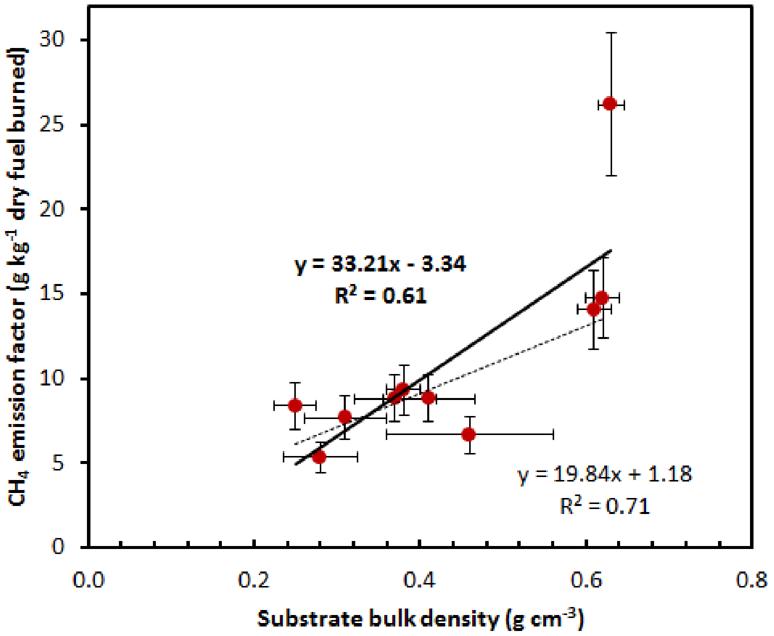

Figure 5. Scatter plot showing the relationship between peat substrate bulk density and the methane emission factor for each of our plumes. A linear regression line of best-fit is presented using all of the data points (solid black line) as well as a best-fit line that excludes the outlier with the highest CH_4 EF (Plume P1). Both lines of best-fit have a statistically significant non-zero slope ($p<0.01$).

4.4 Representativeness and comparison of emission factors to previous studies

Here we present the first tropical peat fire emission factors for Peninsula Malaysia. All previous studies of tropical peat emission factors have been laboratory studies of Sumatran [*Christian et al.*, 2003] or Kalimantan [*Stockwell et al.*, 2014] peat, and only one other comprehensive *in situ* study of peat fires in Kalimantan [*Stockwell et al.*, 2016]. *Hamada et al.* [2013] and *Huijnen et al.* [2016] both provide information for a limited range of species (CO_2, CO, CH_4) as measured *in situ* at peat fires in Kalimantan. These emission factors are summarised in Table 3 for comparison.

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

An important finding from the comparison of our EFs with those from previous studies (Table 3) is the difference between our EFs and those measured in the laboratory study of *Christian et al.* [2003]. The EFs for CO_2, CH_4, and CO from *Christian et al.* [2003] were subsequently adopted by IPCC greenhouse gas guidelines [*Hiraishi et al.*, 2014]. *Stockwell et al.* [2016]

suggest some significant adjustments to the values used by the IPCC, with a notable decrease in CO_2 (–8%) and CH_4 (–55%) EFs, and an increase to the CO (+39%) EF. Our findings also suggest that an adjustment is needed to the IPCC values. We also find a decrease is needed for CO_2 (–5%) and CH_4 (–46%), and an increase needed for CO (+22%). Both this study and *Stockwell et al.* [2016] find significantly smaller NH_3 EFs than *Christian et al.* [2003], finding a decrease of 60% and 86%, respectively. The magnitude of these adjustments are similar to those suggested by the only other comprehensive *in situ* study of tropical peatland emissions [*Stockwell et al.*, 2016], lending confidence to our assertion that field-measured values are more appropriate. We suggest that any future updates to the IPCC guidelines and/or EF databases (e.g. *Akagi et al.* [2011]) use a combination of the improved field-measured EFs presented here in Table 3 and those reported in other field studies, as well as any future results from field campaigns. We find similar EFs to *Stockwell et al.* [2016] for the majority of the other gas species in Table 3 (and thus similar differences from those used by the IPCC), with the exception of ethylene (C_2H_4), which we find to have an EF closer to that found by the previous laboratory studies. We present recommended inter-study averaged EFs for tropical peatland fires in Table 4.

Table 4. Recommended tropical peatland EFs for any future updates to *Akagi et al.* [2011] and/or the IPCC Greenhouse Gas Guidelines [*Hiraishi et al.*, 2014] (an asterisk indicates those species that are provided by the IPCC). The recommended EF is calculated from the mean of EFs from this study and the two other *in situ* studies [*Huijnen et al.*, 2016; *Stockwell et al.*, 2016]. A standard deviation is presented in parentheses where three studies are available (for CO_2, CO, CH_4), otherwise we report the range of values from the two available studies.

Trace Gas	**EF (g kg^{-1})**
CO_2*	1589 (32)
CO*	259 (29)
CH_4*	9.44 (1.6)
C_2H_2	0.09 (0.06–0.12)
C_2H_4	1.63 (0.96–2.30)
C_2H_6	1.84 (1.52–2.17)
H_2CO	0.82 (0.77–0.87)
HCOOH	0.22 (0.18–0.25)
CH_3OH	2.49 (2.14–2.83)
CH_3COOH	4.46 (3.89–5.02)
HCN	4.77 (3.79–5.75)
NH_3	5.34 (2.86–7.82)

5 Summary and conclusions

We present results from open-path FTIR spectroscopy measurements of emission factors for tropical peatland fires from ten fire plumes in Peninsular Malaysia. These represent the first published emission factors for fires burning in Malaysian peatlands, and only the second comprehensive set of field measurements for the tropical peatland ecosystem. We find EFs of similar magnitude to those of *Stockwell et al.* [2016] (the only other comprehensive field study of tropical peatland fire EFs) and we thus echo their suggestion that future total peat fire emissions modelling uses field-measured EFs as a more reliable alternative to the earlier laboratory studies. Mean EFs calculated from our findings, along with those of *Stockwell et al.* [2016] and *Huijnen et al.* [2016] (CO_2, CO, and CH_4 only) are presented in Table 4. We recommend these as the best available ecosystem-specific emission factors for tropical peat fires, as determined by field measurements. Field-derived emission factors for a further ~80 gas species and aerosol optical properties from Indonesian peatland fires can be found in *Stockwell et al.* [2016]

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

Acknowledgments, Samples, and Data

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

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

References

Akagi, S., R. J. Yokelson, C. Wiedinmyer, M. Alvarado, J. Reid, T. Karl, J. Crounse, and P. Wennberg (2011), Emission factors for open and domestic biomass burning for use in atmospheric models, *Atmos Chem Phys*, *11*(9), 4039-4072.

Andriesse, J. P. (1988), *Nature and Management of Tropical Peat Soils*, FAO (UN).

Ballhorn, U., F. Siegert, M. Mason, and S. Limin (2009), Derivation of burn scar depths and estimation of carbon emissions with LIDAR in Indonesian peatlands, *P Natl Acad Sci USA*, *106*(50), 21213-21218.

Benedict, K. B., A. J. Prenni, C. M. Carrico, A. P. Sullivan, B. A. Schichtel, and J. L. Collett (2017), Enhanced concentrations of reactive nitrogen species in wildfire smoke, *Atmospheric Environment*, *148*, 8-15.

Burling, I., R. J. Yokelson, S. Akagi, S. Urbanski, C. E. Wold, D. W. Griffith, T. J. Johnson, J. Reardon, and D. Weise (2011), Airborne and ground-based measurements of the trace gases and particles emitted by prescribed fires in the United States, *Atmos Chem Phys*, *11*(23), 12197-12216.

Burling, I., R. J. Yokelson, D. W. Griffith, T. J. Johnson, P. Veres, J. Roberts, C. Warneke, S. Urbanski, J. Reardon, and D. Weise (2010), Laboratory measurements of trace gas emissions from biomass burning of fuel types from the southeastern and southwestern United States, *Atmos Chem Phys*, *10*(22), 11115-11130.

Christian, T. J., B. Kleiss, R. J. Yokelson, R. Holzinger, P. Crutzen, W. M. Hao, B. Saharjo, and D. E. Ward (2003), Comprehensive laboratory measurements of biomass-burning emissions: 1. Emissions from Indonesian, African, and other fuels, *J. of Geophy. Res.: Atm.*, *108*(D23).

CIFOR (2015), Clearing the smoke: The causes and consequences of Indonesia's fires, edited.

Coggon, M. M., et al. (2016), Emissions of nitrogen-containing organic compounds from the burning of herbaceous and arboraceous biomass: Fuel composition dependence and the variability of commonly used nitrile tracers, *Geophysical Research Letters*, *43*(18), 9903-9912.

Duflot, V., P.-F. Coheur, L. Clarisse, D. Hurtmans, Y. R'Honi, C. Wespes, Y. Ngadi, and C. Clerbaux (2012), Infrared satellite observations of HCN and C2H2 in biomass burning plumes, paper presented at 2012 EUMETSAT Meterologcial Satellite Conference.

Evers, S., C. M. Yule, R. Padfield, P. O'Reilly, and H. Varkkey (2016), Keep wetlands wet: the myth of sustainable development of tropical peatlands–implications for policies and management, *Global Change Biology*.

Gaveau, D. L. A., et al. (2014), Major atmospheric emissions from peat fires in Southeast Asia during non-drought years: evidence from the 2013 Sumatran fires, *Scientific Reports*, *4*, 6112.

Griffith, D. W. T. (1996), Synthetic calibration and quantitative analysis of gas-phase FT-IR spectra, *Appl Spectrosc*, *50*(1), 59-70.

Hamada, Y., U. Darung, S. H. Limin, and R. Hatano (2013), Characteristics of fire-generated gas emission observed during a large peatland fire in 2009 at Kalimantan, Indonesia, *Atmospheric Environment*, *74*, 177-181.

Hao, W. M., and D. E. Ward (1993), Methane production from global biomass burning, *Journal of Geophysical Research: Atmospheres*, *98*(D11), 20657-20661.

Hiraishi, T., T. Krug, K. Tanabe, N. Srivastava, J. Baasansuren, M. Fukuda, and T. Troxler (2014), 2013 supplement to the 2006 IPCC guidelines for national greenhouse gas inventories: Wetlands, *IPCC, Switzerland*.

Huijnen, V., M. J. Wooster, J. W. Kaiser, D. L. A. Gaveau, J. Flemming, M. Parrington, A. Inness, D. Murdiyarso, B. Main, and M. van Weele (2016), Fire carbon emissions over maritime southeast Asia in 2015 largest since 1997, *Scientific Reports*, *6*, 26886.

IPCC (2013), *Climate Change 2013: The Physical Science Basis.*, 1535 pp., Cambridge University Press.

Jayarathne, T., C. E. Stockwell, A. A. Gilbert, K. Daugherty, M. A. Cochrane, K. C. Ryan, E. I. Putra, B. H. Saharjo, A. D. Nurhayati, I. Albar, R. J. Yokelson, and E. A. Stone (2017), Chemical characterization of fine particulate matter emitted by peat fires in Central Kalimantan, Indonesia, during the 2015 El Niño, *Atmos. Chem. Phys. Discuss.*, https://doi.org/10.5194/acp-2017-608, in review.

Könönen, M., J. Jauhiainen, R. Laiho, K. Kusin, and H. Vasander (2015), Physical and chemical properties of tropical peat under stabilised land uses, *Mires Peat*, *16*(8), 1-13.

Koplitz, S. N., L. J. Mickley, M. E. Marlier, J. J. Buonocore, P. S. Kim, T. Liu, M. P. Sulprizio, R. S. DeFries, D. J. Jacob, and J. Schwartz (2016), Public health impacts of the severe haze in Equatorial Asia in September–October 2015: demonstration of a new framework for informing fire management strategies to reduce downwind smoke exposure, *Environmental Research Letters*, *11*(9), 094023.

Langner, A., and F. Siegert (2009), Spatiotemporal fire occurrence in Borneo over a period of 10 years, *Global Change Biology*, *15*(1), 48-62.

Lobert, J. M., and J. Warnatz (1993), Emissions from the combustion process in vegetation, *Fire in the Environment*, *13*, 15-37.

Melling, L., K. Chua, and K. Lim (2009), Managing Peat Soils Under Oil Palm, *Can be accessed at: http://tropicalpeat. sarawak. gov. my/modules/web/pages. php? mod= download&id= Publication&menu_id= 0&sub_id*, *111*.

Meyer, C. P., G. D. Cook, F. Reisen, T. E. L. Smith, M. Tattaris, J. Russell-Smith, S. W. Maier, C. P. Yates, and M. J. Wooster (2012), Direct measurements of the seasonality of emission factors from savanna fires in northern Australia, *J Geophys Res-Atmos*, *117*.

Miettinen, J., A. Hooijer, R. Vernimmen, S. C. Liew, and S. E. Page (2017), From carbon sink to carbon source: extensive peat oxidation in insular Southeast Asia since 1990, *Environmental Research Letters*, *12*(2), 024014.

Ministry of Agriculture (2017) Indonesia peat lands. Accessed through Global Forest Watch on 5 May 2017. Available from: http://data.globalforestwatch.org/datasets/d52e0e67ad21401cbf3a2c002599cf58_10

Moreno, L., M. E. Jimenez, H. Aguilera, P. Jimenez, and A. de la Losa (2011), The 2009 Smouldering Peat Fire in Las Tablas de Daimiel National Park (Spain), *Fire Technology*, *47*(2), 519-538.

Page, S. E., J. O. Rieley, and C. J. Banks (2011), Global and regional importance of the tropical peatland carbon pool, *Global Change Biology*, *17*(2), 798-818.

Page, S. E., F. Siegert, J. O. Rieley, H.-D. V. Boehm, A. Jaya, and S. Limin (2002), The amount of carbon released from peat and forest fires in Indonesia during 1997, *Nature*, *420*(6911), 61-65.

Paton-Walsh, C., T. E. L. Smith, E. L. Young, D. W. T. Griffith, and E. A. Guerette (2014), New emission factors for Australian vegetation fires measured using open-path Fourier transform infrared spectroscopy - Part 1: Methods and Australian temperate forest fires, *Atmos Chem Phys*, *14*(20), 11313-11333.

Penman, J., M. Gytarsky, T. Hiraishi, T. Krug, D. Kruger, R. Pipatti, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe (2003), *Good practice guidance for land use, land-use change and forestry*, Institute for Global Environmental Strategies.

Posa, M. R. C., L. S. Wijedasa, and R. T. Corlett (2011), Biodiversity and Conservation of Tropical Peat Swamp Forests, *Bioscience*, *61*(1), 49-57.

Post, J. (2015), Haze kills 10 people, leaves 503,874 with respiratory ailments: Agency, edited.

Rein, G. (2013), Smouldering fires and natural fuels, in *Fire Phenomena in the Earth System - An Interdisciplinary Approach to Fire Science*, edited by C. Belcher, pp. 15-34, Wiley and Sons.

Rein, G., S. Cohen, and A. Simeoni (2009), Carbon emissions from smouldering peat in shallow and strong fronts, *Proceedings of the Combustion Institute*, *32*(2), 2489-2496.

Sahani, M., N. A. Zainon, W. R. W. Mahiyuddin, M. T. Latif, R. Hod, M. F. Khan, N. M. Tahir, and C.-C. Chan (2014), A case-crossover analysis of forest fire haze events and mortality in Malaysia, *Atmospheric Environment*, *96*, 257-265.

Siegert, F., G. Ruecker, A. Hinrichs, and A. A. Hoffmann (2001), Increased damage from fires in logged forests during droughts caused by El Niño, *Nature*, *414*(6862), 437-440.

Smith, T. E. L., M. J. Wooster, M. Tattaris, and D. W. T. Griffith (2011), Absolute accuracy and sensitivity analysis of OP-FTIR retrievals of CO2, CH4 and CO over concentrations representative of "clean air" and "polluted plumes", *Atmos Meas Tech*, *4*(1), 97-116.

Smith, T. E. L., C. Paton-Walsh, C. P. Meyer, G. D. Cook, S. W. Maier, J. Russell-Smith, M. J. Wooster, and C. P. Yates (2014), New emission factors for Australian vegetation fires measured using open-path Fourier transform infrared spectroscopy - Part 2: Australian tropical savanna fires, *Atmos Chem Phys*, *14*(20), 11335-11352.

Stockwell, C. E., P. R. Veres, J. Williams, and R. J. Yokelson (2015), Characterization of biomass burning emissions from cooking fires, peat, crop residue, and other fuels with high-resolution proton-transfer-reaction time-of-flight mass spectrometry, *Atmos. Chem. Phys.*, *15*(2), 845-865.

Stockwell, C. E., R. J. Yokelson, S. M. Kreidenweis, A. L. Robinson, P. J. DeMott, R. C. Sullivan, J. Reardon, K. C. Ryan, D. W. T. Griffith, and L. Stevens (2014), Trace gas emissions from combustion of peat, crop residue, domestic biofuels, grasses, and other fuels: configuration and Fourier transform infrared (FTIR) component of the fourth Fire Lab at Missoula Experiment (FLAME-4), *Atmos. Chem. Phys.*, *14*(18), 9727-9754.

Stockwell, C. E., T. Jayarathne, M. A. Cochrane, K. C. Ryan, E. I. Putra, B. H. Saharjo, A. D. Nurhayati, I. Albar, D. R. Blake, and I. J. Simpson (2016), Field measurements of trace gases and aerosols emitted by peat fires in Central Kalimantan, Indonesia, during the 2015 El Niño, *Atmos Chem Phys*, *16*(18), 11711-11732.

van der Werf, G. R., D. C. Morton, R. S. DeFries, J. G. J. Olivier, P. S. Kasibhatla, R. B. Jackson, G. J. Collatz, and J. T. Randerson (2009), CO2 emissions from forest loss, *Nat Geosci*, *2*(11), 737-738.

van der Werf, G. R., et al. (2017), Global fire emissions estimates during 1997–2015, *Earth Syst. Sci. Data Discuss.*, *2017*, 1-43.

van Leeuwen, T. T., and G. R. van der Werf (2011), Spatial and temporal variability in the ratio of trace gases emitted from biomass burning, *Atmos. Chem. Phys.*, *11*(8), 3611-3629.

Varkkey, H. (2013), Patronage politics, plantation fires and transboundary haze, *Environmental Hazards*, *12*(3-4), 200-217.

Ward, D., and L. Radke (1993), Emissions measurements from vegetation fires: A comparative evaluation of methods and results.

Warren, M., J. Kauffman, D. Murdiyarso, G. Anshari, K. Hergoualc'h, S. Kurnianto, J. Purbopuspito, E. Gusmayanti, M. Afifudin, and J. Rahajoe (2012), A cost-efficient method to assess carbon stocks in tropical peat soil, *Biogeosciences*, *9*.

Wetlands International (2017) Malaysian peat lands. Accessed through Global Forest Watch on 5 May 2017. Available from: http://data.globalforestwatch.org/datasets/d52e0e67ad21401cbf3a2c002599cf58_10

Wijedasa, L. S., J. Jauhiainen, M. Könönen, M. Lampela, H. Vasander, M. C. LeBlanc, S. Evers, T. E. Smith, C. M. Yule, and H. Varkkey (2016), Denial of long-term issues with agriculture on tropical peatlands will have devastating consequences, *Global change biology*.

Wilson, D., S. Dixon, R. Artz, T. Smith, C. Evans, H. Owen, E. Archer, and F. Renou-Wilson (2015), Derivation of greenhouse gas emission factors for peatlands managed for extraction in the Republic of Ireland and the UK, *Biogeosci Disc*, *12*, 7491-7535.

Wooster, M., G. Perry, and A. Zoumas (2012), Fire, drought and El Niño relationships on Borneo (Southeast Asia) in the pre-MODIS era (1980–2000), *Biogeosciences*, *9*(1), 317-340.

Wooster, M. J., P. H. Freeborn, S. Archibald, C. Oppenheimer, G. J. Roberts, T. E. L. Smith, N. Govender, M. Burton, and I. Palumbo (2011), Field determination of biomass burning emission ratios and factors via open-path FTIR spectroscopy and fire radiative power assessment: headfire, backfire and residual smouldering combustion in African savannahs, *Atmos Chem Phys*, *11*(22), 11591-11615.

Wösten, J. H. M., et al. (2006), Interrelationships between hydrology and ecology in fire degraded tropical peat swamp forests, *Int J Water Resour D*, *22*(1), 157-174.

Yokelson, R. J., D. W. Griffith, and D. E. Ward (1996), Open-path Fourier transform infrared studies of large-scale laboratory biomass fires, *Journal of Geophysical Research: Atmospheres*, *101*(D15), 21067-21080.

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