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Carbon Emissions From Oil Palm Plantations on Peat Soil

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Southeast Asian peatlands have undergone recent land use change with an increase in industrial agricultural plantations, including oil palm. Cultivating peatlands requires creating drainage ditches and other surface microforms (i.e., harvest paths, frond piles, cover plants, and next to the palm). However, it is currently unclear how these management actions affect rates of carbon losses from the peat. Here we report carbon fluxes from each of the different surface microforms measured monthly (soil CO_2 [total soil respiration—R_{tot}] and stem CH_4) and bimonthly (soil CH_4, drain CO_2 and drain CH_4). We calculated annual carbon fluxes and partitioned heterotrophic (R_h) and root-rhizosphere respiration by sampling rhizosphere and root-free soil. Linear mixed effect models were used to determine which environmental factors best-predicted carbon fluxes, and to develop recommendations for management solutions that could reduce carbon losses. Carbon fluxes varied significantly between the different microforms; the greatest CO_2 fluxes were measured next to the palm and the greatest CH_4 fluxes were measured from the drainage ditches. Annual estimates of R_{tot}, R_h and drain CO_2 were 22.08 ± 0.50, 17.75 ± 1.54, and 1.5 ± 0.10 Mg CO_2-C ha^{-1} yr^{-1}, respectively. R_h varied between the two plantations: Sebungan averaged 11.43 ± 1.37 Mg CO_2-C ha^{-1} yr^{-1} and Sabaju averaged 24.08 ± 1.42 Mg CO_2-C ha^{-1} yr^{-1}. Net ecosystem CH_4 fluxes averaged 61.02 ± 17.78 kg CH_4-C ha^{-1} yr^{-1}–similar to unmanaged swamp forests. The two plantations did not vary in overall CH_4 flux, but did vary in transport pathway. CH_4 fluxes from the soil, drains and stems followed a ratio of 50:50:0 from Sabaju (water table depth [WTD]: −0.49 ± 0.004 m) and 11:98:0 from Sebungan (WTD: −0.77 ± 0.007 m). R_h dominated the peat carbon losses. WTD controlled variation in R_h from Sebungan where the WTD was deeper. Air and soil temperature controlled variation in Sabaju, with greater fluxes from the harvest path, attributed to the absence of shade. These results suggest that shading the soil (e.g., through addition of frond piles) and raising the water table may be the most effective ways to reduce peat carbon loss from drained peat soils.

Keywords: oil palm, peat, peat oxidation, heterotrophic respiration, methane

INTRODUCTION

Palm oil currently makes a significant contribution to feeding the world, which is expected to continue with increased population growth, and helps with climate change mitigation, for example through high rates of photosynthesis taking CO_2 from the atmosphere and it's use for bioenergy (Fowler et al., 2011; Fuss et al., 2016; IPCC, 2018; Meijaard et al., 2018). However, agriculture itself is not free from carbon emissions (Bajželj et al., 2014; Smith et al., 2014; Tubiello et al., 2015). Oil palm (*Elaeis guineensis*; the source of palm oil) plantations are grown on both industrial and small-holder scale throughout the tropics (FAOSTAT, 2019). Indonesia and Malaysia currently dominate both the production and export of palm oil (FAOSTAT, 2019; USDA, 2019). Since 1980, oil palm plantations have been established on peat soils in these countries, due to the decline in available suitable mineral soils, which are preferred (Silvius and Diemont, 2007; Corley and Tinker, 2008; Miettinen et al., 2016). However, oil palm plantations growing on peat soils are subject to debate concerning the magnitude of CO_2 and CH_4 losses from the peat (Evers et al., 2017; Wijedasa et al., 2017).

Southeast (SE) Asia has 24.7 Mha of peatlands, storing ~66 Gt C (Page et al., 2011; Miettinen et al., 2016). Industrial oil palm plantations are currently cultivated on 3.1 Mha of SE Asian peatlands (Miettinen et al., 2016). Undisturbed, these peatlands act as an overall long-term carbon sink, due to high water tables providing saturated conditions with low redox potentials (Dommain et al., 2015; Cobb et al., 2017; Hodgkins et al., 2018). Organic matter breaks down in these conditions through anaerobic degradation, releasing CH_4 to the atmosphere (Sundh et al., 1994; Arai et al., 2014; Sjögersten et al., 2014).

Modifying peatlands for agricultural management can alter the biogeochemistry and trace gas fluxes from these systems due to the introduction of artificial drainage ditches that lower the water table and create an aerated zone for root growth, raising the soil redox potential (Hirano et al., 2012; Mishra et al., 2014; Tonks et al., 2017). In these more oxic conditions, methanogenesis is inhibited and aerobic degradation pathways predominate, namely peat oxidation from heterotrophic respiration (R_h; Hooijer et al., 2012; Miettinen et al., 2017; Warren et al., 2017). Additionally, significant CO_2 and CH_4 fluxes have been observed from the surface of drainage ditches in cultivated temperate and tropical peatlands (hereafter drain CO_2, drain CH_4 and stem CH_4; Teh et al., 2011; Jauhiainen and Silvennoinen, 2012). Tree stems have also been shown to act as a pathway for CH_4 transport from tropical peat swamp forests (Pangala et al., 2013, 2017).

Soil R_h and CH_4 fluxes have been measured previously from oil palm plantations. Current estimates of R_h from oil palm plantations on peat suggest that these systems emit a mean flux of 12.2 Mg CO_2-C ha^{-1} yr^{-1}, with reported estimates ranging from 4.1 to 22.9 Mg CO_2-C ha^{-1} yr^{-1} (Farmer, 2013; Melling et al., 2013; Dariah et al., 2014; Husnain et al., 2014; Comeau, 2016; Comeau et al., 2016; Hergoualc'h et al., 2017; Ishikura et al., 2018; Matysek et al., 2018). Only one study has quantified CH_4 from oil palm plantations, finding annual emissions of −0.2 kg CH_4-C ha^{-1} yr^{-1}, suggesting that CH_4 oxidation may predominate in these drained ecosystems (Melling et al., 2005a).

Furthermore, existing studies of R_h and soil CH_4 have failed to fully account for spatial heterogeneity of the trace gas fluxes in oil palm systems, despite the fact that biogeochemical processes are known to be highly variable in space and time (i.e., "hot spots" and "hot moments," *sensu* McClain et al., 2003). Oil palm plantations have different soil surface management microforms, namely highly compacted bare soil harvest paths, piles of decomposing fronds, rows of cover plants, and an extensive rhizosphere in the fertilizer circle around the palm (Manning, 2019; Manning et al., in preparation). R_h and soil CH_4 measurements have predominantly been sampled from the harvest path only (Melling et al., 2005a, 2013; Farmer, 2013; Dariah et al., 2014; Hergoualc'h et al., 2017; Matysek et al., 2018). However, the frond piles and cover plants may give different results for R_h and CH_4 due to potentially different environmental conditions.

Several CO_2 and CH_4 fluxes known to be important in temperate peatlands and tropical forest have not been measured in oil palm plantations on peat soils. In temperate peatlands, drainage ditches have been observed to act as hotspots for CH_4 emissions, making a disproportionately large contribution to net ecosystem exchange (Minkkinen and Laine, 2006; Schrier-Uijl et al., 2010; Teh et al., 2011). Similarly the absence of stem CH_4 may signify the oversight of a notable CH_4 loss from oil palm plantations; it has been found that stem fluxes contribute between 62–87% (Brunei) and 42–53% (Amazon) of ecosystem CH_4 fluxes from mature trees in swamp forests (Pangala et al., 2013, 2017), and may therefore represent an important but so far unexplored transport pathway for CH_4 emission in oil palm systems.

Here we report CO_2 (R_{tot}, R_h and drain) and CH_4 (soil, drain and stem) fluxes from two mature oil palm plantations established on peat soils in Sarawak, Malaysian Borneo. Autotrophic fluxes (R_a and stem CO_2) are noted due to being measured simultaneously. We include a wide spatial resolution, sampling CO_2 and CH_4 from all major surface microforms (i.e., next to palms, harvest paths, frond piles, cover plants, drainage ditches, and tree stems). Temporal trends in fluxes were determined by sampling at monthly (soil CO_2 and stem fluxes) or bi-monthly (soil CH_4 and drain fluxes) intervals. Lastly, we upscaled our surface fluxes and estimates of peat oxidation (i.e., R_h) to the plantation-level using proportional surface area-weighting and temporal integration. The overarching goal of this research was to determine rates of carbon losses that are broadly representative of production systems of this kind elsewhere in Southeast Asia, with a view to presenting effective solutions to reduce these carbon losses. During the course of this work we explored the following research questions:

1. Do CO_2 and CH_4 fluxes vary spatially and temporally in oil palm plantations?
2. What are the annual rates of R_h, drain CO_2, soil CH_4, drain CH_4 and stem CH_4 from oil palm plantations on peat soil—both individually and combined as total peat carbon losses?
3. What are the relationships between key environmental factors and trace gas fluxes?
4. Do opportunities exist to minimize or mitigate CO_2 and CH_4 fluxes, based on our understanding of the drivers of trace gas exchange in this system?

METHODS

Site Description

Data were collected from Sabaju (latitude 003° 12′ N, longitude 113° 30′ E) and Sebungan (latitude 003° 09′ N, longitude 113° 21′ E) oil palm plantations in Sarawak, Malaysia. Sabaju and Sebungan Estates have been established on peat soils broadly classified as histosols (FAO, 2006). The peat depth was measured to be 3.0 m at Sabaju and 4.0 m at Sebungan. The mean annual precipitation was ∼3,200 mm (MET Malaysia, 2017). The northeast monsoon from October to January has the most rainfall, with a slightly drier southwest monsoon between May and August (MET Malaysia, 2017). The two principal dry seasons fall between February to April and in September. The mean annual temperature was 26.5°C (MET Malaysia, 2017).

Prior to planting, the land use was a mixed species swamp forest, which had been heavily logged. The land was converted to a plantation in 2006 and the palms were on their first crop rotation. The palms were 8 years old when measurements began. The plantations were laid out systematically with ∼35 ha blocks and drainage ditches every 28 m leading to a larger ditch running down the center of the block. Palms were planted every 8 m in rows that were 8 m apart, with a planting density of 160 palms per ha. Within the palm blocks, four different surface management microforms were present and two different drain types (**Figure 1**):

- By palm or fertilizer circle—the ring of soil around the palm where the majority of oil palm roots grow and the fertilizer is applied.
- Harvest path—frequently weeded soil between the rows of palms and around the palms to allow access for workers.
- Frond pile—the location of the decomposing, harvested fronds.
- Cover plants—an area where weeds were left to grow freely.
- Field drains—small, 1.5 m wide drains dug every four rows of palms.
- Collection drains—larger, 3 m wide drains running down the center of the plantation blocks.

Experimental Design

Six one hectare plots were established, three in Sabaju and three in Sebungan. Within each plot, three subplots were randomly placed. In each subplot, soil surface collars made from PVC plastic of dimensions 10 cm deep by 10.5 cm diameter were installed to 5 cm depth to measure from the harvest path, underneath a frond pile, in the cover plants and adjacent to three palms in order to take CO_2 and CH_4 measurements. Collars were installed 6 months prior to the commencement of sampling in order to avoid disturbance effects associated with chamber base installation (Varner et al., 2003).

A location was selected to sample the drain fluxes from both the field drain and the collection drain within each subplot. Soil surface collars of 10 cm depth and 10.5 cm diameter were installed into the base of each ditch to 5 cm, to prepare for sampling months when the drains were dry. Floating chambers were made for sampling when there was water in the drains (**Figure 2A**; Kent, 2018). Here two holes were drilled into plastic mixing bowls (30 cm rim diameter) and lengths of Tygon tubing (2.5 m long, 3 mm inner diameter) were attached to each hole using Swagelok fittings. Aluminum foil was taped over the bowls to prevent light from penetrating and foam cylinders were attached to the bowls to help them float.

Stem fluxes were only taken from one plot in Sabaju and one plot in Sebungan, due to time and resource limitations, adapting the chamber methodology used by Pangala et al. (2013) and Siegenthaler et al. (2016) to suit oil palms (**Figure 2B**; **Figure S1**; Manning, 2019). Here, five palms were selected from each plot, including three that had soil collars next to them. Permanent chamber bases were glued onto the palm surfaces—these were made out of 3 cm wide and 6 cm thick strips of neoprene, attached at 0.2 m and 0.7 m height. Expandable polyurethane (PU) foam was applied to the stem, filling any gaps between the neoprene strips and the palm surface that had been created by the uneven distribution of frond bases. Extra neoprene blocks were randomly placed inside the chamber base area to help maintain an even volume inside the chamber. The chamber itself consisted of a 2.5 m × 0.75 m × 0.003 m sheet of plastic, which was wrapped around the chamber base and fixed in place using two ratchet straps to attach the sheet to the neoprene strips, with a third ratchet strap around the middle of the chamber to keep the sheet closed. Prior to attachment, six fans (12 VDC 120 mm computer case fans; flow ∼200 CFM) were distributed within the chamber base. After attaching the chamber, the chamber was wrapped first in plastic wrap to make it gas tight, and then in black plastic sheeting to block sunlight and prevent any photosynthesis. Furthermore, the palm stems were regularly cleaned of vegetation at least one week prior to flux measurement.

Determining the Chamber Volumes

The soil chamber volume was determined by multiplying the height of the chamber (15 cm) with the surface area (radius 5.5 cm). Prior to each measurement, the depth of the collar was measured and included in the volume calculations. The floating drain chamber volume was 7 L. The volume inside the drain chamber did not change when the chamber was placed on the water.

The stem chamber volume needed to be calculated for each measurement due to the uneven surface of the palms and the chamber being flexible rather than rigid. Equation (1) was used to determine the stem chamber volume:

$$V = dh\pi(R + r) \tag{1}$$

where V is the volume of the chamber, d is the mean depth of the chamber base (i.e., radially outwards from palm), h is the internal (vertical) height of each chamber, R is the radius of the outer chamber surface (i.e., that of the plastic sheet), and r is the radius of the inner chamber surface (i.e., the radius of the stem). Multiple measurements were made of d, h, R, and r for each palm and the mean values were used in this equation. More information can be found in Manning (2019).

Flux Measurements

Flux measurements were made using the static chamber approach (Livingston and Hutchinson, 1995). Soil and drain CO_2

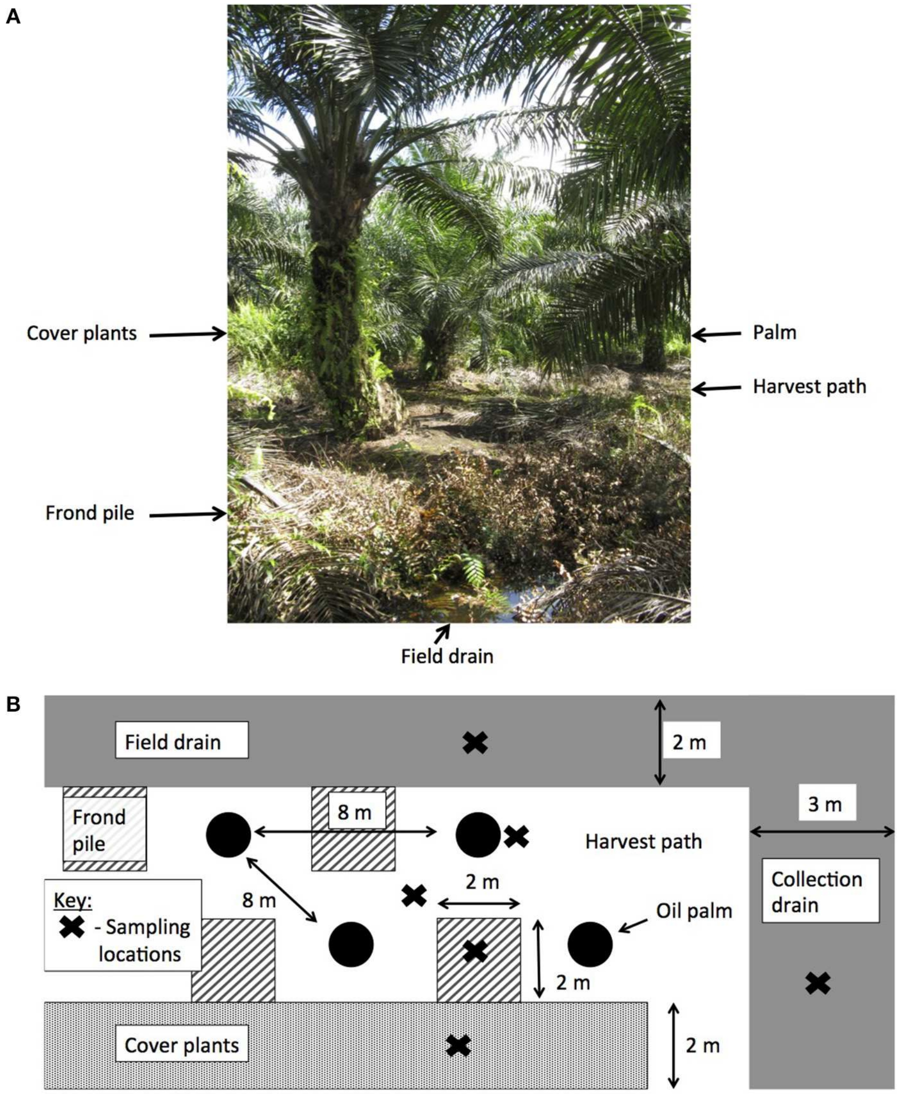

FIGURE 1 | The layout of oil palm plantations on peat soil. **(A)** Sebungan oil palm plantation with the different surface microforms labeled, and **(B)** the experimental design in this study, showing the different sampling locations.

and CH_4 fluxes were collected between June 2015 and May 2016 and stem fluxes were collected from May 2016 to May 2017. The fluxes were measured at different times due to limitations in resource availabilities. Soil, drain and stem fluxes were measured at the same time in May 2016 to ensure comparability. Furthermore, the different instruments were calibrated against each other to ensure compatibility (Manning, 2019).

R_{tot} measurements were made using an EGM-4 and SRC-1 chamber (PP Systems; Hansatech Instruments, Amesbury, USA). Two recordings were made in duplicate (one immediately after the other) and averaged during data processing because the EGM did not always save one of the recordings. For each replicate measurement, CO_2 concentrations were measured over a 2 min enclosure period, with concentrations recorded at 3 s intervals, or until an increase of 100 ppm CO_2 had been observed. Measurements were then made monthly for 12 months (per month $n = 54$ for by palm fluxes and $n = 18$ for each of the harvest path, frond pile and cover plants fluxes). Extra fluxes were measured next to the palm because of high variability in both R_{tot}, root biomass and R_a, and the desire to accurately capture plantation R_{tot} fluxes (Manning, 2019; Manning et al., in preparation).

Soil CH_4, drain CO_2, and drain CH_4 measurements were made using syringe sampling (soil CO_2 data were also obtained using this method but the EGM data are presented due to a larger dataset). Static chambers were placed on the soil collars and floating chambers were deployed on drains when there was water present, otherwise static chambers were used on the drain surface. These chambers were left in place for 40 min, and 30 ml samples were collected with syringes every 0, 10, A

B

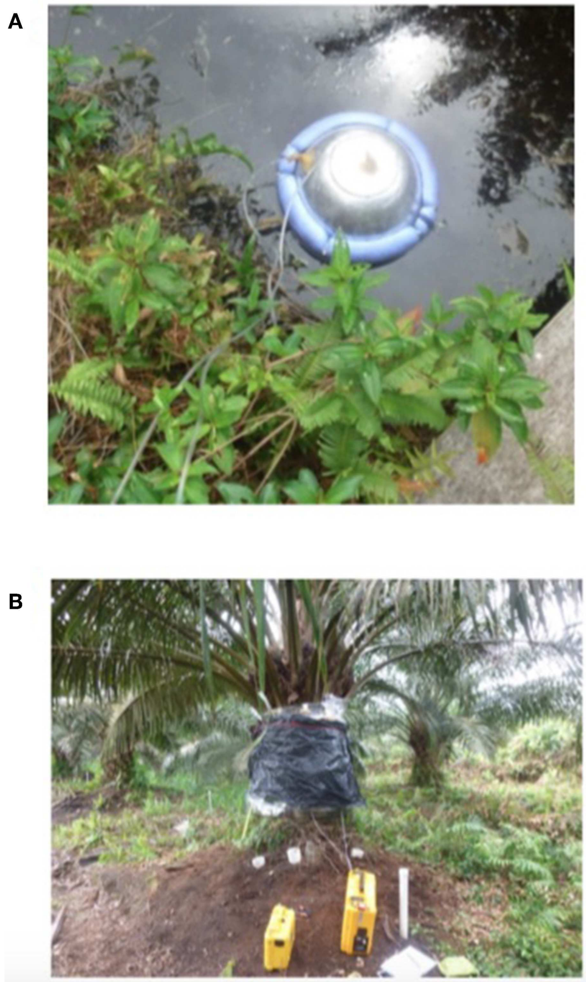

FIGURE 2 | Chambers adapted for this study: **(A)** a floating chamber to measure CO_2 and CH_4 fluxes from the drainage ditches, and **(B)** a novel stem chamber to measure stem CO_2 and CH_4.

20, 30, and 40 min. These samples were transferred into 20 ml pre-evacuated vials, which had been sealed with chlorobutyl rubber septa and aluminum seals (Sigma-Aldrich, Dorset, UK), and the over-pressurized vials were shipped to the UK for analysis. Measurements were made in August 2016, September 2016, November 2016, January 2017, March 2017, and May 2017 providing per month $n = 18$ for each location. The air samples were sent to St. Andrews University for analysis where samples were manually injected into a Thermo TraceGC Ultra Gas Chromatograph, which was fitted with a FID and methanizer for determination of CO_2 (Thermo Electro Corporation). August 2016 samples were analyzed at the University of Aberdeen on an Agilent 6890 Gas Chromatograph Analyser, fitted with an FID (Agilent). The two different analysers were cross-calibrated with three different BOC standards, which comprised of mixes of CO_2 and CH_4 in different concentrations (Manning, 2019).

Stem CO_2 and CH_4 fluxes were measured using a Los Gatos UGGA (Ultraportable Greenhouse Gas Analyzer; Los Gatos Research Inc, San Jose, California, USA). This UGGA was attached to the chamber by 2 m long tubing and data were continuously measured for 10 min at a frequency of 1 Hz. Data were stored on the field laptop and the dry air ppm were reported.

Environmental Measurements

Ancillary measurements were made during and just after the completion of flux measurements. Ambient air temperature was measured at the same time as all flux measurements, using a thermometer (LCD Digital Thermometer, ATP Instrumentation, Leicestershire, UK; precision: ±1°C). Soil temperature and soil moisture measurements at 0–10 cm depth were taken following the completion of soil CO_2 and CH_4 sampling, adjacent to the soil collars, with soil moisture measured using an ML3-probe and HH2 moisture meter (Delta-T, Cambridge, UK; precision for soil moisture: ±1%). Soil moisture measurements at 0–10, 10–20, 20–30, and 30–40 cm intervals were made next to a subset of soil collars following each measurement, namely at one subplot in each plot, using a PR2-probe and HH2 moisture meter (Delta-T, Cambridge, UK; precision: ±4%). If soil collars were being used to measure drain fluxes, soil temperature and soil moisture at 0–10 cm were also sampled from the peat at the base of the drain following the completion of the flux measurement. When floating chambers were being used to measure drain fluxes, water temperature was measured following the completion of the flux measurement, using the same thermometer as used for air and soil temperature. Stem temperature was measured using a Fluke 62 Max Infrared Thermometer (MEA, Dubai, United Arab Emirates; precision: ±2°C). Throughout the study climate data were collected from two weather stations (Davis Vantage Pro2 Plus, Hayward, California, USA), one on each plantation. Measurements from these weather stations include precipitation, air temperature, UV index, and air humidity (precisions: ±4%, ±0.3°C, ±5 and ±2%, respectively).

Water table depth (WTD) and the depth of the water in the drains (drain water depth) were both measured after the flux measurements were completed. To prepare for WTD measurements from the soil, PVC pipes of 3 m length and 5 cm diameter had holes drilled into them at 10 cm intervals along the pipe, in all four directions. These pipes were then installed into the peat to depths of 2.5 m 1 month prior to the commencement of flux measurement. WTD was then measured by inserting a 2.5 cm diameter pipe with a measuring tape attached to it into the PVC pipe. Drain water depth was measured using a pipe with a measuring tape attached to it, which was lowered into the drain until it reached the bottom of the drain. If the drain was dry when CO_2 and CH_4 fluxes had been measured from the drain surface, the WTD was measured by digging a hole 0.5 m away from the flux collar from the drain surface to the water table and measuring this distance.

Calculating Fluxes

Fluxes were calculated using the HMR package in R version 2.15.1 (http://www.R-project.org; Pedersen et al., 2010). Here linear and non-linear regressions were applied to the fluxes in accordance with the HMR methodology, whereby both options were calculated and the fit with the lowest standard error was used. All of the data were included for the flux calculations when the data were collected by the EGM. The vial CO_2 data were first plotted in conjunction with CH_4 to determine whether any of the vials had leaked, before the HMR function was applied, with the leaked vials being excluded from the analysis. The units of the HMR outputs are $\mu L\ m^{-2}\ s^{-1}$. These units were converted to Mg CO_2-C ha^{-1} yr^{-1} or kg CH_4-C ha^{-1} yr^{-1} using Equation (2):

$$F = \frac{\Delta_c PVMY}{\Delta_t TAR} \tag{2}$$

where F is the C flux, Δ_C is the change in CO_2 or CH_4 concentration over the measurements period (ppm), Δ_t is the duration of the measurement period (s), P is pressure (mb), T is temperature (K), V is volume (m^3), A is surface area of the soil (m^2), R is the Universal Gas Constant 8.31432 J mol^{-1} K^{-1}, M is the relative molecular mass of CO_2 or CH_4 and Y is the conversion to upscale the flux to annual emissions.

Upscaling to Annual Flux Estimates

Annual flux estimates were upscaled using spatial and temporal weighting. Fluxes from the soil and drain microforms were spatially weighted by multiplying the mean CO_2 or CH_4 flux by the proportional area of the microform (**Tables S1, S2**). Stem fluxes were first upscaled to the plot level fluxes (F'), expressed as Mg CO_2-C ha^{-1} or kg CH_4-C ha^{-1} soil—first the flux (F) was multiplied by the surface area (A) of each palm to calculate the mean stem flux (A^{-1}) and then A^{-1} was then multiplied by the planting density (166 palm ha^{-1}) to get the per hectare stem carbon flux. Second, each spatially weighted flux (F') was linearly interpolated between months using Equation (3):

$$F^* = \frac{1}{2}\left(F'_{t_1} + F'_{t_2}\right)(t_2 - t_1) \tag{3}$$

where t_1 and t_2 are the timings of the measurements in days. These temporally weighted fluxes F^* were subsequently summed over one year to produce annual flux estimates (F_{tot}). The microform annual estimates were summed to provide component and plantation flux estimates.

Calculating Peat Oxidation Rates (R_h)

The rate of peat oxidation (i.e., R_h) was calculated by sampling root-free soil 4 m away from the palms, based on prior work by Manning et al. (in preparation), where roots and R_{tot} were measured in transects at 0, 0.25, 0.5, 0.75, 1, 1.5, 2, 2.5, 3, 3.5, and 4 m distance from the palm, going into the harvest path, frond piles and cover plants, to 0.3 m depth. Root biomass was found to be negligible further than 1.0 m away from the palm and R_{tot} did not vary with increasing distance more than 0.75 m distance from the palm (Manning et al., in preparation). Therefore, at this site the contribution of R_a to R_{tot} was considered to be negligible more than 1 m from the palm and sites were chosen for R_h measurements exactly 4 m away from the palms (halfway between two palms).

A range of R_h values were proposed, assuming: (1) the harvest path only provided true R_h estimates, (2) the harvest path and frond pile gave R_h estimates, and (3) assuming that surface R_{tot} fluxes measured from the harvest path, frond pile and cover plants only contributed to R_h. We estimated R_h using this range of methods because peat oxidation occurs at all of these different microforms and potentially at different rates due to variations between the microclimates. These estimates of R_h were extrapolated to the plantation level by area-weighting each flux by the proportional surface area of its microform. For methods (1) and (2) the flux measured from the harvest path was used to represent R_h from the microforms that were not included in the specific R_h calculation, when spatially upscaling. In all three methods the harvest path flux was also assumed to represent the rate of R_h for the area next to the palm.

Statistical Analyses

All statistical analyses were done in R (version 3.5.1). Kruskal-Wallis tests were used to test whether there were significant variations in the CO_2 and CH_4 fluxes between the two different plantations, the three plots within each plantation, the three subplots within each plot and the different surface microforms. Kruskal-Wallis tests were used to test for significant variation in the CO_2 and CH_4 fluxes between the months. *Post-hoc* multiple comparisons tests were performed using the R package pgirmess (Giraudoux et al., 2018).

CO_2 and CH_4 measurements were modeled as a function of environmental variables using Gaussian linear mixed effect models from the nlme package in R (Pinheiro et al., 2017). Log or square root transformations of CO_2 and CH_4 measurements were sometimes necessary to normalize model residuals. The random effect structure and correlation structure, the latter used to take into account seasonality, were determined by comparing model residual plots. Fixed effect variables were chosen by top down selection, with the non-significant variables removed one by one from models using the ANOVA function (see **Data Sheets 1–5**, for the selection processes for the fixed effects in each model). The following five models were used for this study, with $*$ used to denote significant interactions between variables:

$$\begin{aligned} R_h = {} & lme\,(log(R_h) \sim Plantation\ x\ Microform\ x\ Soil\ moisture\ (0-10\,cm) \\ & + Plantation\ x\ Microform\ x\ Soil\ temperature\ + Air\ temperature\ + \\ & + Plantation\ x\ WTD, \\ & random\ = \sim 1|Plantation/Plot/Subplot, \\ & correlation = corCompSymm\ (form\ = \sim 1| \\ & Plantation/Plot/Subplot/Microform), \\ & weights = varIdent\ (form = \ \sim 1|Plantation\ x\ Microform)) \end{aligned} \tag{4}$$

$$\begin{aligned} Soil\ CH_4 = {} & lme\,(sqrt(CH_4 + 2.71) \sim Plantation\ x\ Microform\ x\ Soil\ moisture \\ & (30-40\,cm)\ x\ WTD + Plantation\ x\ Soil\ temperature \\ & + Soil\ moisture\ (0-10\,cm), \\ & random\ = \sim 1|Plantation/Plot/Subplot, \\ & weights = varIdent\ (form\ = \ \sim 1|Plantation\ x\ Microform)) \end{aligned} \tag{5}$$

$$\begin{aligned} Drain\ CO_2 = {} & lme\,(log(CO_2) \sim Microform, \\ & random\ = \sim 1|Plantation/Plot/Subplot, \\ & correlation\ = \ corCompSymm\ (form\ = \sim 1| \\ & Plantation/Plot/Subplot/Microform), \\ & weights\ = \ varIdent\ (form\ = \ \sim 1|Plantation\ x\ Microform)) \end{aligned} \tag{6}$$

$$\begin{aligned} Drain\ CH_4\ = {} & lme\,(CH_4 \sim Air\ temperature, \\ & random\ = \sim 1|Plantation/Plot/Subplot, \\ & correlation\ = \ corCompSymm\ (form\ = \sim 1| \\ & Plantation/Plot/Subplot/Microform), \\ & weights\ = \ varIdent\ (form\ = \ \sim 1|Plantation\ x\ Microform)) \end{aligned} \tag{7}$$

$$StemCH_4 = lme\ (CH_4 \sim Mean\ monthly\ relative\ humidity\ x\ Plantation\ x\ Palm + WTD + Plantation\ x\ Palm\ x\ Soil\ moisture + Mean\ monthly\ relative\ humidity\ x\ Soil\ temperature + Air\ temperature\ x\ Plantation,\ random = \sim 1|Plantation/Palm) \quad (8)$$

RESULTS

Environmental Variables

Precipitation, relative humidity and air temperature were measured from weather stations in Sabaju (November 2015–March 2017) and Sebungan (June 2015–March 2017). Annual means for climate variables can be found in **Table 1**. Annual precipitation was recorded at 2,015 mm in Sabaju, using an average of moving annual sums of the data available. Precipitation records from Sebungan were unreliable due to equipment failure. The dry season consisted of February, March and May—all of which recorded <100 mm rain in Sabaju. Collectively, the rainy season had significantly more rainfall than the dry season, averaging 216 ± 25 mm/month in the rainy season and 90 ± 46 mm/month in the dry season (Kruskal-Wallis: chi-squared = 4.5; d.f. = 1; $p = 0.03$). Relative humidity was significantly higher in Sabaju than in Sebungan in both measurement periods (2015–2016: Kruskal-Wallis: chi-squared = 6.2; d.f. = 1; $p = 0.01$; 2016–2017: Kruskal-Wallis: chi-squared = 12.8; d.f. = 1; $p < 0.0001$). Using averages taken between November 2015 and January 2017, where there were complete records of relative humidity from both plantations, relative humidity was significantly higher in the rainy season (88.0 ± 0.5%) than in the dry season (87.3 ± 1.1%; Kruskal-Wallis: chi-squared = 6.5; df = 1; $p = 0.01$). Annual mean air temperatures measured from the weather stations were the same for both plantations, in both measurement periods. Air temperature measured at the time and location of the soil flux sampling was significantly higher in Sabaju than in Sebungan (Sabaju: 30.7 ± 0.1°C; Sebungan: 29.2 ± 0.1°C; Kruskal-Wallis: chi-squared = 109.7; d.f. = 1; $p < 0.0001$). Air temperature measured at the same time as the stem fluxes was not significantly different between the two plantations. Air temperature did not vary significantly between the rainy and dry seasons.

WTD varied between the two plantations during 2015–2016 but not during 2016–2017 (**Table 1**; **Table S3**). During 2015–2016, when the soil and drain measurements were made, mean WTD was −0.49 ± 0.0041 m in Sabaju and −0.76 ± 0.0072 m in Sebungan, which were significantly different (Kruskal-Wallis: chi-squared = 789.2; d.f. = 1; $p < 0.0001$). During 2016–2017, when the stem measurements were made, monthly mean WTD was −0.46 ± 0.16 m for Sabaju and −0.43 ± 0.16 m for Sebungan, which were not significantly different. Seasonal variation was observed in WTD; WTD was significantly higher in the dry season than in the rainy season in both measurement periods (2015–2016: dry season: −0.72 ± 0.00048 m; rainy season: −0.61 ± 0.00046 m; Kruskal-Wallis: chi-squared = 50.11; d.f. = 1; $p < 0.001$; 2016–2017: dry season: −0.49 ± 0.02 m; rainy season: −0.42 ± 0.02 m; Kruskal-Wallis: chi-squared = 5.68; d.f. = 1; $p = 0.017$).

In addition to climate and WTD measurements, different environmental measurements were made at the time of flux sampling, with annual averages reported in **Table 1**. Of particular interest are soil temperature and soil moisture, which varied significantly between the two plantations and between the different surface microforms. Soil temperature was significantly higher in Sabaju than in Sebungan (Kruskal-Wallis: chi-squared = 185.9; d.f. = 1; $p < 0.0001$) and varied significantly between the different surface microforms (Kruskal-Wallis: chi-squared = 253.7; d.f. = 3; $p < 0.0001$). Soil temperature was highest next to the palm and lowest beneath the frond piles, decreasing in order by palm > harvest path > cover plants > frond pile. Soil temperature was also significantly higher in the dry season (29.4 ± 0.05°C) than the rainy season (28.1 ± 0.05°C; Kruskal-Wallis: chi-squared = 29.2; d.f. = 1; $p < 0.001$). This seasonality was measured in both plantations (Sabaju Kruskal-Wallis: chi-squared = 10.60; d.f. = 1; $p = 0.0011$; Sebungan Kruskal-Wallis: chi-squared = 30.31; d.f. = 1; $p < 0.001$).

Soil moisture was significantly greater in Sebungan than in Sabaju (Kruskal-Wallis: chi-squared = 15.8; d.f. = 1; $p < 0.0001$). Soil moisture varied significantly between the different surface microforms (Kruskal-Wallis: chi-squared = 840.0; d.f. = 3; $p < 0.0001$). Soil moisture was consistently drier next to the palm than in the other microforms, decreasing in order harvest path > frond pile > cover plants > by palm, although soil moisture was highest in the frond pile in Sabaju and the harvest path in Sebungan. Soil moisture was significantly greater in the rainy season than in the dry season, with a mean of 39.4 ± 1.1% in the rainy season and 32.4 ± 1.0% in the dry season (Kruskal-Wallis: chi-squared = 23.8; d.f. = 1; $p < 0.001$). This relationship was seen in the different microforms, at the different plantations and in the different microforms at each plantation.

Spatial Variability in CO_2 and CH_4 Fluxes

The CO_2 fluxes are summarized in **Table 2**. Mean R_{tot} was recorded as 0.83 ± 0.048 g CO_2-C m^{-2} hr^{-1}. Drain CO_2 averaged 0.14 ± 0.0012 g CO_2-C m^{-2} hr^{-1}. Mean stem respiration was 0.23 g ± 0.012 CO_2-C m^{-2} hr^{-1}. There was no significant difference in the overall mean CO_2 flux between the plantations.

Significant differences were seen in the magnitude of the CO_2 fluxes between the different surface microforms (**Figure 3**). Considering the plantations together, R_{tot} measured next to the palm gave the highest CO_2 flux from the plantation (Kruskal-Wallis: chi-squared = 1,555.5; d.f. = 6; $p < 0.0001$). Within each plantation, we found differences in the magnitude of CO_2 flux from each microform (Sabaju: Kruskal-Wallis: chi-squared = 572.6; d.f. = 6; $p < 0.0001$; Sebungan: Kruskal-Wallis: chi-squared = 1,078.6; d.f. = 6; $p < 0.0001$). For example, in Sabaju, the harvest path R_{tot} was significantly higher than R_{tot} measured from the frond piles and cover plants—although they themselves did not differ (multiple comparison test for Kruskal-Wallis: $p \leq 0.05$). Drain fluxes were lower than soil fluxes but not significantly different to stem CO_2 (multiple comparison test for Kruskal-Wallis: $p \leq 0.05$). Stem CO_2 fluxes were significantly lower than R_{tot} from next to the palm, the harvest path and beneath the frond piles, but not the cover plants (multiple comparison test for Kruskal-Wallis: $p \leq 0.05$).

TABLE 1 | Mean environmental variables measured from the two plantations, both combined and from Sabaju and Sebungan individually.

Variable	Microform	Combined	Sabaju	Sebungan
ENVIRONMENTAL MEASUREMENTS TAKEN ALONGSIDE ALL FLUXES				
Relative humidity (2015–2016)	All	88.2 (0.4)	89.9 (0.3)[a]	87.2 (0.4)[b]
Relative humidity (2016–2017)	All	87.2 (0.5)	89.4 (0.3)[a]	85.1 (0.3)[b]
Air temperature (2015–2016)—weather station	All	27.3 (0.1)	27.4 (0.2)	27.3 (0.1)
Air temperature (2015–2016)—next to measurement	All	29.9 (0.1)	30.7 (0.1)[a]	29.2 (0.1)[b]
Air temperature (2016–2017)—weather station	All	27.0 (0.1)	27.0 (0.1)	27.0 (0.1)
Air temperature (2016–2017)—next to measurement	All	27.2 (0.04)	27.1 (0.1)	27.2 (0.1)
WTD (2015–2016)	All	−0.62 (0.005)	−0.49 (0.004)[a]	−0.76 (0.007)[b]
WTD (2016–2017)	All	−0.46 (0.16)	−0.47 (0.16)	−0.43 (0.16)
ENVIRONMENTAL MEASUREMENTS TAKEN ALONGSIDE SOIL FLUXES				
Soil temperature (2015–2016)	All	28.2 (0.03)	28.7 (0.05)[a]	27.8 (0.02)[b]
	By palm	28.7 (0.04)[m]	29.3 (0.08)[r]	28.2 (0.03)[w]
	Away from palm	27.7 (0.02)	28.1 (0.03)	27.4 (0.03)
	Harvest path	28.1 (0.04)[n]	28.6 (0.7)[s]	27.6 (0.04)[x]
	Frond pile	27.5 (0.04)[o]	27.8 (0.6)[t]	27.2 (0.04)[y]
	Cover plants	27.7 (0.03)[o]	28.0 (0.04)[t]	27.4 (0.05)[x]
Soil moisture (2015–2016)	All	36.9 (0.4)	33.6 (0.6)	40.2 (0.6)
	By palm	14.7 (0.2)[m]	12.4 (0.3)[m]	16.9 (0.4)[x]
	Away from palm	58.5 (0.5)	53.4 (0.6)	63.2 (0.7)
	Harvest path	64.0 (0.8)[n]	57.8 (0.9)[n]	70.1 (1.1)[y]
	Frond pile	58.5 (0.7)[n]	61.6 (1.0)[n]	55.4 (1.0)[y]
	Cover plants	48.7 (0.8)[o]	40.3 (1.1)[o]	57.0 (1.1)[y]
ENVIRONMENTAL MEASUREMENTS TAKEN ALONGSIDE DRAIN FLUXES				
Drain depth	Collection drain	31.0 (0.03)	34.2 (0.04)	27.6 (0.04)
	Field drain	19.9 (0.01)	24.1 (0.01)[a]	15.5 (0.02)[b]
Water temperature	Collection drain	27.7 (0.1)	28.3 (0.2)[a]	27.3 (0.2)[b]
	Field drain	27.3 (0.9)	27.4 (0.1)	27.2 (0.2)
ENVIRONMENTAL MEASUREMENTS TAKEN ALONGSIDE STEM MEASUREMENTS				
Stem temperature	Palm	32.4 (0.4)	31.8 (0.5)	33.1 (0.7)
Soil temperature (2016–2016)	By palm	28.7 (0.1)	28.7 (0.2)	28.7 (0.2)
Soil moisture (2016–2016)	By palm	22.0 (1.3)	29.4 (1.7)[a]	14.7 (1.3)[b]

Standard errors are in brackets. Relative humidity units are in %, temperature units are in °C, WTD units are in m and soil moisture units are in %. Plantations with significantly different parameters have been denoted by suffix a and b. Microforms with significantly different parameters have been denoted by suffix m, n, and o when considered collectively, or r, s, and t in Sabaju and w, x, and y in Sebungan when considered individually.

In contrast, in Sebungan, frond pile R_{tot} was significantly higher than the field drain CO_2 flux, but otherwise the soil, drain and stem fluxes did not differ significantly, apart from the high R_{tot} fluxes measured next to the palms (multiple comparison test for Kruskal-Wallis: $p \leq 0.05$).

Summaries of the CH_4 fluxes are presented in **Table 2**. The mean soil CH_4 flux was 0.29 ± 0.047 mg CH_4-C m^{-2} hr^{-1}. The mean drain CH_4 flux was 4.24 ± 1.64 mg CH_4-C m^{-2} hr^{-1}. The stem CH_4 flux averaged 0.043 ± 0.0056 mg CH_4-C m^{-2} hr^{-1}. We did not observe a significant difference in the overall CH_4 flux when comparing all the CH_4 fluxes from the two plantations.

CH_4 fluxes varied significantly among the different surface microforms (**Figure 3**; Kruskal-Wallis: chi-squared = 258.79; d.f. = 6; $p < 0.0001$). Multiple comparisons tests indicate that the CH_4 fluxes from different microforms fell into one of two groups; the first (lower emission) group consisted of the harvest path, frond pile, cover plants and stem fluxes, while the second (higher emission) group consisted of the by palm, collection drain and field drain fluxes (multiple comparison test for Kruskal-Wallis: $p \leq 0.05$). This trend was the same in both plantations.

Temporal Variability in CO_2 and CH_4 Fluxes

Seasonal trends were observed in trace gas fluxes between the rainy and dry seasons. CO_2 fluxes varied between the rainy and dry seasons, but this trend was not statistically significant. The rainy season flux averaged 0.74 ± 0.054 g CO_2-C m^{-2} hr^{-1} and the dry season flux averaged 0.94 ± 0.081 g CO_2-C m^{-2} hr^{-1}.

Disaggregating the data by microform showed that each microform had different trends with respect to CO_2 fluxes (**Figure 4**). R_{tot} measured next to the palm was significantly higher in the dry season than in the rainy season (Kruskal-Wallis: chi-squared = 25.6; d.f. = 11; $p < 0.0001$). R_{tot} measured from the harvest path, frond piles and cover plants did not vary significantly between the rainy and dry seasons. Significantly

TABLE 2 | Summaries of the mean, minimum, maximum and number of CO_2 and CH_4 fluxes measured in this study.

	CO_2 (g CO_2-C m^{-2} hr^{-1})				CH_4 (mg CH_4-C m^{-2} hr^{-1})			
	Mean (S.E.)	**Min**	**Max**	***n***	**Mean (S.E.)**	**Min**	**Max**	***n***
COMBINED								
Soil	0.83 (0.048)	0.0044	36.62	1233	0.29 (0.047)	−2.70	15.47	461
Drain	0.14 (0.0012)	0.0016	1.70	280	4.24 (1.64)	−128.87	162.66	165
Stem	0.23 (0.012)	0.000022	0.96	130	0.043 (0.0056)	−0.016	0.44	130
SABAJU								
Soil	0.82 (0.052)	0.029	12.89	587	0.40 (0.087)	−1.77	15.48	237
Drain	0.14 (0.018)	0.0020	1.70	142	5.13 (2.44)	−128.87	110.81	89
Stem	0.24 (0.017)	0.000022	0.89	65	0.048 (0.010)	−0.016	0.44	65
SEBUNGAN								
Soil	0.85 (0.083)	0.044	36.62	646	0.17 (0.030)	−2.70	3.51	224
Drain	0.14 (0.015)	0.0016	1.12	138	3.19 (2.15)	−0.015	162.66	76
Stem	0.23 (0.018)	0.013	0.96	65	0.038 (0.0045)	0.0012	0.15	65

Standard errors of the mean are included in brackets. Fluxes are presented that were measured from the soil, drain and stem surfaces from both plantations combined, or when the plantations were considered separately.

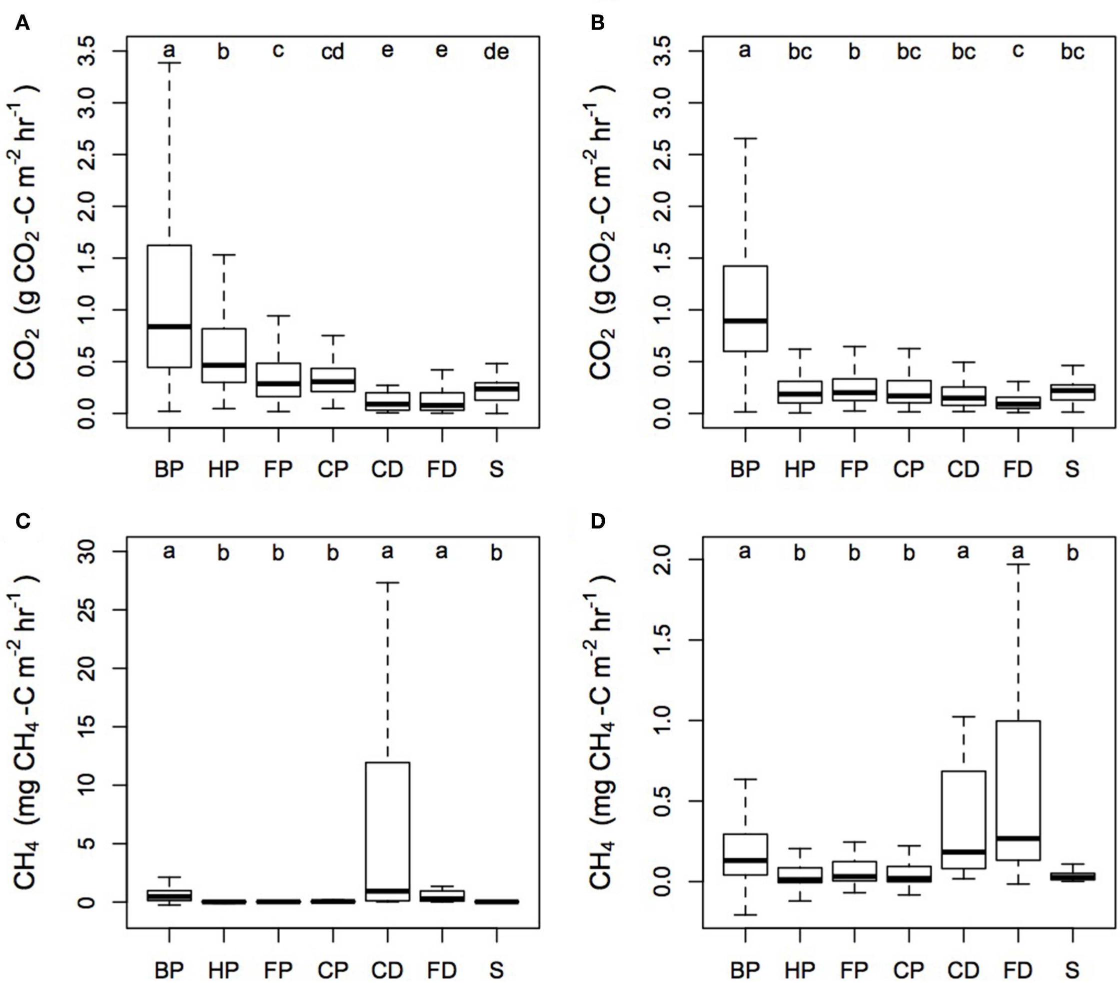

FIGURE 3 | CO_2 and CH_4 fluxes from the different microforms in Sabaju and Sebungan. Microform acronyms are in the top left of each panel and are: BP - by palm; HP - harvest path; FP - frond pile; CP - cover plants; CD - collection drain; FD - field drain; and S - stem. **(A)** the median and interquartile range for CO_2 fluxes from Sabaju and **(B)** Sebungan, and **(C)** the median and interquartile range for CH_4 fluxes from Sabaju and **(D)** Sebungan. Outliers were excluded from the graph for visual clarity.

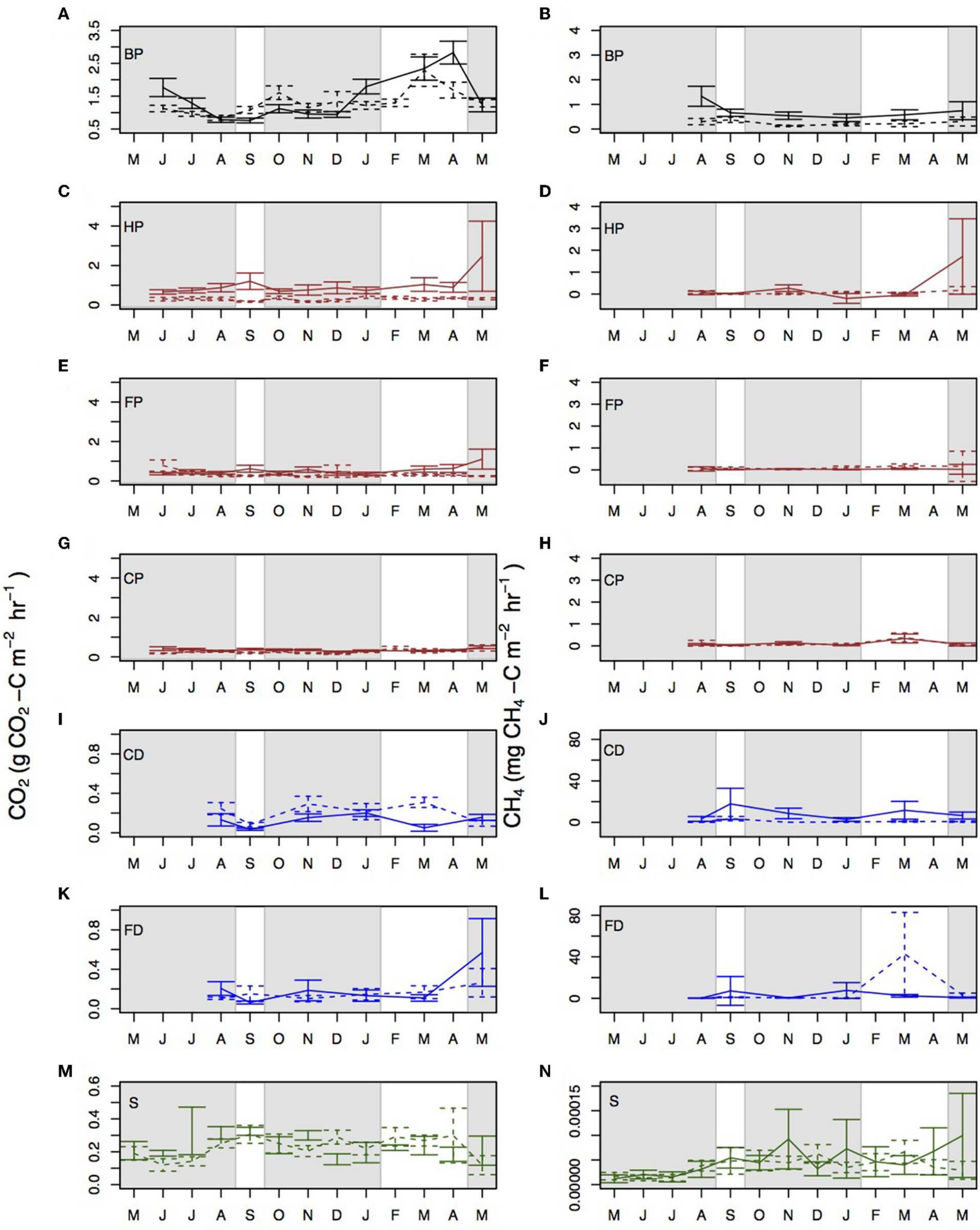

FIGURE 4 | Monthly mean CO_2 and CH_4 measurements taken from the different surface microforms in Sabaju (continuous line) and Sebungan (dashed line) for **(A)** by palm CO_2, **(B)** by palm CH_4, **(C)** harvest path CO_2, **(D)** harvest path CH_4, **(E)** frond pile CO_2, **(F)** frond pile CH_4, **(G)** cover plants CO_2, **(H)** cover plants CH_4, **(I)** collection drain CO_2, **(J)** collection drain CH_4, **(K)** field drain CO_2, **(L)** field drain CH_4, **(M)** stem CO_2, and **(N)** stem CH_4. Microform acronyms are in the top left of

(Continued)

FIGURE 4 | each panel and are: BP - by palm; HP - harvest path; FP - frond pile; CP - cover plants; CD - collection drain; FD - field drain; and S - stem. Furthermore, the lines for by palm fluxes are plotted in black, the lines for harvest path, frond pile, and cover plants are plotted in brown, the drain fluxes are plotted in blue and the stem fluxes are plotted in green. The shaded gray areas signify the rainy seasons and the white areas signify the dry seasons. Standard errors are shown with bars. Data are presented for 2015–2016, apart from stem data which are presented for 2016–2017. Note the different y-axis scales.

more CO_2 was measured from the surfaces of the drainage ditches in the rainy season than in the dry season (Kruskal-Wallis: chi-squared = 11.54; d.f. = 1; $p < 0.0001$). Splitting the drains, the larger collection drains had significant seasonal variation in CO_2 fluxes (Kruskal-Wallis: chi-squared = 8.1; d.f. = 1; $p = 0.004$), with higher CO_2 fluxes in the rainy season than the dry season (multiple comparison test for Kruskal-Wallis: $p \leq 0.05$) and the smaller field drains did not. Stem CO_2 did not show significant variation between the rainy and dry seasons.

Collectively, CH_4 fluxes did not vary significantly between rainy and dry seasons, although the rainy season flux averaged 0.76 ± 0.17 mg CH_4-C m^{-2} hr^{-1} and the dry season flux averaged 2.27 ± 1.14 mg CH_4-C m^{-2} hr^{-1}. Soil and stem CH_4 fluxes did not show significant variation between the rainy and dry seasons at the different plantations. Drain CH_4 fluxes were significantly higher in the rainy season than in the dry season (**Figure 4**; Kruskal-Wallis: chi-squared = 4.33; d.f. = 1; $p = 0.04$). Considering the plantations separately, there was no significant difference between the rainy and dry seasons in the different microforms or locations.

Annual Estimates of CO_2 and CH_4 Flux

Annual estimates of CO_2 fluxes were produced for the plantations both together and separately (**Table 3**). Combining R_{tot} and drain CO_2 fluxes to give the total CO_2 flux from the ground surfaces gave an average of 23.57 ± 0.50 Mg CO_2-C ha^{-1} yr^{-1}. Sabaju and Sebungan differed in their annual combined R_{tot} and drain CO_2 flux. Sabaju was estimated to produce 29.54 ± 0.47 Mg CO_2-C ha^{-1} yr^{-1} and Sebungan was estimated to produce 17.62 ± 0.53 Mg CO_2-C ha^{-1} yr^{-1}. The plantations differed in this CO_2 flux because of the contribution from the harvest path at each plantation; Sebungan averaged 9.21 ± 1.40 Mg CO_2-C ha^{-1} yr^{-1} from the harvest path, while Sabaju emitted 20.19 ± 1.33 Mg CO_2-C ha^{-1} yr^{-1}.

Annual estimates of CH_4 fluxes were calculated, collectively for both plantations and individually, with very little difference between the total CH_4 flux (**Table 4**). Combined, the annual CH_4 flux from oil palm plantations, including soil, drain and stem fluxes, was 61.02 ± 17.78 kg CH_4-C ha^{-1} yr^{-1}. In Sabaju, the annual CH_4 flux was 60.84 ± 4.35 kg CH_4-C ha^{-1} yr^{-1} and in Sebungan the annual CH_4 flux was 61.19 ± 25.28 kg CH_4-C ha^{-1} yr^{-1}.

Partitioning R_{tot} Into R_h and R_a

R_{tot} was partitioned into R_h and R_a at both plantations (**Table 5**). Collectively, R_h ranged from 17.61 to 17.89 Mg CO_2-C ha^{-1} yr^{-1} and R_a ranged from 4.19 to 4.47 Mg CO_2-C ha^{-1} yr^{-1}. Plantation R_a increased from 4.71 to 4.99 Mg CO_2-C ha^{-1} yr^{-1} when stem respiration was included. R_h varied between the two plantations; R_h in Sabaju ranged from 23.89 to 24.39 Mg CO_2-C ha^{-1} yr^{-1}, while in Sebungan it ranged from 11.13 to 11.81 Mg CO_2-C ha^{-1} yr^{-1}. Considering the plantations separately, R_a ranged from 3.10 to 3.60 Mg CO_2-C ha^{-1} yr^{-1} in Sabaju and from 4.36 to 5.04 Mg CO_2-C ha^{-1} yr^{-1} in Sebungan. When stem respiration was combined with soil R_a, plantation R_a increased to range from 3.52 to 4.02 Mg CO_2-C ha^{-1} yr^{-1} in Sabaju and from 4.98 to 5.66 Mg CO_2-C ha^{-1} yr^{-1} in Sebungan.

Plantation Peat Carbon Losses and Percentage Contributions

Plantation peat carbon losses were comprised of R_h, drain CO_2, soil CH_4, drain CH_4, and stem CH_4 components and were estimated in CO_{2-eq}. Overall plantation carbon losses ranged from 72.35 ± 0.14 to 73.38 ± 0.16 Mg CO_{2-eq} ha^{-1} yr^{-1}. Plantation carbon losses varied between the two plantations. In Sabaju, the plantation carbon losses ranged from 95.58 ± 0.14 to 97.41 ± 0.17 Mg CO_{2-eq} ha^{-1} yr^{-1}. In Sebungan, the plantation carbon losses ranged from 48.37 ± 0.16 to 50.86 ± 0.19 Mg CO_{2-eq} ha^{-1} yr^{-1}.

Breaking the carbon losses down by component showed that 92% of the CO_2 produced through R_h and drain CO_2 pathways came from soils and 8% came from the drains (**Table 6**). This was similar for both plantations. In Sabaju, 94% of the CO_2 produced through R_h or drain CO_2 came from R_h and 6% came from drain CO_2. In Sebungan, 89% of the CO_2 produced through R_h or drain CO_2 came from R_h and 11% came from drain CO_2.

The CH_4 losses showed different component contributions to CO_2 (**Table 6**). Overall, 30% of CH_4 fluxes came from the soil and 70% of plantation CH_4 fluxes came from the drainage ditches. Stem CH_4 fluxes gave negligible contributions. The CH_4 pathways varied between the two plantations. In Sabaju, 50% of the plantation CH_4 flux was measured from the soil surface and 50% was recorded from the drainage ditches. In Sebungan, 11% of the plantation CH_4 flux came from the soil and 89% came from the drainage ditches.

In order to isolate which pathways were dominating the plantation peat carbon losses, the fluxes were compared in CO_{2-eq} (**Table 6**). Considering the soil component in isolation, 99% of soil peat carbon losses were attributable to R_h and 1% to CH_4. Considering the drain carbon fluxes, 78% of the carbon losses came through drain CO_2 and 22% of the carbon measured from the drain surfaces came from drain CH_4.

Overall, 89% of plantation peat carbon losses came from R_h, 8% came from drain CO_2, 1% from soil CH_4, 2% from drain CH_4, and 0% from stem CH_4; 90% of plantation carbon losses came from the soil and 10% from drainage ditches (**Table 6**). In Sabaju, 92% of plantation peat carbon losses were attributable to R_h, 6% to drain CO_2, 1% to soil CH_4, 1% to drain CH_4, and 0% to stem CH_4; 93% of peat carbon losses came from the soil and 7% from the drainage ditches. In Sebungan, 84–85% of plantation carbon losses were from R_h, 10–11% were from

TABLE 3 | Annual upscaled CO_2 fluxes from the different surface microforms sampled at both plantations and at Sabaju and Sebungan individually.

Location	Combined	n	Sabaju	n	Sebungan	n
INDIVIDUAL MICROFORM						
By palm	4.99 (0.73)	616	5.11 (0.68)	293	4.87 (0.78)	323
Harvest path	14.70 (1.36)	207	20.19 (1.33)	99	9.21 (1.40)	108
Frond pile	1.04 (0.17)	206	1.13 (0.19)	98	0.96 (0.13)	108
Cover plants	1.34 (0.26)	204	1.55 (0.20)	97	1.14 (0.32)	107
Collection drain	0.42 (0.02)	107	0.32 (0.03)	54	0.53 (0.00)	53
Field drain	1.08 (0.15)	173	1.24 (0.22)	88	0.91 (0.03)	85
Stem	0.52 (0.01)	130	0.42 (0.05)	65	0.62 (0.08)	65
COMPONENT SUMS						
Sum (R_{tot})	22.08 (0.77)	1233	27.98 (0.73)	587	16.17 (0.81)	646
Sum (drain CO_2)	1.50 (0.10)	280	1.56 (0.14)	142	1.44 (0.02)	138
Sum (R_{tot} + drain CO_2)	23.57 (0.50)	1513	29.54 (0.47)	729	17.62 (0.53)	784
Sum (R_{tot} + drain CO_2 + stem CO_2)	24.09 (0.48)	1643	29.96 (0.45)	794	18.24 (0.51)	849

Temporally and spatially weighted fluxes are presented for each individual microform. The sums of the different surface components (R_{tot} + drain CO_2 and R_{tot} + drain CO_2 + stem CO_2) are included. All flux values are given in Mg CO_2-C ha^{-1} yr^{-1}. Standard errors are in brackets.

TABLE 4 | Annual upscaled CH_4 fluxes from the different surface microforms sampled at both plantations and at Sabaju and Sebungan individually.

Location	Combined	n	Sabaju	n	Sebungan	n
INDIVIDUAL MICROFORM						
By palm	0.18 (0.31)	171	0.29 (0.44)	85	0.07 (0.040)	86
Harvest path	17.35 (6.30)	95	29.38 (8.53)	52	5.31 (0.74)	43
Frond pile	0.36 (0.06)	97	0.17 (0.02)	49	0.56 (0.08)	48
Cover plants	0.53 (0.15)	98	0.55 (0.14)	51	0.50 (0.17)	47
Collection drain	14.37 (2.09)	70	22.71 (2.06)	34	6.03 (2.12)	36
Field drain	28.14 (46.00)	95	7.67 (6.49)	55	48.62 (71.71)	40
Stem	0.09 (0.01)	130	0.08 (0.04)	65	0.11 (0.02)	65
COMPONENT SUMS						
Sum (soil CH_4)	18.41 (2.88)	461	30.39 (4.02)	237	6.44 (0.34)	224
Sum (drain CH_4)	42.51 (34.72)	165	30.38 (5.24)	89	54.64 (51.43)	76
Sum (soil CH_4 + drain CH_4)	60.93 (17.92)	626	60.76 (4.39)	326	61.08 (25.49)	300
Sum (soil CH_4 + drain CH_4 + stem CH_4)	61.02 (17.78)	756	60.84 (4.35)	391	61.19 (25.28)	365

Temporally and spatially weighted fluxes are presented for each individual microform. The sums of the different surface components (soil CH_4 + drain CH_4 and soil CH_4 + drain CH_4 + stem CH_4) are included. All flux values are given in kg CH_4-C ha^{-1} yr^{-1}. Standard errors are in brackets.

drain CO_2, 0% from soil CH_4, 4% from drain CH_4, and 0% from stem CH_4; 85–86% came from the soil and 14–15% from the drainage ditches.

Environmental Models for CO_2 and CH_4 Losses

R_h, the most dominant component in the peat carbon losses, was controlled by variations in air temperature, WTD, soil temperature, and soil moisture (**Table S4**). R_h increased as air temperature increased (**Figure 5**). Whilst the interaction between air temperature and plantation was not significant, the rate of increase in R_h as air temperature increased was predicted to be almost three times greater in Sabaju than in Sebungan (**Table S5**). Unexpectedly, R_h increased as WTD rose, with a modeled increase of 0.75 Mg CO_2-C ha^{-1} yr^{-1} for every 10 cm decrease in WTD. The interaction between WTD and plantation was significant, with opposite relationships seen in both plantations (**Figure 5**). In Sabaju, R_h increased by 0.85 Mg CO_2-C ha^{-1} yr^{-1} for every 10 cm rise in WTD. R_h increased in Sebungan as the WTD was lowered, by a modeled rate of −0.29 Mg CO_2-C ha^{-1} yr^{-1} for every 10 cm drawdown of WTD.

Overall, R_h increased as soil temperature increased and R_h increased as soil moisture decreased (**Tables S4, S5**). Soil temperature and soil moisture had significant relationships with R_h when their individual interactions with plantation and microform were included in the model. Considering the plantations together and the microforms separately, the harvest path increased in R_h as soil temperature increased, and the frond pile and cover plants decreased in R_h as soil temperature increased. This pattern was seen in Sebungan but not in Sabaju when the plantations were considered separately. In Sabaju, R_h increased when soil temperature increased throughout the

TABLE 5 | R_{tot}, R_h and R_a estimates from both plantations combined, and Sabaju and Sebungan considered individually.

Partitioning method	R_{tot}	R_h	R_a
COMBINED			
(1) Partitioned using harvest path fluxes	22.08 (0.77)	17.76 (1.65)	4.32 (0.95)
(2) Partitioned using harvest path and frond pile fluxes	22.08 (0.77)	17.61 (1.09)	4.47 (0.86)
(3) Partitioned using harvest path, frond pile and cover plants fluxes	22.08 (0.77)	17.89 (0.85)	4.19 (0.80)
SABAJU			
(1) Partitioned using harvest path fluxes	27.49 (0.73)	24.39 (1.61)	3.10 (0.91)
(2) Partitioned using harvest path and frond pile fluxes	27.49 (0.73)	23.89 (1.07)	3.60 (0.83)
(3) Partitioned using harvest path, frond pile, and cover plants fluxes	27.49 (0.73)	23.97 (0.82)	3.52 (0.77)
SEBUNGAN			
(1) Partitioned using harvest path fluxes	16.17 (0.81)	11.13 (1.69)	5.04 (0.98)
(2) Partitioned using harvest path and frond pile fluxes	16.17 (0.81)	11.34 (1.12)	4.83 (0.89)
(3) Partitioned using harvest path, frond pile and cover plants fluxes	16.17 (0.81)	11.81 (0.87)	4.36 (0.82)

R_{tot} has been partitioned into R_h and R_a using three methods: partitioning method one has been estimated from harvest path fluxes only; partitioning method two has been estimated from harvest path and frond pile fluxes only; and partitioning method three has been estimated from harvest path, frond pile and cover plants fluxes only. Spatially weighted results are presented in Mg CO_2-C ha^{-1} yr^{-1} for each flux. Standard errors are in brackets.

microforms. Increasing soil moisture decreased the rate of R_h, with the greatest effect beneath the frond pile, followed by the harvest path and then the cover plants. This trend was also observed when the microforms in Sebungan were considered in isolation. In Sabaju, rates of R_h decreased as soil moisture increased in the cover plants but not in the harvest path and frond piles.

Soil CH_4 was controlled by soil moisture between 0 and 10 cm, soil moisture between 30 and 40 cm, WTD and soil temperature (**Table S6**). Soil CH_4 increased as soil moisture between 0 and 10 cm increased (**Table S5**). The interaction between plantation, microform, WTD and soil moisture between 30 and 40 cm also significantly explained the variation in soil CH_4. Here the expected relationship of soil CH_4 increasing as WTD decreased was observed in the harvest path and next to the palm. This trend was seen when considering the plantations together or in Sabaju. In Sebungan, soil CH_4 was modeled to increase as WTD decreased in the frond piles and cover plants. The opposite relationship was seen in the other microforms. Similarly, variation was seen in the relationship between soil CH_4 and soil moisture between 30 and 40 cm. Soil CH_4 increased as soil moisture between 30 and 40 cm increased in the harvest path, frond pile and next to the palm, with the opposite relationship in the cover plants. In Sabaju, soil CH_4 increased as soil moisture between 30 and 40 cm increased in the harvest path and by the palm. In Sebungan, soil CH_4 increased as soil moisture between 30 and 40 cm increased in the frond pile and cover plants. Soil CH_4 increased as soil temperature decreased. The interaction between soil temperature and plantation was significant, with the rate of soil CH_4 increasing twice as quickly in Sabaju than in Sebungan when soil temperature decreased.

Drain CO_2 and drain CH_4 had different environmental relationships (**Tables S5, S7**). Drain CO_2 did not have a significant relationship with any of the environmental variables measured in this study, but did vary significantly depending on the size of the microform. Overall, the field drain had a greater drain CO_2 flux. Drain CH_4 increased significantly as air temperature increased. This was seen at both plantations.

Stem CH_4 was explained by variations in monthly relative humidity, WTD, soil moisture, air temperature and soil temperature (**Table S8**). Stem CH_4 decreased as monthly relative humidity increased (**Table S5**). This relationship was seen on both plantations and the interaction between the individual palms within each plantation with monthly relative humidity was significant. Stem CH_4 increased as WTD increased. This was also seen at both plantations. For soil moisture, air temperature and soil temperature, opposite trends were seen between the two plantations. Stem CH_4 increased as soil moisture increased, this trend was the same when the plantations were considered together and also in Sebungan when the plantations were considered separately, but not in Sabaju. Stem CH_4 increased as air temperature and soil temperature increased, when both plantations were considered together. These trends were seen in Sebungan but not in Sabaju when the plantations were considered separately.

DISCUSSION

Carbon Fluxes Vary Spatially in Managed Tropical Peatlands

CO_2 and CH_4 fluxes varied significantly when measured from different surface microforms in two oil palm plantations on peat soil. The highest soil CO_2 and CH_4 fluxes were measured next to the palms. This pattern was attributed to the high density of roots in the palm rhizosphere; root biomass was greatest within the immediate 1 m radius around each palm, and decreased with increasing distance from the palm (Farmer, 2013; Dariah et al., 2014; Manning, 2019; Manning et al., in preparation). In these studies R_{tot} and soil respiration were measured at consistent intervals from the palm into the harvest path (Farmer, 2013; Dariah et al., 2014), frond pile and cover plants (Manning, 2019; Manning et al., in preparation) from mature oil palm plantations in Jambi, Indonesia (Farmer, 2013; Dariah et al., 2014) and

TABLE 6 | Percentage contributions of the soil, drain, and stem components to plantation CO_2, CH_4 and CO_{2-eq} fluxes.

	Combined	Sabaju	Sebungan
PLANTATION CO_2 CONTRIBUTIONS PER COMPONENT FLUX (EXCLUDING R_a)			
Soil: Plantation carbon losses	92%	94%	89%
Drain: Plantation carbon losses	8%	6%	11%
Stem: Plantation carbon losses	–	–	–
Total	100%	100%	100%
PLANTATION CH_4 CONTRIBUTIONS PER COMPONENT FLUX			
Soil: Plantation carbon losses	30%	50%	11%
Drain: Plantation carbon losses	70%	50%	89%
Stem: Plantation carbon losses	0%	0%	0%
Total	100%	100%	100%
CONTRIBUTION OF CO_2 AND CH_4 TO EACH COMPONENT			
Soil (R_h + CH_4)	99% CO_2, 1% CH_4	99% CO_2, 1% CH_4	99% CO_2, 1% CH_4
Drain	78% CO_2, 22% CH_4	83% CO_2, 17% CH_4	72% CO_2, 28% CH_4
Stem (CH_4 only)	0% CO_2, 100% CH_4	0% CO_2, 100% CH_4	0% CO_2, 100% CH_4
Plantation carbon losses	97% CO_2, 3% CH_4	98% CO_2, 2% CH_4	95–96% CO_2, 4–5% CH_4
PLANTATION CO_2 AND CH_4 CONTRIBUTIONS PER COMPONENT			
Soil: Plantation carbon losses	90%	93%	85–86%
Drain: Plantation carbon losses	10%	7%	14–15%
Stem: Plantation carbon losses	0%	0%	0%
Total	100%	100%	100%
OVERALL CO_2 OR CH_4 CONTRIBUTION TO PLANTATION CARBON LOSSES, PER COMPONENT			
R_h: Plantation carbon losses	89% CO_2	92% CO_2	84–85% CO_2
Drain CO_2: Plantation carbon losses	8% CO_2	6% CO_2	10–11% CO_2
Soil CH_4: Plantation carbon losses	1% CH_4	1% CH_4	0% CH_4
Drain CH_4: Plantation carbon losses	2% CH_4	1% CH_4	4% CH_4
Stem CH_4: Plantation carbon losses	0% CH_4	0% CH_4	0% CH_4
Total	100% CO_{2-eq}	100% CO_{2-eq}	100% CO_{2-eq}

Firstly, the percentage contribution of peat CO_2 carbon losses to the total plantation CO_2 losses by soil, drain and stem components are presented (R_a and stem CO_2 are not included). Secondly, the percentage contribution of net peat CH_4 to the total plantation net CH_4 flux by soil, drain and stem components are presented. Thirdly, the percentage contribution of CO_2 and CH_4 to each component and for the overall plantation carbon losses are presented, when the CO_2 and CH_4 fluxes have been combined in CO_{2-eq}. Here plantation carbon losses are defined as the sum of R_h, drain CO_2, soil CH_4, drain CH_4 and stem CH_4. Fourthly, the percentage contribution of the combined CO_2 and CH_4 fluxes in CO_{2-eq} to plantation carbon losses by soil, drain and stem components are presented. Finally, the percentage contributions of individual CO_2 and CH_4 fluxes to overall plantation carbon losses by soil, drain, and stem components are given. The plantations are considered together and separately.

this plantation (Manning, 2019; Manning et al., in preparation). Respiration from root biomass has been shown to drive high R_{tot} rates next to the palm, with a progressive decline in R_{tot} with increasing distance from each palm (Farmer, 2013; Dariah et al., 2014; Manning, 2019; Manning et al., in preparation). Likewise, high CH_4 fluxes from the rhizosphere could be due to a number of causes, including accelerated organic matter turnover facilitated by the metabolism of root exudates (Girkin et al., 2018a,b), or transport of CH_4 from deeper in the profile via porous tissues in the roots.

Outside the palm rhizosphere (i.e., >1 m distance from the palm), different soil surface management practices appeared to influence R_{tot} but not CH_4. R_{tot} was significantly higher in the harvest path than from either the frond piles or beneath the cover plants. There was no significant difference in CH_4 measured from these microforms. Considering the plantations separately gave different trends for R_{tot}, but did not change the pattern of CH_4. For example, in Sebungan, there was no significant difference in R_{tot} between the non-rhizosphere fluxes. In contrast, in Sabaju the harvest path had significantly higher R_{tot} than the frond pile and cover plants. These differences in R_{tot} among microforms are noteworthy because few other studies consider the effects of surface management practices on R_{tot}, with the exception of work by Arifin et al. (2015), who also found that R_{tot} was significantly lower when measured from beneath cover plants than from the harvest path. These differences in R_{tot} among microforms are significant because they have direct bearing not only predicting and upscaling land-atmosphere fluxes, but also because they provide insight into how soil surface management practices are affecting soil CO_2 and CH_4 dynamics.

Drainage ditches made a substantial contribution to land-atmosphere CO_2 and CH_4 fluxes, particularly with respect to CH_4. Drain CH_4 was significantly higher than CH_4 fluxes from all soil microforms, with the exception of the CH_4 flux measured next to the palm. Comparing our drain data against other datasets, we found that our CH_4 fluxes fell within the range observed in drained peatlands and drained *Acacia sp.* plantations in Kalimantan (Jauhiainen and Silvennoinen, 2012). These high drain CH_4 fluxes could be attributable to the photochemical or microbial breakdown of DOC, or lateral transport of dissolved

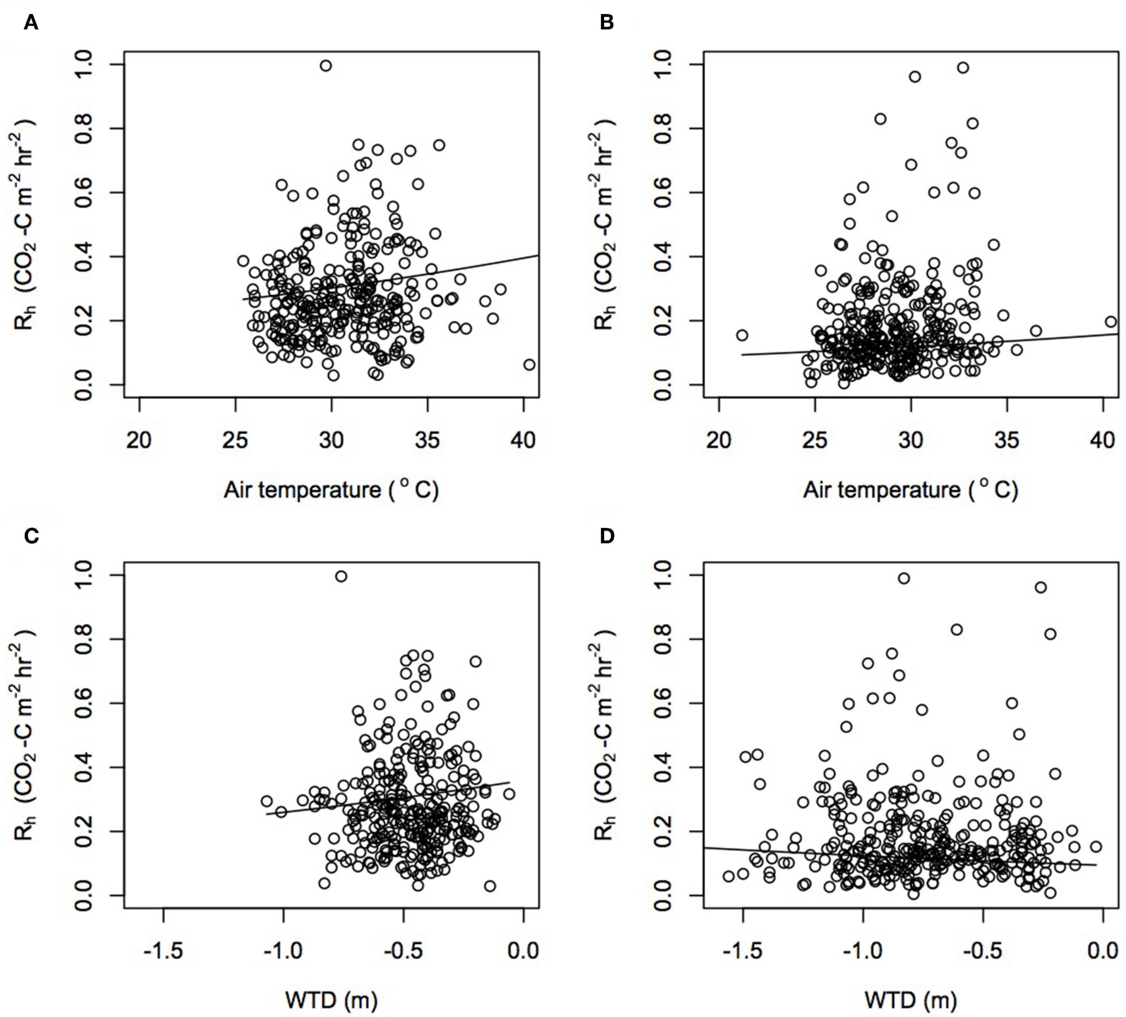

FIGURE 5 | R_h estimates modeled from changes in **(A)** air temperature in Sabaju, **(B)** air temperature in Sebungan, **(C)** WTD in Sabaju, and **(D)** WTD in Sebungan, using the linear mixed effect model parameters. Actual data points from the harvest path, frond pile and cover plants are plotted.

CH_4 produced in the peat into surface waters (Billett and Moore, 2008; Teh et al., 2011; Cory et al., 2014; Logue et al., 2016). These data are significant because there are currently no published data on drain CO_2 and CH_4 fluxes from oil palm plantation drainage ditches, and they have implications for extrapolating both plot-level CO_2 and CH_4 fluxes to larger spatial scales. In particular, the estimates of CO_2 and CH_4 fluxes based on straight mean averaging or non-spatially explicit sampling may tend to overestimate the net release of CO_2 to the atmosphere and underestimate the net release of CH_4 from tropical peatlands, given that drainage ditches form a small but significant portion of the landscape.

Stem respiration fell within a similar range to drain CO_2 and the R_{tot} fluxes when excluding the high fluxes next to the palm. Once again, disaggregation of the dataset by plantation revealed local differences in stem respiration relative to other CO_2-emitting processes. Stem respiration was lower in Sabaju than in Sebungan. Furthermore, in Sabaju, stem respiration was significantly lower than R_{tot} measurements taken from next to the palm, the harvest path and the frond pile. In contrast, in Sebungan, stem respiration was similar to all other soil fluxes with the exception of R_{tot} measured next to the palm. We believe that these local differences in stem respiration may reflect differences in productivity between the two plantations. Generally, stem respiration correlates with photosynthetic rate (Yang et al., 2016); hence, the higher stem respiration in Sebungan may reflect that this plantation shows higher rates of CO_2 uptake and growth than Sabaju, evidenced by higher rates of net primary productivity, larger fronds and formation of a denser, more closed canopy.

Stem CH_4 fluxes were recorded from the palms in both plantations, with lower CH_4 fluxes than those reported from the soil or drain surfaces, by factors of 22 and 200, respectively. Stem CH_4 has been recorded from the stems of tropical trees growing in swamp forests in Brunei and the Amazon (Pangala et al., 2013, 2017). Stem fluxes from Brunei ranged between similar magnitudes to the stem fluxes measured at this site (here:

−0.016–0.440 mg CH_4-C m^{-2} hr^{-1}; Brunei: 0.013–0.139 mg CH_4-C m^{-2} hr^{-1}) when the fluxes were considered per m^{-2} of stem surface area (Pangala et al., 2013). Stem fluxes in the Amazon were considerably higher than the stem fluxes in Borneo (0.248–435.75 mg CH_4-C m^{-2} hr^{-1}; Pangala et al., 2017). Stem CH_4 has been shown to correlate with rates of evapotranspiration (Pangala et al., 2014). We propose that the similar rates of relative humidity between Sarawak and Brunei may contribute to the similarities in range of fluxes from the stems of plants at these sites. The CH_4 oxidation reported from this site was measured four times and only when relative humidity exceeded 93% (Manning, 2019). We suggest that this may be due to methanotrophs on the palm surface, that are normally masked from stem CH_4 fluxes, but observable when high relative humidity prevents transpiration (Raghoebarsing et al., 2005).

Temporal Variation in Carbon Fluxes

Both CO_2 and CH_4 fluxes were greater in the dry season than the rainy season, but these differences were not statistically significant. In this region, two rainy seasons occur, with the main rainy season between October and January, and a secondary rainy season between May and August. Dry season falls from February to April and in September.

Considering the surface microforms separately, significant seasonal variation was seen from R_{tot} measured next to the palm, with higher fluxes in the dry season than in the rainy season. R_{tot} next to the palm was predominately attributed to R_a (Farmer, 2013; Dariah et al., 2014; Manning et al., in preparation). Stem respiration gave similar overall trends to by palm R_{tot}, but differences were not statistically significant. Overall these fluxes, dominated by autotrophic processes, suggest strong seasonal growth from the palms, with more photosynthetic activity in the dry season than in the rainy season. Seasonality has been recorded from R_{tot} next to the palm in other plantations (Comeau, 2016; Hergoualc'h et al., 2017), as well as from R_a sampled from the edge of the canopy (Melling et al., 2013).

In contrast, R_{tot} measured from the harvest path, frond pile and cover plants did not show significant seasonal variation. R_{tot} fluxes measured from these locations were dominated by R_h. R_h was shown to have significant seasonality in a rubber plantation in Kalimantan, Indonesia growing on peat soil, where the seasonality in R_h was driven by seasonal changes in WTD (Wakhid et al., 2017). Similar to this study, those on other oil palm plantations have not found significant seasonality in R_h (Comeau, 2016; Hergoualc'h et al., 2017). The lack of apparent seasonality in R_h from oil palm plantations could be due to reduced variability in the environmental variables driving R_h. For example, Melling et al. (2013) found that R_h varied in the forest due to variations in WTD but not in the oil palm plantation where the WTD was more consistent.

Drain CO_2 and CH_4 fluxes showed seasonality; drain CO_2 fluxes were significantly higher in the rainy season than the dry season and drain CH_4 fluxes were significantly higher in the dry season than in the rainy season. Cook et al. (2018) found that drain discharge varied seasonally but total organic carbon (DOC plus particulate organic carbon) concentrations in the drains did not vary seasonally from Sabaju and Sebungan. Billett and Moore (2008) found that drain CO_2 increased when flow rate increased, whilst DOC concentrations remained consistent regardless of flow rate.

Peat Oxidation Rates and Major Loss Pathways?

R_h was estimated to range from 17.61 ± 1.65 to 17.89 ± 0.85 Mg CO_2-C ha^{-1} yr^{-1} (mean: 17.75 ± 1.54 Mg CO_2-C ha^{-1} yr^{-1}). For these calculations, R_h was partitioned from R_{tot} using the distance from palm approach, as this was deemed sufficient in these plantations (Manning, 2019; Manning et al., in preparation). We present a range of estimates that include (1) only the harvest path—comprising of bare soil and often the only microform measured in R_h studies; (2) the harvest path and the frond pile—the latter being bare soil covered in dead fronds; (3) the harvest path, frond pile and cover plants—with the cover plants being included, despite the presence of cover plant roots, due to the increased R_h being potentially from priming, as opposed to R_a or decomposition from the cover plants (Manning et al., in preparation). In this study the lowest R_h estimate was obtained from when the harvest path and frond pile were both included in the calculations and the highest estimate came from when the cover plants were included as well. However, the estimates did not vary significantly regardless of which microforms were included.

R_h estimates from Sebungan were found to range from 11.13 ± 1.69 to 11.81 ± 0.87 Mg CO_2-C ha^{-1} yr^{-1} (mean: 11.43 ± 1.37 Mg CO_2-C ha^{-1} yr^{-1}) and R_h from Sabaju was measured ranging between 23.89 ± 1.07 and 24.39 ± 1.61 Mg CO_2-C ha^{-1} yr^{-1} (mean: 24.08 ± 1.42 Mg CO_2-C ha^{-1} yr^{-1}). In these estimates R_h was lowest from Sebungan when the harvest path only was measured, and highest when the cover plants were included. In Sabaju the lowest R_h estimate used the harvest path and frond pile data and the highest R_h estimate only used the harvest path results. The Sebungan R_h estimate fell within the reported range of R_h from oil palm plantations (4.1 to 22.9 Mg CO_2-C ha^{-1} yr^{-1}, but the Sabaju estimate was greater than this range (Farmer, 2013; Melling et al., 2013; Dariah et al., 2014; Husnain et al., 2014; Comeau, 2016; Comeau et al., 2016; Hergoualc'h et al., 2017; Ishikura et al., 2018; Matysek et al., 2018).

These data are relevant to policy because they suggest that the IPCC emissions factor for R_h is underestimated. For example, whilst R_h estimates from Sebungan have been shown to be similar to the IPCC (2014) emissions factor of 11 Mg CO_2-C ha^{-1} yr^{-1}, R_h from Sabaju is at least twice as large. This has implications when upscaling—estimating the R_h emissions from industrial oil palm plantations using the areal extent of plantations given in Miettinen et al. (2016) increases predicted R_h from 34.1 Tg CO_2-C yr^{-1} if the IPCC emission factor is used to 55.8 Tg CO_2-C yr^{-1} if the mean R_h from this study is used.

Another important policy-relevant finding is that area-weighted CH_4 fluxes from these managed systems are similar to swamp forests in SE Asia, suggesting that drainage has not diminished the CH_4 emissions potential of these systems. Annual estimates of CH_4 were 61.02 ± 17.78 kg CH_4-C ha^{-1} yr^{-1}

including soil, drain and stem fluxes. Sabaju and Sebungan produced similar rates of CH_4 of 60.84 ± 4.35 kg CH_4-C ha^{-1} yr^{-1} and 61.19 ± 25.28 kg CH_4-C ha^{-1} yr^{-1}, respectively. Annual estimates from forest CH_4 have been shown to range between 0.2 and 72 kg CH_4-C ha^{-1} yr^{-1} from Malaysian, Indonesian and Brunei peatlands (Inubushi et al., 1998, 2003; Furukawa et al., 2005; Hadi et al., 2005; Jauhiainen et al., 2005; Melling et al., 2005b; Hirano et al., 2009; Pangala et al., 2013). The results from this study are potentially controversial because current conceptual ideas of peatland drainage predict a net reduction in CH_4 emission linked to peatland drainage (Jauhiainen et al., 2005, 2008; Lai, 2009; Couwenberg et al., 2010). This is reflected in the IPCC (2014) emissions factors for oil palm plantations that are 0 kg CH_4-C ha^{-1} yr^{-1} from the peat soil and 45.18 kg CH_4-C ha^{-1} yr^{-1} from the drainage ditches. The results from this study show that draining peat does not reduce CH_4 fluxes. The high CH_4 fluxes from the drains suggest that either the drain sediments have increased rates of CH_4 production, or that the CH_4 transported in the water may be carried to the drains before being egressed, rather than diffusing through the soil and being oxidized by methanotrophs (Müller et al., 2015; Evans et al., 2016).

Combining rates of R_h, drain CO_2, soil CH_4, drain CH_4, and stem CH_4 in CO_{2-eq} gave overall plantation peat carbon losses. Here, net peat carbon losses averaged across plantations ranged between 72.35 ± 0.14 and 73.38 ± 0.16 Mg CO_{2-eq} ha^{-1} yr^{-1}. Of this flux, 89% was attributed to R_h. Drain CO_2 was the next largest driver, contributing 8% of the plantation carbon losses. CH_4 contributed 2, 1, and 0% to plantation carbon losses for drain, soil and stem fluxes, respectively. We suggest this particularly low contribution from palm stems is due to two factors: (1) a strong gradient for CH_4 transport to the atmosphere through the drainage ditches, and (2) the low density of palms growing on the soil. As previously mentioned, the measured stem CH_4 fluxes were in the same range as the stem fluxes from trees in a swamp forest in Brunei (Pangala et al., 2013). Following upscaling the stem CH_4 fluxes from Brunei were 10–23 times greater than the stem CH_4 fluxes measured here (Pangala et al., 2013). However, the swamp forest trees were taller and more densely populated than oil palms, allowing for a greater overall stem surface area and therefore a greater total plot-scale stem CH_4. Similarly, the total contribution of tree stem CH_4 to plot-scale CH_4 was 62–87% of the total ecosystem flux—but there were no drainage ditches in the forest plot, meaning that stem fluxes had a greater overall representation (Pangala et al., 2013). Excluding the drainage ditches from the estimates in this study increased the stem contribution to 0.5%.

Sabaju and Sebungan differed in their overall net peat carbon losses. Sabaju produced double the amount of peat carbon losses compared to Sebungan, with peat carbon losses ranging between 95.58 ± 0.14 and 97.41 ± 0.17 Mg CO_{2-eq} ha^{-1} yr^{-1} in Sabaju. In Sebungan, net peat carbon losses fell within the range of 48.37 ± 0.16 to 50.86 ± 0.19 Mg CO_{2-eq} ha^{-1} yr^{-1}. Sabaju and Sebungan peat carbon losses were made up from slightly different proportions of CO_2 and CH_4. R_h dominated the proportional losses of peat carbon in Sabaju; 92% of the total flux was from R_h, 6% from drain CO_2, 1% from soil CH_4, 1% from drain CH_4, and 0% from stem CH_4. In Sebungan, R_h was still the predominant peat carbon loss pathway, but the drain CO_2 and CH_4 fluxes doubled in contribution compared to Sabaju; 84–85% of plantation carbon losses in Sebungan was made up from R_h, 10–11% was from drain CO_2, 4% was from drain CH_4, and 0% was from both soil and stem CH_4.

Role of Temperature and Water Table Depth in Modulating Carbon Fluxes

Air temperature, soil temperature, WTD and soil moisture controlled rates of R_h. WTD, soil moisture at 0–10 cm, soil moisture at 30–40 cm and soil temperature controlled soil CH_4 fluxes. Drain CO_2 did not correlate with the environmental variables measured in this study. Drain CH_4 was controlled by air temperature. Stem CH_4 had significant relationships with relative humidity, WTD, air temperature, soil temperature and soil moisture.

Air and soil temperatures have been shown to control the rate of R_h, both on these plantations and in other studies (Jauhiainen et al., 2012; Farmer, 2013; Hergoualc'h et al., 2017). Temperature has been shown to increase the rate of R_{tot} and R_h due to increased activation energy for the chemical reactions (Lloyd and Taylor, 1994). Air temperature increased the rate of R_h in both plantations and the model predicted it was at a three times greater rate in Sabaju than in Sebungan. This steeper gradient in Sabaju might explain why Sabaju was only 1.5°C warmer than Sebungan but rates of R_h were twice as high. R_h also increased as soil temperature increased in both plantations—with differences seen in the relationships between the microforms. As soil temperature increased, R_h was predicted to increase in the harvest path and in the cover plants in Sabaju, which also did not always have a closed canopy, exposing the soil directly to the Sun. This relationship with temperature was not seen in the frond piles, potentially due to extra shading, a different microclimate and the interaction of other variables, such as moisture.

Hydrology also controlled rates of R_h, with soil moisture and WTD acting as proxies for redox potential. Increasing soil moisture lowered the rate of R_h, as supported by Farmer (2013), Comeau (2016) and Hergoualc'h et al. (2017). This was seen in every microform in Sebungan, particularly in the frond pile, and in the frond pile and cover plants in Sabaju. R_h increased as soil moisture increased in Sabaju, but the effect size was negligible. WTD had opposite relationships with R_h at both plantations. Sebungan gave the expected relationship with R_h increasing as the WTD lowered. This trend has also been seen by Hergoualc'h et al. (2017). However, Sabaju had the opposite relationship with WTD, with increasing WTD decreasing rates of R_h. The WTD measurements made in Sebungan were deeper and had a wider range than those made in Sabaju. Within the WTD range sampled, the more labile carbon may have already been oxidized in Sabaju, with fresher labile carbon exposed at the deeper WTDs in Sebungan, explaining the variation in relationship with WTD (Hooijer et al., 2012).

Soil CH_4 was controlled by soil temperature, soil moisture between 0 and 10 cm, soil moisture between 30 and 40 cm and WTD. Melling et al. (2005b) also found that soil temperature, water filled pore space and WTD controlled soil CH_4 fluxes. Here, soil CH_4 increased as soil moisture between 0 and 10 cm increased. This result would be expected, as CH_4 is more likely to be produced in anoxic conditions. The interaction between soil CH_4, soil moisture between 30 and 40 cm, plantation and location was significant. In the different plantations and at different microforms, the expected relationship of soil CH_4 increasing as WTD increased and soil moisture between 30 and 40 cm increased was seen, but not in every microform. It would be expected that soil CH_4 increased as WTD decreased and soil moisture between 30 and 40 cm increased due to a larger volume of anoxic conditions for methanogens to break the peat down, and a lower volume of oxic conditions for methanotrophs to break down the CH_4 (Iiyama et al., 2012; Carlson et al., 2015). Soil moisture at 0–10 cm did not have a significant interaction with soil moisture between 30 and 40 cm or WTD. Furthermore, Manning (2019) found that surface soil moisture correlated with climatic trends and soil moisture between 30 and 40 cm was determined by WTD. We propose that redox potential nearer the surface of the peat is more important than WTD for soil CH_4 fluxes, with CH_4 oxidized to CO_2 regardless of WTD, if the surface of the peat does not inhibit methanotrophs. Finally, soil CH_4 increased as soil temperature decreased. This may be due to seasonality and soil temperatures being cooler when the peat was wetter.

Drain CO_2 and drain CH_4 were controlled by different variables. Drain CO_2, produced from DOC, did not have a significant relationship with the environmental variables but did have a significant relationship with drain type, being higher in the smaller field drains than the larger collection drains. DOC was greater in Sebungan than Sabaju during this measurement period and this was associated with the increased WTD at time of measurement (Cook et al., 2018). This same relationship was not observed in this study for drain CO_2. The smaller field drains may therefore have a higher drain CO_2 flux than the collection drains due to being the first drain that DOC reaches from the soil—after all the field drains feed into the collection drains. Drain CH_4 was controlled by the rate of air temperature in both plantations. This was presumably due to the increase in rate of diffusion for the CH_4 (Billett and Moore, 2008).

Stem CH_4 was controlled by relative humidity, WTD, air temperature, soil temperature and soil moisture. Stem CH_4 reduced as relative humidity increased. We hypothesize that this is due to reduced rates of evapotranspiration at higher relative humidities, from a reduced moisture gradient. Evapotraspiration has been shown to control the rates of stem CH_4 (Pangala et al., 2014). Slowing the rate of water through the xylem would reduce the speed of transport for dissolved CH_4 and thus reduce the rate of stem CH_4. Increasing WTD increased the rate of stem CH_4. This has been seen in a manipulation experiment by Pangala et al. (2014), who found that if there is soil volume between the WTD and plant roots, CH_4 is oxidized before it reaches the roots. Air temperature, soil temperature and soil moisture gave opposite relationships with stem CH_4 at each plantation, with stronger relationships in Sebungan where increasing air temperature, soil temperature and soil moisture all increased stem CH_4. Increasing temperatures would be expected to increase the rate of methanogenesis, whilst increasing soil moisture would reduce the redox potential, also increasing methanogenesis or transport of stem CH_4 to the roots (Pangala et al., 2014). These relationships were negative in Sabaju but had very small effects.

Mitigation Options

The most effective way to reduce carbon losses from oil palm plantations on peat soil is to reduce the rate of R_h. The strong influence of temperature and WTD on R_h suggest that means of controlling soil surface temperatures and WTD are the best means of mitigating carbon losses from the peat. For example, the impact of temperature could be reduced by providing better coverage of the soil surface—particularly when the plantation canopy has not closed. Here, in Sebungan the canopy was closed, soil and air temperatures were lower and the R_h flux was half the rate of Sabaju. In Sabaju, the canopy was open and air temperature increased the rate of R_h at three times the extent in Sebungan. Covering the soil in Sabaju with frond piles lowered the mean soil temperature (harvest path: $28.6 \pm 0.7°C$; frond pile: $27.8 \pm 0.6°C$) and increased mean soil moisture (harvest path: $57.8 \pm 0.9\%$; frond pile $61.6 \pm 1.0\%$); both changes in environmental conditions have been shown to reduce the R_h flux. Jauhiainen et al. (2014) found that R_h could be reduced by 30% if the tropical peat was shaded. Annual R_{tot} was 30% lower beneath the frond pile in Sabaju than from the harvest path—extending the shade could therefore reduce Sabaju R_h to range between 16.9 ± 1.61 and 17.4 ± 0.82 Mg CO_2-C ha^{-1} yr^{-1}, reducing the plantation net carbon losses to between 69.59 ± 0.62 and 71.75 ± 0.65 Mg CO_{2-eq} ha^{-1} yr^{-1}.

Raising the water table is also an effective way of suppressing R_h. This was particularly apparent in Sebungan, where the canopy was closed and temperatures were lower. Sebungan had a lower mean WTD than the RSPO recommendations at the time of measurement and thus fresh peat may have been exposed to heterotrophic bacteria, increasing the rate of R_h from Sebungan (Lim et al., 2012; Mishra et al., 2014; Carlson et al., 2015).

Furthermore, temperature control may be more important than WTD control. Sebungan had a lower WTD than Sabaju but Sabaju had higher rates of R_h. It would be expected that R_h decreased with WTD (Carlson et al., 2015). However, the result from Sabaju did not fit the trend. We propose this is due to the open canopy in Sabaju and thus there being no barrier for the Sun to heat up the peat and increase the rate of its decomposition.

CONCLUSIONS

CO_2 and CH_4 fluxes vary spatially and temporally in oil palm plantations on peat soil. R_{tot} and soil CH_4 fluxes were both higher next to the palm than from the "away from palm" soil surface microforms (the bare soil harvest path, beneath frond piles and beneath cover plants). Drain CO_2 did not differ significantly from the "away from palm" R_{tot} fluxes but drain CH_4 was significantly greater than the "away from palm" soil CH_4 fluxes. CH_4 emitted through the palm stems, after being transported through the xylem from the soil, was measured at both plantations. R_{tot} next to the palm, drain CO_2 and drain CH_4 showed seasonality. Here R_{tot} and drain CO_2 were higher in the dry season than in the rainy season. Drain CH_4 was higher in the rainy season than in the dry season.

Annual CO_2 fluxes varied between the two plantations but annual CH_4 fluxes did not—and were within the range of CH_4 reported from swamp forests in the literature—draining the peat did not reduce the CH_4 flux (here 61.02 ± 17.78 kg CH_4-C ha^{-1} yr^{-1}). R_{tot} from Sabaju and Sebungan were 27.98 ± 0.73 Mg CO_2-C ha^{-1} yr^{-1} and 16.17 ± 0.81 Mg CO_2-C ha^{-1} yr^{-1}, respectively. The larger flux in Sabaju was due to higher R_h measurements: R_h ranged from 23.89 ± 1.07 to 24.39 ± 1.61 Mg CO_2-C ha^{-1} yr^{-1} in Sabaju and 11.13 ± 1.69 to 11.81 ± 0.87 Mg CO_2-C ha^{-1} yr^{-1} in Sebungan.

Plantation carbon losses were dominated by R_h, with drain CO_2, soil CH_4, drain CH_4 and stem CH_4 also contributing, in order of proportion. In Sabaju the plantation carbon losses were between 95.58 ± 0.14 and 97.41 ± 0.17 Mg CO_{2-eq} ha^{-1} yr^{-1}, with 92% of the flux attributed to R_h. In Sebungan, the plantation carbon losses fell within the range of 48.37 ± 0.16 and 50.86 ± 0.19 Mg CO_{2-eq} ha^{-1} yr^{-1}, with 84–85% of the flux made up from R_h. Therefore, the optimal management strategies to reduce plantation carbon losses are to focus on reducing R_h.

We propose shading the peat and raising the WTD to reduce R_h. In Sabaju, where the canopy was open, air temperature dominated the drivers of R_h, with fluxes measured below the frond piles being 30% lower than fluxes measured from the bare soil harvest path. Temperatures were lower in Sebungan, attributed to a closed canopy, and rates of R_h were also lower. In Sebungan, WTD had a significant effect on rates of R_h. WTD was lower in Sebungan than in Sabaju, (Sabaju: −0.49 m; Sebungan: −0.77 m) providing a greater peat volume for R_h.

AUTHOR CONTRIBUTIONS

FM designed and conducted the study, performed the data analysis, and wrote the manuscript. TH and YT were integrally involved in the study design, data interpretation, and writing the manuscript. LK was involved in the study design, data collection, field support, and data interpretation. TC helped with the mixed model analysis.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2019.00037/full#supplementary-material

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