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Immediate environmental impacts of transformation of an oil palm intercropping to a monocropping system in a tropical peatland

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SUMMARY

The expansion of oil palm plantations is one of the greatest threats to carbon-rich tropical peatlands in Southeast Asia. More than half of the oil palm plantations on tropical peatlands of Peninsular Malaysia are smallholder-based, which typically follow varied cropping systems, such as intercropping. In this case study, we compare the immediate biogeochemical impacts of conversion of an oil palm and pineapple intercropping to an oil palm monocropping system. We also assess how these changes affect the subsequent temperature sensitivity of greenhouse gas (GHG) production. We found that peat bulk density is unchanged, while organic matter content, pH and temperature is slightly yet significantly altered after conversion from oil palm intercropping to monocropping. Both *in-situ* and *ex-situ* CO_2 emissions and temperature sensitivity of CO_2 and CH_4 production did not significantly vary between conversion stages; however, *in-situ* CO_2 emissions in monocropping system exhibited a unique positive correlation with moisture. The findings show that some of the defining peat properties, such as bulk density and organic matter content, were mostly conserved immediately after conversion from intercropping to oil palm monocropping. However, there were signs of deterioration in other functional relationships, such as significantly greater CO_2 emissions observed in the wet season to that of the dry season, showing moisture limitation to CO_2 emissions in monocropping, post-conversion. Nevertheless, there is a need for further research to identify the long-term impacts, and also the sustainability of intercropping practices in mature oil palm plantations for the benefit of these peat properties.

KEY WORDS: carbon dioxide, methane, oil palm intercropping, temperature sensitivity, tropical peat

INTRODUCTION

The expansion of oil palm plantations is one of the biggest threats to carbon rich tropical peatlands in Southeast Asia (Wijedasa *et al*. 2018). It is not a coincidence that the rapid expansion of oil palm plantations in recent decades occurred at the same time as when Southeast Asia witnessed the greatest extent of deforestation in the 21st century (Miettinen *et al.* 2012, Hansen *et al.* 2013, Dhandapani 2014). Recent estimates show that smallholder oil palm plantations make a substantial contribution to land-use changes in Southeast Asia (Wijedasa *et al.* 2018). Smallholding plantations also play a major role in oil palm expansion outside Asia in Africa and South America (Sayer *et al.* 2012, Bennett *et al.* 2019).

Smallholder plantations are known to follow less intensive management practices compared to industrial plantations (Azhar *et al.* 2011) and follow varied cropping systems such as intercropping or polyculture (Azhar *et al.* 2015, Azhar *et al.* 2017, Dhandapani *et al.* 2019a, Dhandapani *et al.* 2020a). It is particularly relevant for peatlands in Peninsular Malaysia, where smallholder oil palm plantations cover almost as much area as industrial oil palm. The conversion of natural peatlands to oil palm monocultures increases peat temperature, pH and bulk density, and greatly decreases peat moisture (due to accompanying drainage), organic matter and carbon (C) contents (Cooper *et al.* 2019, Srisunthon & Chawchai 2020). This affects two of the major ecosystem services provided by the peatlands – C storage and hydrological regulation through water storage (Tonks *et al.* 2017). However, intercropping systems have been found to reduce some of the negative effects on defining peat properties, such as carbon content and bulk density, and maintain peat functional relationships such as the negative relationship between peat moisture and peat CO_2 emissions (Dhandapani *et al.* 2019a).

In addition to changing land-use, tropical peatlands are expected to undergo 3 – 4 °C warming by 2100 (IPCC 2013), with warming predicted to be a major driver of future tropical peatland carbon dynamics (Loisel *et al.* 2017). The impact of temperature on soil GHG emissions can be defined by calculating the temperature sensitivity factor, Q_{10} (Oertel *et al.* 2016). As GHGs trap heat and increase atmospheric temperature, there is a strong potential for positive feedback effects, resulting in ongoing increases in GHG emissions and atmospheric temperature (Conant *et al.* 2011). However, in a natural environment such feedbacks are complex, and are moderated by interactions among multiple, highly variable, biotic and abiotic factors (Briones *et al.* 2014, Oertel *et al*. 2016, Jackson *et al.* 2017), which makes it harder to study and infer the impacts of one particular variable such as temperature on GHG emissions *in-situ*. Kirschbaum (1995) suggest that positive feedbacks in the tropics may be less severe than temperate regions, as the C decomposition rate and ecosystem productivity become similar at higher temperatures, while the temperature dependency of decomposition decreases with increasing temperature. Therefore, with controlled studies being scarce for tropical peatlands (Sjögersten *et al.* 2018, Girkin *et al.* 2020b), there are considerable disagreements with the above positive-feedback hypotheses, and there is no clear consensus on this feedback effect (Davidson & Janssens 2006, Conant *et al.* 2011).

Irrespective of the validity of the feedback hypotheses, if the C stored in the peat is transferred to the atmosphere at faster rate, it would drastically affect the global climate, unless there is an increased rate of C uptake from the atmosphere by plants, though this is still a less stable C pool than the more stable peat C store (Strack 2008). This is more complex in degraded tropical peatlands that are naturally submerged systems but are exposed to aerobic conditions by drainage through anthropogenic disturbance. In addition to aerobic conditions in oil palm plantations inhibiting any peat formation, it is plausible that easily degradable homogenous organic matter inputs from oil palm lack the chemical complexity required for tropical peat formation (Kerdraon 2018), when even leaf litter from some forest species lack the required chemical complexity (Yule & Gomez 2009). Soil carbon inputs represent a combination of decaying stem, leaf and root debris (Davidson & Janssens 2006) as well as root exudates (Girkin *et al.* 2018a, Girkin *et al.* 2018b). The release of C from the soil is generally in the form of gas through carbon dioxide (CO_2) and methane (CH_4) emissions, or in the form of fluvial leaching. CO_2 in peat is produced by a combination of root respiration, CH_4 oxidation and microbial decomposition, which together is commonly known as soil/peat respiration (Oertel *et al.* 2016, Girkin *et al.* 2020a, Dhandapani *et al.* 2021b). Root contribution to soil respiration in young oil palm plantations, in particular the sites used in this study, were insignificant (Dhandapani *et al.* 2019b). Nevertheless, any changes in land-use that alter prevailing environmental conditions and microbial community structure (Dhandapani *et al.* 2019c) will significantly affect *in-situ* heterotrophic soil respiration through the regulation of complex biogeochemical interactions (Couwenberg *et al.* 2010, Oertel *et al.* 2016, Dhandapani *et al.* 2021a). However, it is unclear how changes in peat properties, in particular those driven by management, affect the temperature sensitivity of GHG fluxes.

Previous studies of the temperature response of GHG fluxes *ex-situ* have shown variation amongst peats of contrasting botanical origins (Sjögersten *et al.* 2018). These same peats feature significant differences in peat chemistry (Upton *et al.* 2018), and microbial community structure (Troxler *et al.* 2012, Girkin *et al.* 2020c), likely a key driver of these differences. The significant changes in properties driven by the conversion from intact forest to oil palm monocropping and intercropping managements may therefore have a significant effect on both fluxes and their response to changes in prevalent environmental conditions, including warming. It is important to understand greenhouse gas emission responses to increased temperature in these C rich ecosystems.

In general, recent studies on land-use change in tropical peatlands of Peninsular Malaysia show that the conversion of forest to agricultural landscapes affects the belowground microbial ecosystem (Dhandapani *et al.* 2020b) and depletes soil carbon, along with driving changes in soil chemical and physical properties, which are difficult to reverse (Tonks *et al.* 2017, Dhandapani *et al.* 2019a, Dhandapani *et al.* 2021a). However, the effect of conversion between different agricultural systems in tropical peatlands is not known. This is important, because smallholder oil palm plantations are known to practice intercropping in the initial stage of oil palm plantation, which provide them with some income during the non-productive young years of the oil palm lifecycle (Adila *et al.* 2017, Saadun *et al.* 2018, Dhandapani *et al.* 2020a). In North Selangor peatlands, it has been observed that such intercropping is practiced in the early years of the second-generation of the oil palm life cycle (Dhandapani *et al.* 2019a, Dhandapani & Evers 2020), but then converted back to monocropping when oil palm becomes mature and the canopy closes. These conversions from intercropping to monocropping in the region were always accompanied by additional drainage, possibly to avoid potential lower yields (Hashim *et al.* 2019). Despite this common practice, the changes in peat properties that accompany conversion from intercropping to monocropping and accompanying additional drainage is not documented or known.

In this study, we aim to evaluate the direct impacts of conversion of an oil palm intercropping system to a monocropping system, and to understand the impact of this conversion on the regulation of GHG production. We hypothesise (i) that the conversion of an intercropping to a monocropping system significantly reduces surface peat organic content, increases bulk density, and significantly impacts other surface peat properties due to disturbance associated with drainage, harvesting and killing of intercrops that covered most of the surface of the site; (ii) that conversion reduces total CO_2 emissions from peat because of the removal of autotrophic root contributions from intercrop; (iii) that conversion reduces peat CH_4 emissions due to increased drainage; (iv) that functional relationships between peat properties and CO_2 emissions are maintained from before conversion, cohering to common observations in different peat land-uses in the region; (v) that peat after conversion to monocropping has a greater temperature sensitivity, considering that labile carbon input via root exudation from the oil palm monoculture is less than intercropping systems with greater vegetation cover.

METHODS

Study site

The study site used in this research is the same as that reported in Dhandapani *et al.* (2019a) and Dhandapani *et al.* (2019b). The site is in the North Selangor peatlands, the second largest peatland area in Peninsular Malaysia. The site is roughly 2 ha in size. The site was converted from the forest around late 1980s to early 1990s. This location on the southern edge of North Selangor peatlands is of historical importance, as it is adjacent to Thennamaran region where oil palm was first commercially planted in Malaysia.

The oil palm (*Elaeis guineensis* Jacq.) and pineapple intercropping site (3° 25' 20.6" N, 101° 19' 56.6" E; Figure 1) in Kampung Raja Musa was in the second-generation that consisted of approximately one- to two-year old oil palm plants in rows with pineapple (*Ananas comosus* (L.) Merr.) planted densely between the oil palm rows. There were two drainage ditches along the border on the either side of the site, but none within the site. There was stagnant water of 1 to 2 cm over most of the site during wet season measurements. Some open regions without any stagnant water were covered with grass. During dry season measurements, the pineapple plants were fully grown and covered any remaining open spaces between pineapple rows and there was no stagnant water at the surface. The depth of the peat is roughly between 1.5 to 2 metres. This site is referred to as 'Pineapple intercropping'.

The intercropping existed in this second-generation oil palm plantation for approximately three years before being converted to monocropping after the pineapples were harvested. During the conversion to monocropping, two additional drainage ditches were dug to further drain the land. The surface of the converted site was covered with dried pineapple leaves, indicating that biomass from the pineapple crop were not removed from the site The site was also fertilised with animal manure after conversion to monocropping, which is a common practice in smallholder mature oil palm monocultures. The animal waste is usually added in sacks near the mature oil palm stems, with a small opening in each sack pointing towards each oil palm stem. After conversion, no stagnant water was observed during either season of the measurements, and some grass cover was observed in the field during both wet and dry season measurement. The oil palm plantations are older (3 to 4 years of age) in the monocropping system. After conversion, this site is referred to as 'Converted monocropping'.

Sampling strategy

The sampling strategy and other methodologies used for this study are the same as Dhandapani *et al.* (2019a) and Dhandapani *et al.* (2019c).

Sampling was carried out during both wet and dry seasons from November 2016 to December 2018, with only the measurement for wet season 2017–18 missing due to logistical limitations. The conversion to monocropping also happened during this missing season. The wet season sampling was carried out during November 2016 to January 2017, and dry season sampling was carried out during July 2017 for Pineapple intercropping. The site was visited three times each season. After the Pineapple intercropping was converted to oil palm monocropping, the site was visited during July 2018 and December 2018 for dry and wet season measurements, respectively. The conversion to monocropping happened earlier in the year 2018, though the exact month for this land-use conversion is not known.

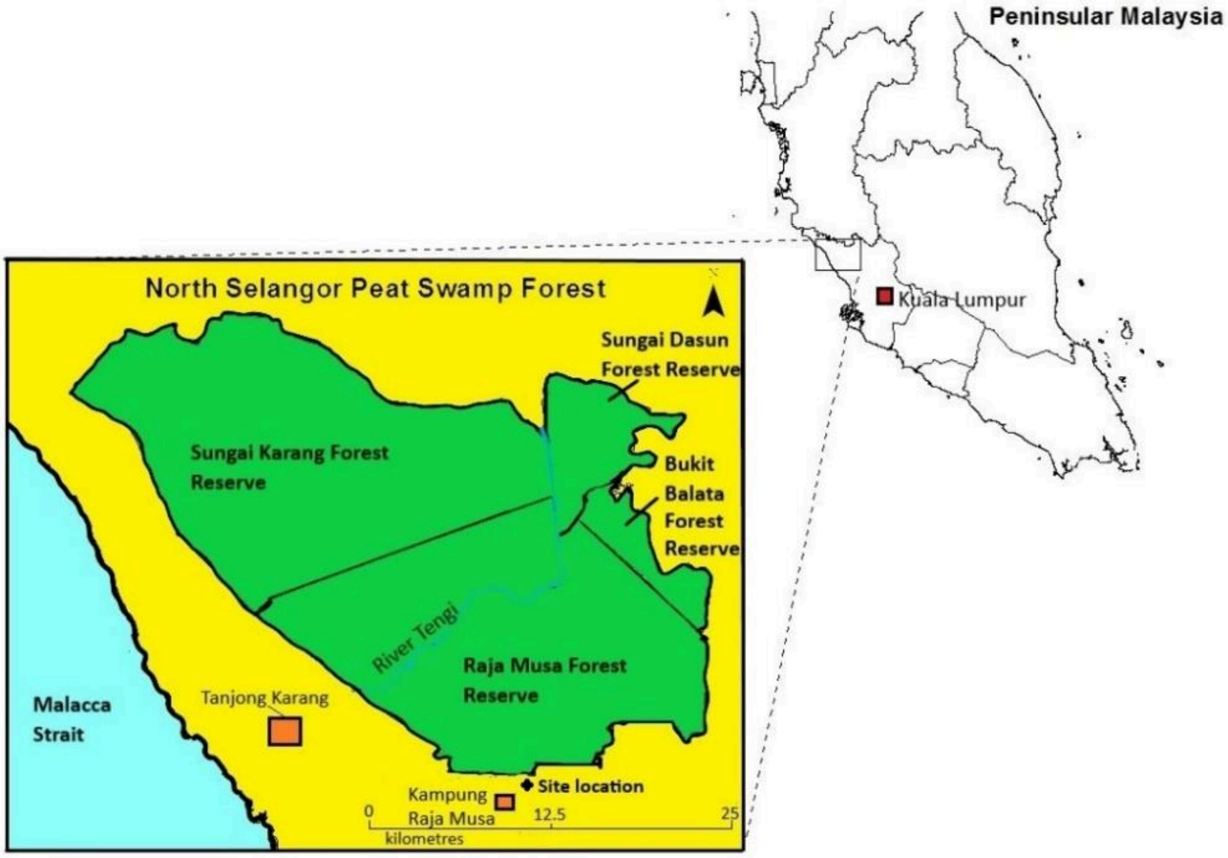

Figure 1. Site location.

The pineapple plants were killed off using a herbicide and left to decompose in the field, which is a typical practice for conversion from intercropping to monocropping by smallholders in the region (Global Environment Centre, personal communication, Aug 2018).

Mean weather data for each sampling period for Kampong Raja Musa, the village where the study site is located, are provided in Table 1 (World Weather Online 2022).

During each site visit, samples were collected from 25 random points distributed over the site. Complete random sampling (except areas with vegetation such as oil palm, pineapple and grass) as described in Dhandapani *et al.* (2019b) was used over other sampling methods to quantify the impact of ecosystem or land-use type as a whole, as opposed to identifying any specific effects such as autotrophic contributions from different crops and sampling locations. However, Dhandapani *et al.* (2019b) show that young oil palm and pineapple crop do not significantly contribute to increase in total peat respiration, and only autotrophic contributions from mature oil palm (>10 years old) significantly increase total peat CO_2 emissions. At each sampling point, greenhouse gas fluxes were measured, and the surface peat (0-5 cm) was collected for laboratory analyses. This resulted in 150 independent sampling points per site, with 75 samples from each season for pineapple intercropping. For converted monocropping, the sample number totalled 50, with 25 samples from each season. Of these, 10 random samples from each season were used for C and N analyses.

***In-situ* greenhouse gas measurements**

CO_2 and CH_4 emissions from soil surface were measured using a Los Gatos® (San Jose, USA) ultraportable greenhouse gas analyser. The gas analyser works on the principle of laser absorption spectroscopy. The instrument gives readings of CH_4, CO_2 and H_2O (ppm) and gas temperature (°C). The measurements were made using closed chamber method using an opaque chamber with a height of 15 cm and an inner diameter of 13.5 cm. The chamber was home-made and had an inlet and an outlet port on the top of the chamber that were connected to the gas analyser, using a quarter inch outer diameter

Table 1. Weather data for each field sampling period. Data obtained from World Weather Online (2022) for Kampong raja Musa where the study area is located. Nov 2016 – Jan 2017 reflects mean value per month.

Units per month	Wet season		Dry season	
	Nov-16 to Jan-17	Dec-18	Jul-17	Jul-18
Rainfall, mm	400	338.9	97.3	116
Rainfall, days	29	30	25	24
Mean temperature, °C	29	29	30	30
Sun hours	357	364	371	372
UV scale	6	6	7	8
Average humidity, %	75.7	78	69	70
Average cloud cover, %	37	33	23	24

polytetrafluoroethylene (PTFE) tube. During each measurement the chamber was carefully inserted into an un-vegetated area of peat to approximately 1 cm depth to provide a good seal. Gas measurements were taken at 20 second intervals for 5 minutes, resulting in at least 12 recorded measurement points for each plot. The gas concentrations in ppm were converted to mg m^{-2} hr^{-1} and µg m^{-2} hr^{-1} for CO_2 and CH_4 respectively, as described in Samuel & Evers (2016), using the Ideal Gas Law (Equation 1):

$$PV = nRT \quad [1]$$

where: P = atmospheric pressure (Pa); V = volume of headspace (cm^3); n = number of moles (mol); R = universal Gas Constant law (8.314 J K^{-1} mol^{-1}) and T = temperature in kelvin (K), with the conversion factors, 1 mol of CO_2 = 44.01 g and 1 mol CH_4 = 16.02 g.

The lag time for the gas concentration change in the chamber to reach the analyser (i.e., the time it takes for the chamber and analyser to reach an equilibrium) was just under a minute for most of our measurements, but to maintain the same standard for all measurements, the first minute of each measurement was discarded. Following omission of the first minute in each measurement period, linear fits of CO_2 concentration increase to sample rate showed an $R^2 > 0.99$ in all instances. CO_2 flux gradients were used as confirmation that CH_4 sampling (of much lower emission rates) within the same chamber may be reliable.

Peat analysis

All the procedures used for laboratory peat analysis are described in detail in Dhandapani *et al.* (2019b). Peat temperature and moisture (for 0-5 cm depth) were measured *in-situ*, using a digital thermometer from Fisher Scientific (Loughborough, UK) and a digital volumetric moisture meter, ThetaProbe® (Delta-T Devices, Cambridge, UK) respectively. During some sampling visits, peat samples (0-5 cm) were collected to measure gravimetric moisture due to failure of the ThetaProbe. Here, fresh peat was dried in an oven at 105 °C for 48 hours. The gravimetric moisture was calculated as the ratio of the mass of the water lost in oven drying to the mass of oven-dried peat.

Peat bulk density samples (0-7cm) were collected by inserting a tube of known volume (20 ml) into the peat surface. The collected peat was then dried in an oven at 105 °C for 48 hours and the dry weight was recorded. The calculated gravimetric moisture was then converted to volumetric moisture using the bulk density data.

For pH measurements, 5 mL volume of peat was suspended in 10 mL deionised water in a centrifuge tube and shaken on a shaker for 30 minutes. The pH of the supernatant was then measured using a pH meter (Mettler Toledo, Leicester, UK). For Converted Monocropping, the pH was measured using a different pH meter, Eutech pH700 supplied by Thermo Scientific (Loughborough, UK).

Oven dried peat samples (105 °C for 48 h) were used to calculate the organic matter content. Dried peat samples were placed in silica crucibles and then transferred to a muffle furnace and maintained at 550 °C for 4 h. The organic matter content was then determined by calculating the loss on ignition using Equation 2:

$$OM = \frac{(soil - ash)}{soil} \times 100 \qquad [2]$$

where: OM = organic matter content (%), *soil* = weight of oven dried soil (g), *ash* = weight of ash (g)

To analyse total C and N content, all samples were oven dried (105 °C for 48 h) and finely ground using a Retsch PM400 ball mill (Verder Scientific, Haan, Germany). Approximately 10 mg of sample was weighed into an aluminium foil cup and the exact weight was recorded. The samples were then transferred to an autosampler attached to a Flash 2000 CHNS-O elemental analyser supplied by Thermo Scientific (Loughborough, UK). The analyser was set at 55 °C oven temperature, with helium as the carrier gas at the flow rate of 140 mL min^{-1}. L-aspartic acid supplied by Sigma Aldrich (St Louis, USA) was used as quality control and peaty soil supplied by Elemental Microanalysis (Okeham, UK) was used as a standard. For converted monocropping, C/N analysis was carried out using a Skalar Primacs series C and N analyser (Breda, The Netherlands).

Temperature sensitivity analysis

Temperature sensitivity was measured under "mesic" moisture conditions following an approach modified from Sjögersten *et al.* (2018) by quantifying production at 20, 25, 30 and 35 °C. Peat samples (12 g dry weight equivalent) were placed in twelve replicate 120 mL glass serum bottles (Kinesis, St. Neots, UK). Bottles containing water-logged fresh peat were allowed to evaporate gradually over one week at 30 °C until there was no free water remaining on the samples, corresponding to field moisture conditions (Sjögersten *et al.* 2018, Girkin *et al.* 2020b). Three replicates were placed in 20, 25, 30 and 35 °C incubators for one month for acclimation.

For measurement of headspace gases, bottles were temporarily removed from their incubators and flushed for one minute with air of known CO_2 and CH_4 concentration (374.97 ± 14.17 and 1.00 ± 0.03 ppm of CO_2 and CH_4 respectively), before sealing with a butyl rubber stopper (13 × 19 × 12 mm; Rubber B.V., Hilversum, NL). Previous incubation studies have predominantly assessed production under anoxic conditions, with bottles flushed with N_2 to displace oxygen (Girkin *et al.* 2018a, Girkin *et al.* 2018b). However, this method is inappropriate for drained aerobic peats. Therefore, flushing bottles with air of known GHG concentrations creates equivalent standardised conditions prior to beginning the incubation. Bottles were then returned to their incubators for 1 hour after which a 5 mL gas sample was collected and analysed.

Gas samples were analysed by gas chromatography (GC 2014, Shimadzu, Milton Keynes, UK) using a 1 mL sampling loop and a molecular sieve column (12 m, 0.53 mm internal diameter). CO_2 and CH_4 concentrations were measured by thermal conductivity and flame ionisation detectors respectively. Fluxes were calculated using the concentration difference between the initial headspace concentrations compared to those measured after one-hour incubation, according to the ideal gas law (Girkin *et al.* 2018).

Potential fluxes were measured on three occasions over two weeks for each peat type. Temperature sensitivity (Q_{10}), describing the change in reaction rates with a 10 °C rise in temperature) of CO_2 and CH_4 production, was calculated using exponential models (Equation 3), where k is the rate constant (Lloyd & Taylor 1994):

$$Q_{10} = e^{10k} \qquad [3]$$

Statistical analysis

All statistical analyses were carried out using Genstat® 17th edition (VSN international, 2017). Significant differences between sites for *in-situ* GHG fluxes and other environmental parameters were evaluated using two-way analysis of variance (ANOVA), incorporating seasons and sites as fixed affects. For the data sets that were not normally distributed, the data was log-transformed. For data that did not meet normality assumption after log-transformation, a non-parametric Kruskal-Wallis test was performed.

Backward stepwise elimination multiple regressions were performed with CO_2 flux as response variables and other environmental parameters as fitted terms. The most non-significant driver is dropped one by one in the regression model, until only significant drivers are left in the model. Backward stepwise regression was not performed for CH_4 because such fluxes did not meet the required normality assumptions even after various transformations.

For *ex-situ* temperature sensitivity data, differences in basal CO_2 and CH_4 fluxes (measured at 25 °C), and differences in the temperature response of GHG production were assessed using a two-way ANOVA. CO_2 and CH_4 fluxes were log-transformed for normality.

RESULTS

In-situ greenhouse gas emissions

CO_2 emissions did not significantly vary between the two conversion stages when the seasons were taken together. Nevertheless, Tukey's multiple comparison tests show that there was no significant difference in CO_2 emissions between the conversion stages in the dry season (mean values of 490 and 440 mg m^{-2} hr^{-1} for intercropping and monocropping respectively). However, for the wet season, CO_2 emissions from monocropping are significantly greater than that of intercropping. CH_4 emissions significantly decreased after conversion from oil palm and pineapple intercropping to oil palm monocropping (Figure 2, Table 2). Both CO_2 and CH_4 emissions also exhibited significant seasonal variations. CO_2 emissions showed a significant interaction between conversion stages and season. This interaction was driven by an increase in CO_2 emissions in converted monocropping from dry season to wet season, where wet season CO_2 emissions (1198 mg m^{-2} hr^{-1}) were more than double those of the dry season (448 mg m^{-2} hr^{-1}). Wet season CH_4 emissions were considerably higher in intercropping before conversion (497 µg m^{-2} hr^{-1}), while CH_4 emissions were very low in the dry season before conversion (11 µg m^{-2} hr^{-1}) and in both seasons after conversion (dry = 1 µg m^{-2} hr^{-1}; wet = 36 µg m^{-2} hr^{-1}).

Peat properties

There was a slight yet significant reduction in organic matter content after conversion from intercropping (wet = 88.91%; dry = 87.54%) to monocropping (wet = 86.62%; dry = 85.50%), though there was no seasonal variation or significant interaction either before or after conversion (Figure 3a, Table 2). However, Tukey's multiple comparison test showed that there was no significant difference in peat organic matter content between conversion stages or between seasons (Figure 3a). Peat moisture was significantly higher before conversion in both wet

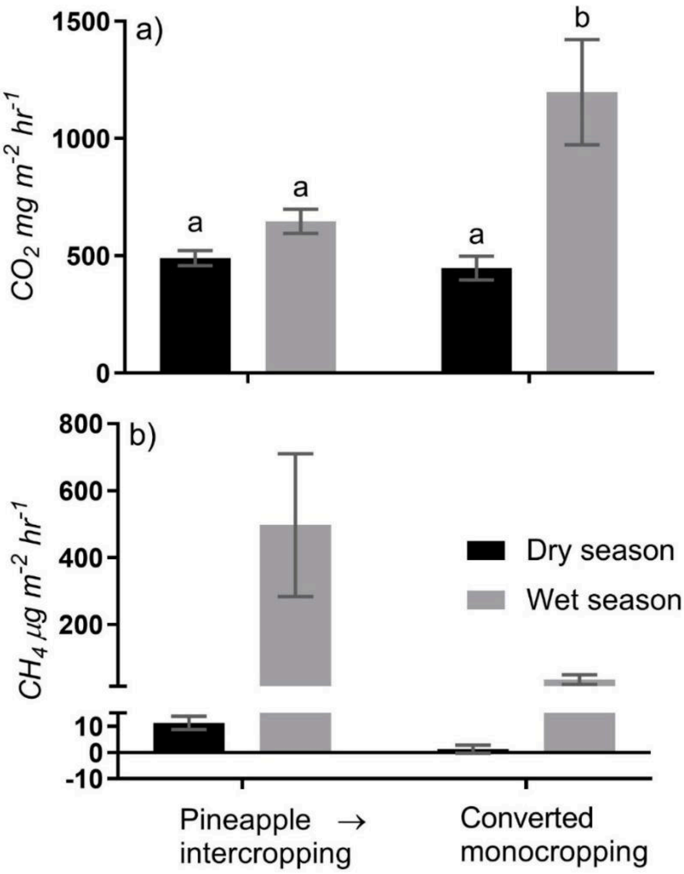

Figure 2. Effect of conversion and season upon (a) CO_2 emissions, (b) CH_4 emissions from peat in the studied site during dry (black) and wet (grey) seasons. Bars denote mean values (n=74 for pineapple intercropping wet season, n=75 for pineapple intercropping dry season, and n= 25 each for wet and dry season in converted monocropping) and whiskers denote standard errors. Bars with different letters show that they significantly differ from each other according to Tukey's multiple comparison test.

and dry seasons, with the wet season having significantly higher moisture levels than dry season both before and after conversion (Figure 3b, Table 2). There was a significant increase in pH after conversion from intercropping to monocropping, however the pH was well below 4 in all conversion stages and seasons (Figure 3c). Even though the pH changes between seasons were not significant, pH showed significant interaction between conversion stage and seasons due to slight increase in pH from dry to wet season before conversion, and no significant change in pH from dry to wet season after conversion. There was slight yet significant increase in temperature after conversion from intercropping to monocropping (Figure 3d, Table 2). There was also a slight yet significant increase in temperature in the wet season compared to the dry season for monocropping. There was no significant interaction between conversion stage and season for temperature (Table 2).

Total N content significantly increased ($F_{(1,18)}$ = 249, $p < 0.001$), while the C content ($F_{(1,18)}$ = 14.04, p = 0.001) and C/N ($F_{(1,18)}$ = 159, $p < 0.001$) decreased after conversion from intercropping to monocropping (Figure 4). There was no significant change in bulk density after the conversion of intercropping to monocropping (Figure 4; $F_{(1,33)}$ = 0, p = 0.950).

In-situ **functional correlations with CO_2 emissions**

Backward step-wise elimination multiple regression showed that CO_2 emissions in the pineapple intercropping site were positively correlated with pH and negatively correlated with moisture (Figure 5a and 5b; Pineapple Intercropping multiple regression: $F_{(2,148)}$ = 9.08, $p < 0.001$, R^2 = 0.098). In converted monocropping, CO_2 emissions were positively correlated with moisture and temperature (Figure 5c and 5d; Converted Monocropping multiple regression: $F_{(2,48)}$ = 7.51, p = 0.002, R^2 = 0.213).

Temperature sensitivity assay

There were no significant differences in basal (25 °C) CO_2 or CH_4 production between conversion stages (CO_2: $F_{(1,8)}$=9.39, p=0.092; CH_4: $F_{(1,8)}$=1.45, p=0.35).

CO_2 fluxes increased significantly with temperature (Figure 6, Table 3), but there was no significant difference in fluxes between conversion stages (Table 3). There was no significant change in CH_4 fluxes to increased temperature (Figure 6, Table 3).

Mean Q_{10} values for CO_2 ranged from 0.61 to 3.80 (Table 4) but there was no significant difference between conversion stages ($F_{(1,2)}$ = 45.26, p = 0.09). Q_{10} values for CH_4 fluxes were < 1 (Table 4) for peat in pineapple intercropping and following conversion, and there was no significant difference between the two ($F_{(1,2)}$ = 0.05, p = 0.85).

Table 2. Two-way ANOVA for peat properties, showing statistical significance of the effects of conversion, season and the interactions between conversion stage and season. Statistically significant figures are presented in bold italics.

	Conversion stage	Season	Conversion*Season
$logCO_2$	$F_{(1,195)}$ = 3.06, p = 0.082	$F_{(1,195)}$ = 18.3, ***p < 0.001***	$F_{(1,195)}$ = 9.46, ***p = 0.002***
CH_4 (Kruskall-Wallis)	H = 4.823, ***p = 0.028***	H = 31.3, ***p < 0.001***	N/A
Organic Matter %	$F_{(1,197)}$ = 4.17, ***p = 0.043***	$F_{(1,197)}$ = 2.04, p = 0.154	$F_{(1,197)}$ = 0.01, p = 0.909
Moisture	$F_{(1,196)}$ = 23.2, ***p < 0.001***	$F_{(1,196)}$ = 41.0, ***p < 0.001***	$F_{(1,196)}$ = 0.08, p = 0.772
pH	$F_{(1,197)}$ = 71.33, ***p < 0.001***	$F_{(1,197)}$ = 3.71, p = 0.055	$F_{(1,197)}$ = 12.43, ***p < 0.001***
Temperature	$F_{(1,185)}$ = 82.1, ***p < 0.001***	$F_{(1,185)}$ = 11.26, ***p < 0.001***	$F_{(1,185)}$ = 2.71, p = 0.101

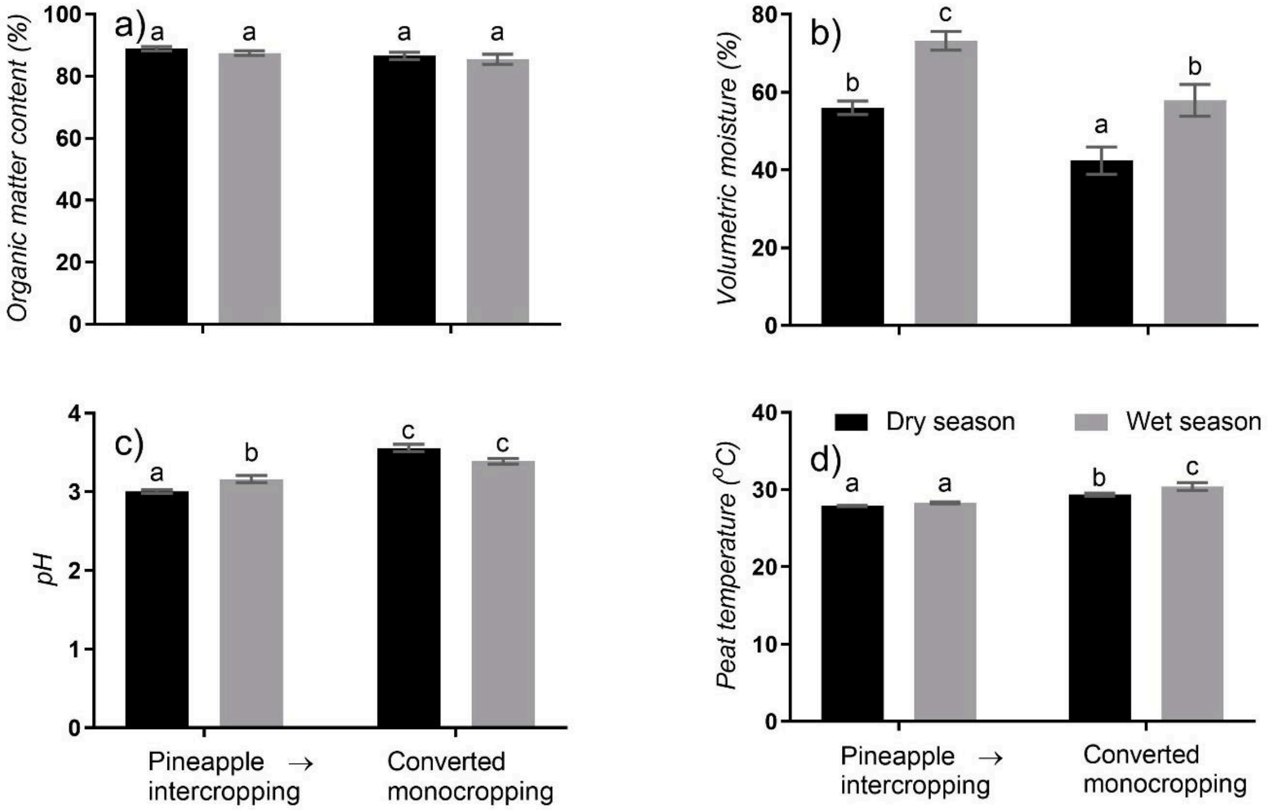

Figure 3. Effect of conversion and season upon (a) organic matter content (b) moisture (c) pH (d) temperature of peat in the studied site during dry (black) and wet (grey) seasons. Bars denote mean values (n = 75 for each season in Pineapple intercropping; n = 25 for each season in converted monocropping), and whiskers denote standard errors. Bars with different letters show that they significantly differ from each other according to Tukey's multiple comparison test.

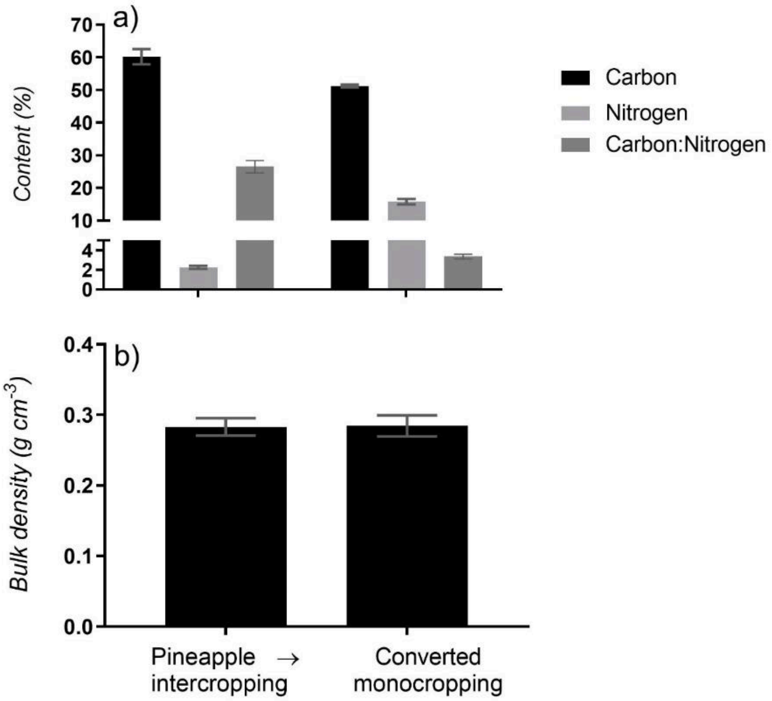

Figure 4. Effect of conversion upon (a) carbon, nitrogen, carbon:nitrogen ratio (C/N) (b) bulk density of peat in the studied site. Bars denote mean values (n=10) and whiskers denote standard errors.

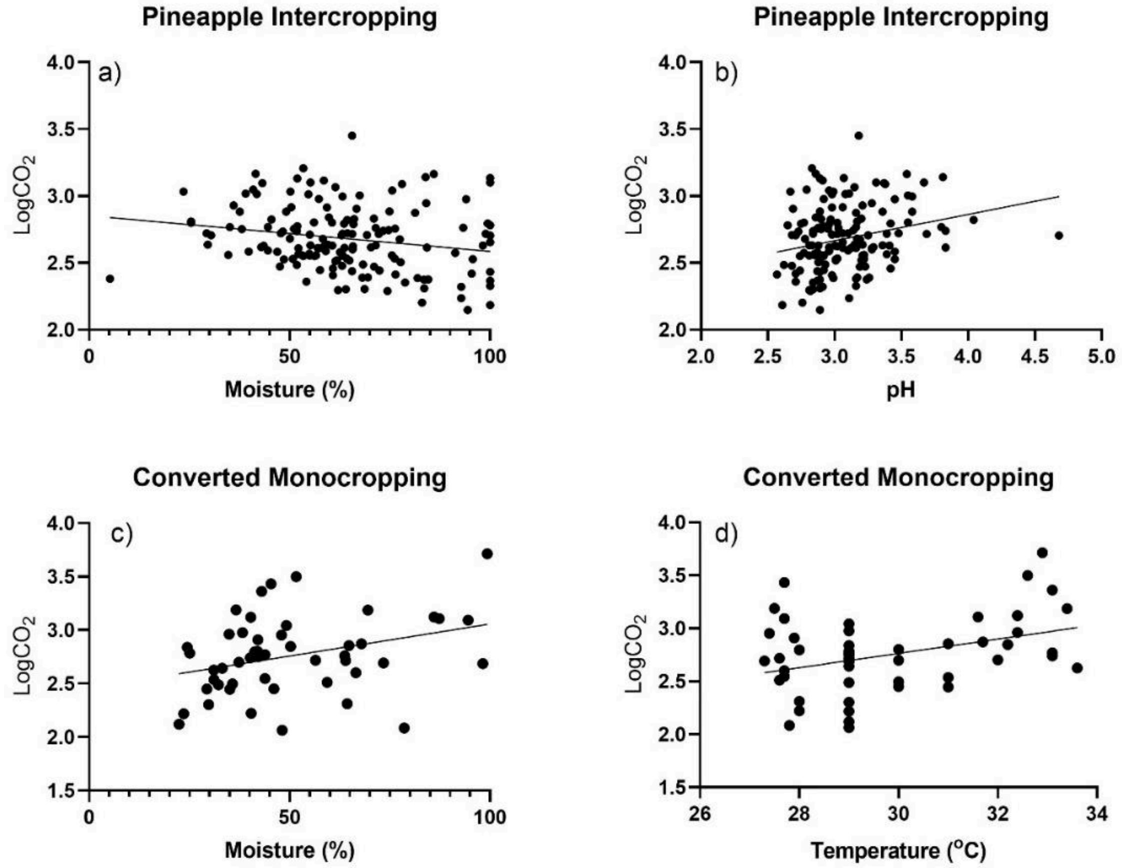

Figure 5. Relationship between (a) logCO_2 and moisture in Pineapple Intercropping (b) logCO_2 and pH in Pineapple Intercropping (c) logCO_2 and moisture in Converted Monocropping (d) logCO_2 and moisture in Converted Monocropping.

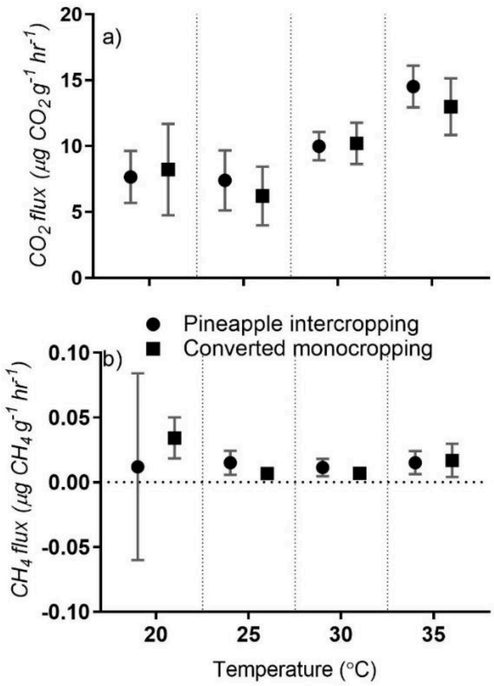

Figure 6. Potential production of (a) CO_2 and (b) CH_4 at 20 – 35°C. Mean values are presented (n=3), and whiskers denote standard errors.

Table 3. Two-way ANOVA for CO_2 and CH_4 production at 20 - 35°C. Statistically significant figures are presented in bold italics.

	Conversion stage	Temperature	Conversion*Temperature
logCO_2	$F_{(1,63)} = 2.81$, $p = 0.099$	***$F_{(3,63)} = 3.6$, $p = 0.018$***	$F_{(3,63)} = 0.93$, $p = 0.429$
logCH_4	$F_{(1,61)} = 0.57$, $p = 0.152$	$F_{(3,61)} = 2.01$, $p = 0.123$	$F_{(3,61)} = 0.40$, $p = 0.752$

Table 4. Calculated Q_{10} for CO_2 and CH_4 fluxes. Mean ± 1 standard error.

CO_2	Q_{10}	R^2	Best fit
Pineapple intercropping	2.32 ± 0.37	0.84	Exponential growth
Converted monocropping	3.37 ± 0.29	0.78	Exponential growth
CH_4	Q_{10}	R^2	Best fit
Pineapple intercropping	0.85 ± 0.13	0.58	Exponential decay
Converted monocropping	0.8 ± 0.13	0.54	Exponential decay

DISCUSSION

Soil organic matter content is a parameter generally used for classification of peats (RSPO 2019), and bulk density is considered an intrinsic peat characteristic by the FAO (Andriesse 1988) that influences several other defining peat characteristics and functional properties. In a previous study (Dhandapani *et al.* 2019a), we showed that oil palm intercropping in tropical peatlands can ameliorate the negative impact on defining peat properties, such as organic matter content and bulk density, following conversion from forest to oil palm plantations. We have now shown that the previously observed ameliorating effect of the intercropping is carried over even after conversion to monocropping in the short term with only a slight reduction in organic matter content and no significant change in bulk density. However, there were indications of a deterioration in the functional relationship between moisture and CO_2 emissions (relative to such relationships in natural forested peatlands), which show strong negative correlations between moisture and peat CO_2 emissions (Dhandapani *et al.* 2019c), and significant seasonal variations in CO_2 emissions between wet and dry seasons. Similar studies in other tropical systems found similar results of improved soil properties and favourable ecosystem functioning in intercropping relative to oil palm or other such monocultures (Wang *et al.* 2015, Ashton-Butt *et al.* 2018, Ashraf *et al.* 2019, Chen *et al.* 2019), but the immediate and long-term impact of conversion of such soil systems after intercropping cycle is not well documented.

Even though the bulk density of surface peat in the site, both before and after conversion to monocropping, was higher than that reported in drained and disturbed peatlands, including secondary forests (Tonks *et al.* 2017, Dhandapani *et al.* 2019a, Sinclair *et al.* 2020) or even some first-generation oil palm monocultures (Tonks *et al.* 2017), it is still considerably lower than what is observed in the second-generation oil palm monocropping in the region with no history of intercropping (Dhandapani *et al.* 2019a). This is important as the bulk density of 0.43 g cm^{-3} observed in second-generation monocropping (Dhandapani *et al.* 2019a) is quite close to the upper limit for tropical peatlands as defined by FAO (Andriesse 1988), and which can have serious consequences on other peat organic matter properties and negative impacts on wider peat ecosystem services, such as water and C storage (Andriesse 1988, Tonks *et al.* 2017). Such high bulk density values could result in de-classification of these peatlands for oil palm certification and conservation purposes in the region. This is especially important as currently many oil palm plantations in peat in the region are entering the second-generation of monocropping (Dhandapani *et al.* 2020a).

Organic matter content was slightly yet significantly reduced after conversion from intercropping to monocropping; however, it is much higher than second-generation continuous monocropping system of similar age in the same peat dome reported by Dhandapani *et al.* (2019a). This may be due to relatively greater and more diverse organic matter inputs in the intercropping system compared to oil palm monocultures. The organic matter waste from the removal of the pineapple crop were left in the field, which possibly helped in further sustaining the organic matter properties after conversion of intercropping to monocropping. In comparison, the second-generation of continuous monocropping reported by Dhandapani *et al.* (2019a) in the same peat dome, only few hundred metres away from this study site, contains peat with only 54% organic matter. This is less than 65% of organic matter content set by the Roundtable on Sustainable Palm Oil (RSPO 2019) for a site to remain classified as a peatland, although this still can be classified as peat under other published definitions of 45 % organic content (Osaki *et al.* 2016). RSPO and local governmental regulations mean that this specific property is particularly important both for oil palm certification and conservation regulations. Our findings suggest that these beneficial and defining properties were not greatly impacted immediately after conversion from intercropping to monocropping where this also involved increased drainage.

The surface peat moisture levels were significantly lower in monocropping following conversion than in intercropping (Figure 3b). The decrease in moisture after conversion is directly linked to increased drainage from the construction of two additional ditches in the site and potentially increased evaporation due to increased exposure to sunlight of a larger area of peat surface. Several factors such as increased water use efficiency and microclimate in the oil palm intercropping system, as observed in mineral soils (Balasundram *et al.* 2006, Ashraf *et al.* 2019), or higher moisture retention due to low bulk density and high organic content (Archer & Smith 1972, Tonks *et al.* 2017), may have further influenced the higher moisture condition in the intercropping site before conversion. The first hypothesis is partially validated by the observation that peat surface temperature, moisture and pH were significantly changed after conversion, however, changes after conversion were minimal for important defining peat properties such as organic matter content and bulk density.

Even though there were significant changes in relevant peat physio-chemical properties such as pH, moisture and temperature after conversion, mean total peat CO_2 emissions did not significantly change after conversion for dry season measurements. However, peat CO_2 emissions from wet season monocropping was significantly greater than all the other measurement periods. Such greater emissions in the wet season were previously observed only for second-generation continuous monocropping in the region, while the other land-uses such as primary forests, secondary forest, first-generation monocropping, cleared peatlands or burnt peatlands or different second-generation intercropping systems, were found to not show significant variations in CO_2 emissions between seasons (Dhandapani *et al.* 2019a, Dhandapani *et al.* 2019c). The mean CO_2 emissions in the dry season for both intercropping and monocropping, and in the wet season for intercropping, were within the range reported for agricultural peatlands in the North Selangor region (Dhandapani *et al.* 2019a); however, the wet season CO_2 emissions for monocropping were markedly higher than previously observed CO_2 emissions from Selangor peatlands of any land-use.

One notable characteristic observed was the moisture limitation of CO_2 production observed in the site immediately after conversion (Figure 5c), similar to a second-generation monocropping site reported in Dhandapani *et al.* (2019a). This positive correlation between moisture and CO_2 is unusual for agricultural peatlands in the region (Couwenberg *et al.* 2010, Hergoualc'h *et al.* 2017, Wakhid *et al.* 2017), however, it is commonly observed in dry inland mineral soils (Werner *et al.* 2006).

The lack of significant change in CO_2 in the dry season after conversion from intercropping to monocropping was unforeseen, considering the autotrophic contribution from large portion of the belowground root system is affected by the removal of pineapple crop. However, there may be a significant contribution from decomposing pineapple leaves and the root system that were left over from clearing of the pineapple crop in the conversion to monocropping. Pineapple crops have shallow root systems (around 0.85 m deep) although they can extend up to a 2 m radius around the plant stem (DAF 2009). Dhandapani *et al.* (2019b) found CO_2 emissions were not influenced by distance from the pineapple plants and inferred that this is possibly due to the pineapple roots contributing to fluxes at all sampling points in the site, as none of the measurements were more than 1 m away from a nearby pineapple crop (Dhandapani *et al.* 2019b). It is possible that autotrophic contribution to total peat CO_2 emissions from live pineapple roots were replaced by heterotrophic decomposition of dead pineapple roots after conversion. Further measurement of CO_2 emissions after complete decomposition of pineapple roots and leaves would provide more information on the autotrophic contribution of pineapple root system, and longer-term impact of this conversion. Thus, our second hypothesis that total peat CO_2 emissions decrease immediately after conversion of intercropping to monocropping was rejected as total emissions did not significantly differ between conversion stages, although the scale of seasonal change in emissions was altered after conversion. This functional change in relationship between CO_2 and moisture conditions, and significantly greater CO_2 emissions in the wet season after conversion, which is not commonly observed for any peat land-use in the region, shows that our fourth hypothesis is not validated.

The reduction in CH_4 emissions following conversion was expected because of the increased drainage during conversion to monocropping. This was additionally supported by killing of pineapple plants with adventitious root system that were found to increase CH_4 emissions in tropical peatlands irrespective of the moisture level (Dhandapani *et al.* 2019b). This may be due to the differences in root exudate and oxygen inputs and consequent changes in rhizosphere and peat microbial communities that can significantly impact CH_4 emissions (Girkin *et al.* 2018a, Dhandapani *et al.* 2019c, Girkin *et al.* 2020a). CH_4 emissions were reduced after conversion as expected, validating the third hypothesis.

The temperature sensitivity for CO_2 emissions did not significantly vary after conversion from intercropping to monocropping. Mature first-generation oil palm plantations in the region have been found to have more recalcitrant peat because of the loss of labile carbon due to the longer duration since drainage which allows aerobic decomposition of labile carbon (Tonks *et al.* 2017, Cooper *et al.* 2019). However, the studied newly converted monocropping field still contained labile carbon in the form of decomposing pineapple leaves and roots in the system, and the temperature sensitivity did not significantly vary after conversion from intercropping to monocropping, thus rejecting the fifth hypothesis. The Q_{10} for CO_2 production is notably higher than previous observations for pristine peat from Peninsular Malaysia (Girkin *et al.* 2020b) and a range of Neotropical peats (Sjögersten *et al.* 2018, Girkin *et al.* 2020b). This may be due to the higher water table in both Malaysian pristine peatland (Dhandapani *et al.* 2019c) and Neotropical peatlands in Panama (Sjögersten *et al.* 2018), which supports a rich labile carbon store, whilst such labile carbon is lost over time in oil palm plantations (Tonks *et al.* 2017, Cooper *et al.* 2019). This is in line with "Carbon-quality temperature hypothesis" postulated by Sjögersten *et al.* (2018) that the temperature sensitivity increases with increased recalcitrance because of the higher energy requirement for aerobic decomposition. The *ex-situ* CH_4 production remained low and was unaffected by the conversion or by temperature changes, further confirming the previous field observations that southeast Asian tropical peatlands are low methane emitting systems compared to peatlands of other geographical regions (Couwenberg *et al.* 2010).

In conclusion, in this case study, some of the defining characteristics of peatlands such as peat organic matter content and bulk density were mostly conserved in monocropping immediately after conversion from intercropping. Nevertheless, there were signs of deterioration in functional relationships immediately after conversion, such as significant variations in CO_2 emissions between seasons, and positive relationship between moisture content and CO_2 emissions. However, there is a need for expanded research to understand the long-term impacts of practicing intercropping in early stages of oil palm age. There is also a need for further research into the sustainability of such intercropping practices even after the palm grows older in the later stages of plantations to prolong these peat properties in the longer term. We also found no significant difference in total CO_2 emissions from peat after conversion from intercropping to monocropping, where the pineapple intercrops were removed. It should be noted that this effect is specific to pineapple crop, which may be different for other intercrops with greater biomass allocation to roots. Pineapple is the most commonly intercropped plant with oil palm, however, rare instances of crops such as cassava (Dhandapani *et al.* unpublished data), yam (Dhandapani *et al.* 2019a) and banana (Dhandapani & Evers 2020) were also found to be intercropped by certain smallholders in the region. Thus, there is a further need to research the environmental impacts of different oil palm intercropping systems to understand the regional impact of intercropping practiced by smallholders. Although this study, along with other limited research on this subject, report some indications in the field showing environmental benefits of oil palm intercropping over monocropping systems in tropical peatlands, there is a lack of long-term regional data on environmental and social sustainability of oil palm intercropping by smallholding farmers.

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AUTHOR CONTRIBUTIONS

SD originated and planned the work, carried out the field work, lab and statistical analyses, wrote the first draft, led subsequent editing, and is the lead and corresponding author; NTG designed and carried out incubation experiment and relevant analyses, wrote first draft for the methods and results of incubation experiment, and contributed to the editing of final manuscript. SE, KR & SS contributed to editing of the manuscript.

REFERENCES

Adila, N., Sasidhran, S., Kamarudin, N., Puan, C.L., Azhar, B., Lindenmayer, D.B. (2017) Effects of peat swamp logging and agricultural expansion on species richness of native mammals in Peninsular Malaysia. *Basic and Applied Ecology*, 22, 1–10.

Andriesse, J. (1988) *Nature and Management of Tropical Peat Soils*. Food and Agriculture Organization (FAO) of the United Nations, Rome, 181 pp.

Archer, J.R., Smith, P.D. (1972) The relation between bulk density, available water capacity and air capacity of soils. *Journal of Soil Science*, 23, 475–480.

Ashraf, M., Sanusi, R., Zulkifli, R., Tohiran, K.A., Moslim, R., Ashton-Butt, A., Azhar, B. (2019) Alley-cropping system increases vegetation heterogeneity and moderates extreme microclimates in oil palm plantations. *Agricultural and Forest Meteorology*, 276–277, 107632, 9 pp.

Ashton-Butt, A., Aryawan, A.A.K., Hood, A.S.C., Naim, M., Purnomo, D., Suhardi, Wahyuningsih, R., Willcock, S., Poppy, G.M., Caliman, J.-P., Turner, E.C., Foster, W.A., Peh, K.S.-H., Snaddon, J.L. (2018) Understory vegetation in oil palm plantations benefits soil biodiversity and decomposition rates. *Frontiers in Forests and Global Change*, 1, 10, 13 pp.

Azhar, B., Lindenmayer, D.B., Wood, J., Fischer, J., Manning, A., McElhinny, C., Zakaria, M. (2011) The conservation value of oil palm plantation estates, smallholdings and logged peat swamp forest for birds. *Forest Ecology and Management*, 262, 2306–2315.

Azhar, B., Saadun, N., Puan, C.L., Kamarudin, N., Aziz, N., Nurhidayu, S., Fischer, J. (2015) Promoting landscape heterogeneity to improve the biodiversity benefits of certified palm oil production: Evidence from Peninsular Malaysia. *Global Ecology and Conservation*, 3, 553–561.

Azhar, B., Saadun, N., Prideaux, M., Lindenmayer, D.B. (2017) The global palm oil sector must change to save biodiversity and improve food security in the tropics. *Journal of Environmental Management*, 203, 457–466.

Balasundram, S.K., Robert, P.C., Mulla, D.J., Allan, D.L. (2006) Relationship between oil palm yield and soil fertility as affected by topography in an Indonesian plantation. *Communications in Soil Science and Plant Analysis*, 37, 1321–1337.

Bennett, A., Ravikumar, A., McDermott, C., Malhi, Y. (2019) Smallholder oil palm production in the Peruvian Amazon: Rethinking the promise of associations and partnerships for economically sustainable livelihoods. *Frontiers in Forests and Global Change*, 2, 14, 16 pp.

Briones, M.J.I., McNamara, N.P., Poskitt, J., Crow, S.E., Ostle, N.J. (2014) Interactive biotic and abiotic regulators of soil carbon cycling: evidence from controlled climate experiments on peatland and boreal soils. *Global Change Biology*, 20, 2971–2982.

Chen, C., Liu, W., Wu, J., Jiang, X., Zhu, X. (2019) Can intercropping with the cash crop help improve the soil physico-chemical properties of rubber plantations? *Geoderma*, 335, 149–160.

Conant, R.T., Ryan, M.G., Ågren, G.I., Birge, H.E., Davidson, E.A., Eliasson, P.E., Evans, S.E., Frey, S.D., Giardina, C.P., Hopkins, F.M., Hyvönen, R., Kirschbaum, M.U.F., Lavallee, J.M., Leifeld, J., Parton, W.J., Megan Steinweg, J., Wallenstein, M.D., Martin Wetterstedt, J.Å., Bradford, M.A. (2011) Temperature and soil organic matter decomposition rates - synthesis of current knowledge and a way forward. *Global Change*

Biology, 17, 3392–3404.

Cooper, H.V., Vane, C.H., Evers, S., Aplin, P., Girkin, N.T., Sjögersten, S. (2019) From peat swamp forest to oil palm plantations: The stability of tropical peatland carbon. *Geoderma*, 342, 109–117.

Couwenberg, J., Dommain, R., Joosten, H. (2010) Greenhouse gas fluxes from tropical peatlands in south-east Asia. *Global Change Biology*, 16, 1715–1732.

DAF (2009) Chapter 01: The pineapple. In: *Pineapple Best Practice Manual*, Australian Government Department of Agriculture and Water Resources, Canberra, 1–15.

Davidson, E.A., Janssens, I.A. (2006) Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature*, 440, 165–173.

Dhandapani, S. (2014) *Biodiversity Loss Associated with Oil Palm Plantations in Malaysia: Serving the Need versus Saving the Nature*. MSc thesis, Lancaster University, Lancaster, UK, 41 pp.

Dhandapani, S., Evers, S. (2020) Oil palm 'slash-and-burn' practice increases post-fire greenhouse gas emissions and nutrient concentrations in burnt regions of an agricultural tropical peatland. *Science of The Total Environment*, 742, 140648, 13 pp.

Dhandapani, S., Ritz, K., Evers, S., Sjögersten, S. (2019a) Environmental impacts as affected by different oil palm cropping systems in tropical peatlands. *Agriculture, Ecosystems & Environment*, 276, 8–20.

Dhandapani, S., Ritz, K., Evers, S., Sjögersten, S. (2019b) GHG emission under different cropping systems in some Histosols of Malaysia. *Geoderma Regional*, 18, e00229, 8 pp.

Dhandapani, S., Ritz, K., Evers, S., Yule, C.M., Sjögersten, S. (2019c) Are secondary forests second-rate? Comparing peatland greenhouse gas emissions, chemical and microbial community properties between primary and secondary forests in Peninsular Malaysia. *Science of The Total Environment*, 655, 220–231.

Dhandapani, S., Girkin, N.T., Evers, S., Ritz, K., Sjögersten, S. (2020a) Is intercropping an environmentally-wise alternative to established oil palm monoculture in tropical peatlands? *Frontiers in Forests and Global Change*, 3, 70, 8 pp.

Dhandapani, S., Ritz, K., Evers, S., Cooper, H., Tonks, A., Sjögersten, S. (2020b) Land-use changes associated with oil palm plantations impact PLFA microbial phenotypic community structure throughout the depth of tropical peats. *Wetlands*, 40, 2351–2366.

Dhandapani, S., Evers, S., Ritz, K., Sjögersten, S. (2021a) Nutrient and trace element concentrations influence greenhouse gas emissions from Malaysian tropical peatlands. *Soil Use and Management*, 37, 138–150.

Dhandapani, S., Girkin, N.T., Evers, S. (2021b) Spatial variability of surface peat properties and carbon emissions in a tropical peatland oil palm monoculture during a dry season. *Soil Use and Management,* 38, 381–395.

Girkin, N.T., Turner, B.L., Ostle, N., Craigon, J., Sjögersten, S. (2018a) Root exudate analogues accelerate CO_2 and CH_4 production in tropical peat. *Soil Biology and Biochemistry*, 117, 48–55.

Girkin, N.T., Turner, B.L., Ostle, N., Sjögersten, S. (2018b) Composition and concentration of root exudate analogues regulate greenhouse gas fluxes from tropical peat. *Soil Biology and Biochemistry*, 127, 280–285.

Girkin, N., Vane, C.H., Turner, B., Ostle, N., Sjogersten, S. (2020a) Root oxygen mitigates methane fluxes in tropical peatlands. *Environmental Research Letters,* 15, 064013, 11 pp.

Girkin, N.T., Dhandapani, S., Evers, S., Ostle, N., Turner, B.L., Sjögersten, S. (2020b) Interactions between labile carbon, temperature and land use regulate carbon dioxide and methane production in tropical peat. *Biogeochemistry*, 147, 87–97.

Girkin, N.T., Lopes dos Santos, R.A., Vane, C.H., Ostle, N., Turner, B.L., Sjögersten, S. (2020c) Peat properties, dominant vegetation type and microbial community structure in a tropical peatland. *Wetlands* 40, 1367–1377.

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O., Townshend, J.R.G. (2013) High-resolution global maps of 21st-century forest cover change. *Science*, 342, 850–853.

Hashim, S.A., Teh, C.B.S., Ahmed, O.H. (2019) Influence of water table depths, nutrients leaching losses, subsidence of tropical peat soil and oil palm (*Elaeis guineensis* Jacq.) seedling growth. *Malaysian Journal of Soil Science*, 23, 13–30.

Hergoualc'h, K., Hendry, D.T., Murdiyarso, D., Verchot, L.V. (2017) Total and heterotrophic soil respiration in a swamp forest and oil palm plantations on peat in Central Kalimantan, Indonesia. *Biogeochemistry*, 135, 203–220.

IPCC (2013) *Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the*

Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1522 pp.

Jackson, R.B., Lajtha, K., Crow, S.E., Hugelius, G., Kramer, M.G., Piñeiro, G. (2017) The ecology of soil carbon: Pools, vulnerabilities, and biotic and abiotic controls. *Annual Review of Ecology, Evolution, and Systematics*, 48, 419–445.

Kerdraon, D. (2017) *The Effects of Forest Degradation on Soil Carbon Dynamics in the Tropics*. PhD thesis, Lancaster University, Lancaster, UK, 147 pp.

Kirschbaum, M.U.F. (1995) The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage. *Soil Biology and Biochemistry*, 27, 753–760.

Lloyd, J., Taylor, J.A. (1994) On the temperature dependence of soil respiration. *Functional Ecology*, 8, 315–323.

Loisel, J., Yu, Z., Beilman, D.W., Kaiser, K., Parnikoza, I. (2017) Peatland ecosystem processes in the maritime Antarctic during warm climates. *Scientific Reports*, 7, 12344, 9 pp.

Miettinen, J., Hooijer, A., Tollenaar, D., Malins, C., Vernimmen, R., Shi, C., Liew, S.C. (2012) *Historical Analysis and Projection of Oil Palm Plantation Expansion on Peatland in Southeast Asia*. White Paper Number 17, International Council on Clean Transportation, Washington DC, 51 pp.

Oertel, C., Matschullat, J., Zurba, K., Zimmermann, F., Erasmi, S. (2016) Greenhouse gas emissions from soils—A review. *Geochemistry*, 76, 327–352.

Osaki, M., Hirose, K., Segah, H., Helmy, F. (2016) Tropical peat and peatland definition in Indonesia. In: Osaki, M., Tsuji, N. (eds.) *Tropical Peatland Ecosystems*, Springer, Tokyo, 137–147.

RSPO (2019) *Revision of RSPO Organic & Peat Soil Classification*. Online at: https://rspo.org/principles-and-criteria-review/revision-of-rspo-organic-and-peat-soil-classification, accessed 24 Mar 2022.

Saadun, N., Lim, E.A.L., Esa, S.M., Ngu, F., Awang, F., Gimin, A., Johari, I.H., Firdaus, M.A., Wagimin, N.I., Azhar, B. (2018) Socio-ecological perspectives of engaging smallholders in environmental-friendly palm oil certification schemes. *Land Use Policy*, 72, 333–340.

Samuel, M.K., Evers, S. (2016) Tropical peatland carbon emissions from oil palm plantations microsites. Abstract No. A039, *Proceedings of the 15th International Peat Congress (Volume 2)*, International Peat Society, Kuching, Malaysia, 6 pp.

Sayer, J., Ghazoul, J., Nelson, P., Boedhihartono, A. K. (2012) Oil palm expansion transforms tropical landscapes and livelihoods. *Global Food Security*, 1, 114–119.

Sinclair, A.L., Graham, L.L.B., Putra, E.I., Saharjo, B.H., Applegate, G., Grover, S.P., Cochrane, M.A. (2020) Effects of distance from canal and degradation history on peat bulk density in a degraded tropical peatland. *Science of The Total Environment*, 699, 134199, 12 pp.

Sjögersten, S., Aplin, P., Gauci, V., Peacock, M., Siegenthaler, A., Turner, B.L. (2018) Temperature response of ex-situ greenhouse gas emissions from tropical peatlands: Interactions between forest type and peat moisture conditions. *Geoderma*, 324, 47–55.

Srisunthon, P., Chawchai, S. (2020) Land-use changes and the effects of oil palm expansion on a peatland in southern Thailand. *Frontiers in Earth Science*, 8, 559868, 16 pp.

Strack, M. (2008) *Peatlands and Climate Change*. International Peat Society, Saarijarvi, 223 pp.

Tonks, A.J., Aplin, P., Beriro, D.J., Cooper, H., Evers, S., Vane, C.H., Sjogersten, S. (2017) Impacts of conversion of tropical peat swamp forest to oil palm plantation on peat organic chemistry, physical properties and carbon stocks. *Geoderma*, 289, 36–45.

Troxler, T.G., Ikenaga, M., Scinto, L., Boyer, J.N., Condit, R., Perez, R., Gann, G.D., Childers, D.L. (2012) Patterns of soil bacteria and canopy community structure related to tropical peatland development. *Wetlands*, 32, 769–782.

Upton, A., Vane, C.H., Girkin, N., Turner, B.L., Sjögersten, S. (2018) Does litter input determine carbon storage and peat organic chemistry in tropical peatlands? *Geoderma*, 326, 76–87.

Wakhid, N., Hirano, T., Okimoto, Y., Nurzakiah, S., Nursyamsi, D. (2017) Soil carbon dioxide emissions from a rubber plantation on tropical peat. *Science of The Total Environment*, 581–582, 857–865.

Wang, Z.-g., Bao, X.-g., Li, X.-f., Jin, X., Zhao, J.-h., Sun, J.-h., Christie, P., Li, L. (2015) Intercropping maintains soil fertility in terms of chemical properties and enzyme activities on a timescale of one decade. *Plant and Soil*, 391, 265–282.

Werner, C., Zheng, X.H., Tang, J.W., Xie, B.H., Liu, C.Y., Kiese, R., Butterbach-Bahl, K. (2006) N_2O, CH_4 and CO_2 emissions from seasonal tropical rainforests and a rubber plantation in Southwest China. *Plant and Soil*, 289, 335–353.

Wijedasa, L.S., Sloan, S., Page, S.E., Clements, G. R., Lupascu, M., Evans, T.A. (2018) Carbon emissions from South-East Asian peatlands will increase despite emission-reduction schemes. *Global Change Biology*, 24, 4598–4613.

World Weather Online (2022) Kampong Raja Musa Historical Weather. Online at: https://www.worldweatheronline.com/kampong-raja-musa-weather/selangor/my.aspx, accessed 27 Mar 2022.

Yule, C.M., Gomez, L.N. (2009) Leaf litter decomposition in a tropical peat swamp forest in Peninsular Malaysia. *Wetlands Ecology and Management*, 17, 231–241.

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