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RESEARCH PAPER

Spatial variability of surface peat properties and carbon emissions in a tropical peatland oil palm monoculture during a dry season

Selva Dhandapani[1,2] | **Nicholas T. Girkin**[3,4] | **Stephanie Evers**[1,2,5]

[1]School of Biological and Environmental Sciences, Liverpool John Moores University, Liverpool, UK

[2]Tropical Catchment Research Initiative (TROCARI), Kuala Lumpur, Malaysia

[3]School of Biosciences, University of Nottingham, Sutton Bonington, UK

[4]School of Water, Energy and Environment, Cranfield University, Cranfield, UK

[5]School of Biosciences, University of Nottingham Malaysia Campus, Semenyih, Malaysia

Correspondence
Selva Dhandapani, Centre for Agri-Environmental Research (CAER), University of Reading, Reading RG6 6EU, UK.
Email: sccalva@gmail.com

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Abstract

The expansion of oil palm monocultures into globally important Southeast Asian tropical peatlands has caused severe environmental damage. Despite much of the current focus of environmental impacts being directed at industrial scale plantations, over half of oil palm land-use cover in Southeast Asia is from smallholder plantations. We differentiated a first generation smallholder oil palm monoculture into 8 different sampling zones, and further divided the 8 sampling zones into oil palm root influenced (Proximal) and reduced root influence (Distal) areas, to assess how peat properties regulate in situ carbon dioxide (CO_2) and methane (CH_4) fluxes. We found that all the physico-chemical properties and nutrient concentrations except sulphur varied significantly among sampling zones. All physico-chemical properties except electrical conductivity, and all nutrient content except nitrogen and potassium varied significantly between Proximal and Distal areas. Mean CO_2 fluxes (ranged between 382 and 1191 mg m^{-2} h^{-1}) varied significantly among sampling zones, and between Proximal and Distal areas, with notably high emissions in Dead Wood and Path zones, and consistently higher emissions in Proximal areas compared to Distal areas within almost all the zones. CH_4 fluxes (ranged between −32 and 243 μg m^{-2} h^{-1}) did not significantly vary between Proximal and Distal areas, however significantly varied amongst sampling zones. CH_4 flux was notably high in Canal Edge and Understorey Ferns zones, and negative in Dead Wood zone. The results demonstrate the high heterogeneity of peat properties within oil palm monoculture, strengthening the need for intensive sampling to characterize a land use in the tropical peatlands.

KEYWORDS

carbon dioxide, methane, oil palm plantation, peat nutrient content, peat physico-chemical properties, tropical peatlands

1 | INTRODUCTION

The dramatic expansion of oil palm monocultures into globally important Southeast Asian tropical peatlands in recent decades has caused severe environmental, health and socio-political problems because of their role in haze, climate change and endemic biodiversity loss (Cheong et al., 2019; Danielsen et al., 2009; Dhandapani, 2015; Dislich et al., 2017). Oil palm (*Elaeis guineensis*) is native to West Africa and was first commercially planted in Malaysia in 1917 in the Thennamaran region in North Selangor, close to the largest area of tropical peatlands in Selangor state (Abdullah et al., 2009; Danielsen et al., 2009; Dhandapani et al., 2019a; Rizal et al., 2018). Even though initially most expansion was on existing plantations (Basiron, 2007; Dhandapani, 2015; Shevade & Tatiana, 2019), land for further expansion became scarce, exerting pressure on forests (Hansen et al., 2013). In recent decades, oil palm plantations have expanded rapidly across carbon-rich peatlands (Miettinen & Liew, 2010; Miettinen et al., 2016; Shevade & Tatiana, 2019). Peatlands are scarcely populated, making them easy to claim and gain ownership for establishing plantations, without any social conflict (Casson et al., 2007).

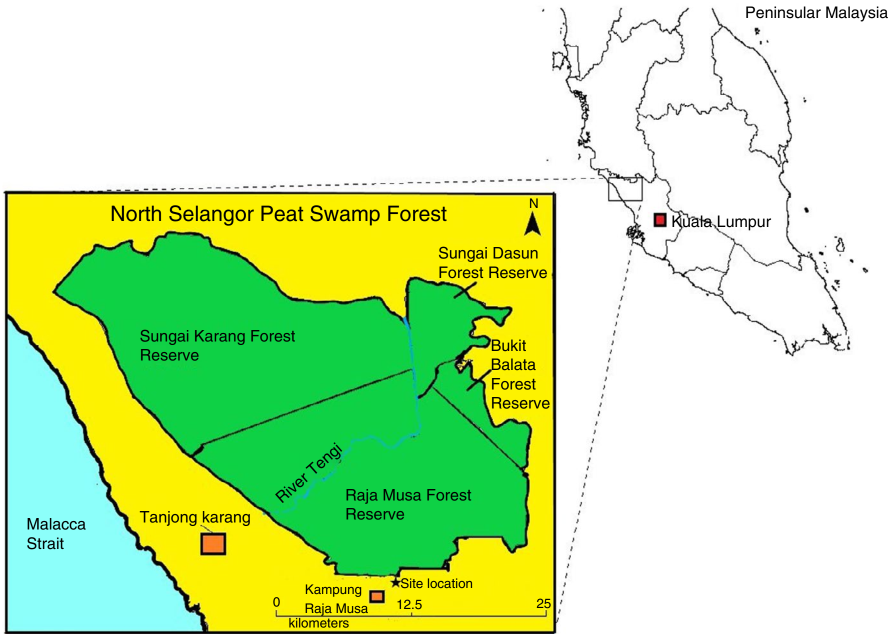
Tropical peatlands in Southeast Asia, which are naturally forested and wet ecosystems, have to be drained and completely cleared to establish oil palm plantations (Dhandapani et al., 2019a; Luskin & Potts, 2011; Matysek et al., 2017; Yule, 2010). A recent estimate by Wijedasa et al. (2018) shows that smallholder plantations had a greater contribution to land use change in Southeast Asia than industrial plantations. Smallholder plantations are less strictly managed, without the use of any advanced equipment (Azhar et al., 2011), resulting in increased habitat heterogeneity even in monocropping systems (Azhar et al., 2015), relative to well-maintained homogenous industrial monocropping (Matysek et al., 2017). It is notable that globally, 40% of the land used for oil palm cultivation are smallholder plantations (Saadun et al., 2018), and smallholder plantations are playing major part in expansion of oil palm plantations in Latin America and Africa (Azhar et al., 2017; Bennett et al., 2019; Sayer et al., 2012).

Smallholder plantations vary widely from industrial plantations, in terms of land clearing, drainage, understorey vegetation and harvesting paths in the plantations (Azhar et al., 2011; Dhandapani et al., 2019a,b; Matysek et al., 2017). In their intact state, tropical peatlands are complex ecosystems with a high degree of spatial heterogeneity (Girkin et al., 2019), which, when converted to agricultural plantations, manipulates the complexity to varying degrees, resulting in a wide range of heterogeneous zones. Estimates of the impacts of land use as a whole on carbon emissions are difficult, in part because of the varying management practices in oil palm plantations, with some management practices unique to particular smallholders (S. Dhandapani, pers. observ.).

A range of approaches have previously been used to evaluate the response of greenhouse gas (GHG) fluxes of oil palm land use in tropical peatlands, including complete random sampling (Dhandapani et al., 2019a), stratified random sampling (Matysek et al., 2017), field plots (Cooper et al., 2019; Hergoualc'h et al., 2017; Melling et al., 2005a,b; Tonks et al., 2017), transects (Dariah et al., 2014) and area weighted plots accounting for some heterogeneity (Manning et al., 2019). Dhandapani et al. (2019b) evaluated the impacts of nearby crops on peat properties and carbon emissions, but other heterogeneous zones in plantations, for example canal edge effects, were not reported. Although Manning et al. (2019) reported some heterogeneous zones in plantations in Borneo, the management practices vary widely between smallholders (Dhandapani et al., 2019a,b), and it is important to assess such variations within plantations in other regions such as Peninsular Malaysia and Indonesia. There is a need to know the individual impacts of all the heterogeneous regions in oil palm plantations to address knowledge gaps and allow full evaluation of different field sampling techniques, upscale emissions estimations appropriately and understand the effects of land-use change and management.

Soils store three times more carbon than the atmosphere, and the natural emission of carbon from soil through microbial decomposition is more than 10 times larger than that of the world fossil fuel industries (Oertel et al., 2016). Intact Southeast Asian peatlands absorb 2.6 tonnes of CO_2 per hectare per year and store approximately 69 Gt of Carbon (Norwana et al., 2011; Page et al., 2011), thus playing an important role in global carbon cycle. GHG emissions from peatlands or any soil are affected by changes in a range of environmental parameters including peat temperature, pH, electrical conductivity, redox potential and nutrient concentrations (Dhandapani et al., 2019a,c). pH affects cation exchange capacity, influences soil nutrient availability for plants and trees and affects microbial community structure (Gillman, 1981; Sawhney et al., 1970). Redox potential is electron exchange capacity of atoms for reduction and oxidation reactions, which can change the forms of soil nutrients by changing the charge of ions and may impact nutrient availability in soil (DeLaune & Reddy, 2005; Pezeshki & DeLaune, 2012; Søndergaard, 2009). A decrease in redox potential can put pressure on living cells and rhizosphere in soil, and may indicate a lack of oxygen (Pepper & Gentry, 2015). Both pH and redox potential impact soil nutrient dynamics and directly or indirectly influence GHG emissions (Hénault et al., 2019; Weslien et al., 2009). Redox potential affects the balance between methanogenic and methanotrophic microbial communities and can significantly affect CH_4 emissions (Topp & Pattey, 1997). Electrical conductivity is a measure of salinity and rough estimate of nutrients

FIGURE 1 Site location



and also impacts soil–plant, water and nutrient dynamics, microbial activity and GHG emissions (Marton et al., 2012). Thus, understanding the relationships between peat physico-chemical properties and carbon emissions hotspots in micro-habitats within this heterogeneous ecosystem would provide insights into better management of the plantations and also better experimental design for future studies.

Tropical peatlands are naturally nutrient poor (Sjögersten et al., 2011); however, some nutrients exhibit functional correlations with soil microbial communities and carbon emissions (Dhandapani et al., 2019c). Despite their potential functional interaction and impact, the change in nutrient concentration with land-use conversion to oil palm plantations is virtually unknown, let alone the nutrient dynamics within the oil palm plantations. Dhandapani et al. (2019c) suggest that anthropogenic disturbances involving drainage of tropical peat forests may result in nutrient leaching and reduced nutrient concentration; however, such loss in agricultural landscapes and their functional relationship with carbon emissions are yet to be explored. Conversion of forests to oil palm plantations involving drainage in tropical peatlands was known to increase pH, temperature and redox potential, and decrease moisture; however, their variations within oil palm plantations are not well documented (Cooper et al., 2019; Dhandapani et al., 2019a; Tonks et al., 2017).

In this study, we define and evaluate the heterogeneity of peat properties in 16 sampling regions in an oil palm monoculture to identify possible carbon emission hotspots. We hypothesize (1) that the peat properties and nutrient content significantly vary amongst sampling zones considering the varied physical and environmental features among the zones. We further hypothesize that (2) changes in nutrient concentrations and peat properties significantly affects carbon emissions, resulting in significantly different carbon emissions between zones. We anticipate higher carbon emissions from the regions with higher labile carbon availability such as regions with dead wood or understorey vegetation, and regions with high degree of disturbance such as harvesting paths. We also hypothesize that (3) areas closer to oil palm plants will have higher emissions, because of significant autotrophic contributions from mature oil palm roots, along with other influence of rhizosphere such as microbial community structure and root exudate additions, further adding to the heterogeneity in carbon emissions among the zones.

2 | MATERIALS AND METHODS

2.1 | Study sites

This study was conducted in a smallholder oil palm monocropping plantation (3°25′25.8″N 101°20′12.9″E) located adjacent to Raja Musa forest reserve on the southern edge of the North Selangor peatlands. Indicative view of the location is given in Figure 1. The oil palm trees were approximately 17–18 years old and of first-generation plantation. The total site size was approximately 2 ha. The site bordered other oil palm plantations, which were abandoned for forest regeneration inside Raja Musa protected forest reserve. A drainage ditch, running down the middle, divided the site into two halves. The site had a sizeable cover of understorey vegetation, predominantly ferns. There was abundant decaying dead wood of non-oil palm plants on the site, in particular legacy tree stumps from prior forest cover. There were some dead cut stems of other plants and

TABLE 1 Description of sampling zones and areas

Zone		Area	
Name	Description	Each zone is divided into 2 Areas as given below. This classification is based on Matysek *et al* (2017) that found no root contribution to CO_2 emissions for measurements that are more than 3m away from oil palm stem.	
Canal	represents the canal that runs on the border on two sides of the plantation, which is about 2-3 metres wide and 1-1.5 metres deep. Surface layers were dry throughout the measurement period.		
Canal Edge	represents the edge on the side of the plantation that is within 0.5 metre from the canal		
Cleared (Figure 2a)	is the open area in the plantation that is free of any understorey vegetation or other distinct features.		
Dead Wood (Figure 2b)	is similar to the cleared zone, with only difference being protruding stem of previous generation of forest plants, from the ground. The dead stems are within 0.5 metre from any sampling point in Dead Wood zone.	Name	Description
Ditch (Figure 2c)	is on a 1 m wide, 0.5-1 m deep ditch that runs in the middle of the plantation, dividing it into two. The ditch drains into the large canal at the end. Surface layers were dry throughout the measurement period.	Proximal	within 3 metres from nearest oil palm stem
Ditch Edge (Figure 2d)	is on either side of the ditch, within 0.5 metre from the ditch.		
Understorey Fern (Figure 2e)	represents peat that is within 0.5 metre from nearby fern.	Distal	further than 3 metres away from nearest oil palm stem
Path (Figure 2f)	represents the area of peat within 0.5 metre on either side of the harvest path filled with gravel, running throughout the plantation.		

trees of previous land use, visibly protruding from the surface. There were also harvesting paths running throughout the plantation. The peat depth in the site was approximately 3 m. The water table level during the time of sampling was c. 60 cm below the ground surface. The water table level fluctuates from 30 cm belowground to 80 cm belowground throughout the year (S. Dhandapani et al., Unpublished). The average rainfall in the region is 1349–2480 mm yr^{-1} (Global Environmental Centre, 2014), with rainfall measured nearby at Kuala Selangor town (9 km away) recording weather data for August 2018 of mean 37.7 mm rainfall, 18 rainfall days, a mean temperature of 28°C and 68% average (World Weathers Online, 2020).

This site has previously been included in two studies of oil palm monocropping, where it was referred to as "1^{st} gen OP" in Dhandapani et al. (2019a,b).

2.2 | Sampling strategy

The site was divided into 8 sampling zones (see Table 1), and the sampling zones were further divided into root influence area referred as Proximal area (within 3 m from nearest oil palm stem) and non-root influence area referred as Distal area (further than 3 m away from nearest oil palm stem), making a total of 16 different sampling regions. These distances were selected based on the extent of roots within an oil palm plantation previously identified by Matysek et al. (2017).

A total of five sampling points were chosen for each sampling zone. At each sampling point, CO_2 and CH_4 measurements were taken, and surface peat (0–5 cm) samples were subsequently collected from the exact spots where the carbon emissions measurements were made, for laboratory analyses. All of five independent sampling within each individual sampling zone were collected on the same day. This resulted in 80 independent sampling points in total for the site, covering both Distal and Proximal areas in all sampling zones. Each sampling point was sampled only once for this study. Sampling was carried out over 3 days in a dry season from 18th to 20th of August 2018 between 11:00 and 14:00 each day.

2.3 | Peat characteristics

The procedure used for peat analyses was based on Dhandapani et al. (2019a,b,c). Peat temperature was measured *in situ*, using a digital thermometer. About 20 g of peat samples was collected using a metal spoon from the top 5 cm of the surface from each individual sampling point. For measuring gravimetric moisture, about 20 g of fresh peat from each individual sampling points was dried in an oven at 105°C for 48 h. The gravimetric moisture was calculated as follows:

$$\text{Gravimetric moisture } (\%) = \frac{\text{Mass of the water lost in oven drying}}{\text{Mass of oven dried peat}} \times 100.$$

For pH, redox and electric conductivity measurements, 5 ml volume of peat sample was diluted in 10 ml deionized water in a centrifuge tube and shaken on a table shaker for

FIGURE 2 Example pictures of Distal areas of sampling zones (except Canal and Canal Edge), (a) Cleared, (b) Dead wood, (c) Ditch, (d) Ditch Edge, (e) Understorey Ferns, (f) Path

2 h. The pH of the supernatant was then measured using a Eutech pH 700 pH meter supplied by Thermo scientific. The redox potential and electrical conductivity were measured using Eutech Ion 2100 (Thermo scientific) and Groline HI98331 probe (Hanna), respectively.

For analysing total carbon (C) and nitrogen (N) content, all samples were oven-dried (105°C for 48 h) and finely ground using a Fritsch mortar grinder pulverisette 2 (Brackley, UK). Approximately 70 mg of sample was weighed into a Skalar ceramic crucible, and the exact weight was recorded. The samples were then transferred to an auto sampler in Skalar primacs series SNC100 TC TN analyser (Breda, The Netherlands) and analysed for total C and total N content.

2.4 | Nutrient analysis

The peat nutrient concentrations were analysed using inductively coupled plasma mass spectroscopy (ICP-MS). For this, approximately 0.15 g of oven dried (105°C for 48 h) and ground peat was weighed in microwave digestion tubes (MARSXpress vessels, CEM Microwave Technology Ltd.). The digestion tubes were sealed with a stopper and a screw lid, after adding 10 ml of nitric acid to each sample. The digestion tubes were then placed in a MARSXpress microwave (CEM Microwave Technology Ltd.) and run at 1600 W & 100% power with a ramp for 20 min and held for 20 min at 170°C. The tubes are left overnight in the microwave to cool down. The digested samples are then filtered and made up to 30 ml using milliQ water. Then, 1 ml of each sample was transferred in to 10-ml tube and further diluted with 9 ml of milliQ water. The samples were then analysed using 'Agilent Technologies' (Milton Keynes, UK) 7900 ICP-MS fitted with 'SPS 4' autosampler.

2.5 | Carbon emissions

CO_2 and CH_4 emissions from the peat surface were measured using a Los Gatos (San Jose, California, USA) ultraportable greenhouse gas analyser as described in Dhandapani et al. (2019a,b,c). The gas analyser works on the principle of laser absorption spectroscopy and gives readings of CH_4

and CO_2 ppm as well as gas temperature. The measurements were made using closed dynamic chamber method using a chamber with a height of 15 cm and the inner diameter of 13.5 cm. The chamber had an inlet and an outlet port that were connected to the gas analyser, using a 6.35-mm outer diameter polytetrafluoroethylene (PTFE) tube. During each measurement, about 1 cm of the chamber was carefully inserted into the ground until it was sealed to the ground surface, and gas measurements were taken over 3 min. There was no surface vegetation in any of the measurement points. The gas analyser was set to record gas flux every 20 s, resulting in at least six recorded measurement points for each plot. The first minute of each measurement was ignored allowing the gas flux to settle down after initial disturbance of placing the chambers. Following omission of the first minute in each measurement period, linear fits of CO_2 concentration increase to sample rate showed an $R^2 > .99$ 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. The gas measurements in ppm were converted to mg CO_2 m^{-2} h^{-1} and μg CH_4 m^{-2} h^{-1} for CO_2 and CH_4, respectively, as described in Samuel and Evers (2016), using the ideal gas law PV = nRT, where P = atmospheric pressure; V = volume of headspace; n = number of moles (mol); R = universal Gas Constant law (8.314 J K^{-1} mol^{-1}); and T = temperature in kelvin (K), with conversion factor, 1 mol of CO_2 = 44.01 g and 1 mol CH_4 = 16.02 g.

2.6 | Statistical analyses

Differences in peat properties and carbon fluxes among heterogeneous zones and between Proximal and Distal areas were assessed using a two-way analysis of variance (ANOVA). Fishers multiple comparison test was carried out for each of the measured peat property to identify the significance of difference between each heterogeneous zones. For data sets that are not normally distributed, log transformation or boxcox transformation was used. Significance was assessed at $p \leq .05$. Backwards, stepwise elimination regression was used to assess relationships between peat properties and carbon fluxes. Proximal measurements, however, were not used for multiple regression because of the unknown extent of root contributions attached to each measurement. All statistical analyses were carried out in Genstat v19.

3 | RESULTS

3.1 | Peat properties

Gravimetric moisture content (Figure 3a) varied significantly among sampling zones, between Proximal and Distal areas, and in the interaction term (Table 2). Moisture content was greatest at Proximal areas on the Canal and Ditch zones, and decreased in the Distal areas. Along the path, moisture content was particularly low. The interaction terms were significant because Canal and Ditch Edge zones showed significantly higher moisture levels in Proximal than Distal areas, while other zones were either unchanged between the two areas or showed higher moisture in Distal areas (Figure 3a). Redox potential also varied significantly among different sampling zones and was lower in Proximal than Distal areas (Table 2, Figure 3b). Redox potential was highest in the Drainage Ditch (340 and 442 mV) but was lowest in Proximal areas of Canal Edge and Understorey Ferns zones. pH was consistently acidic and <4 (Figure 3c), but also varied significantly among sampling zones, and was slightly lower in Distal areas compared to the Proximal areas (Table 2; Figure 3c). In contrast, while electrical conductivity varied between different sampling zones, it did not vary between Proximal and Distal areas within those zones, but did vary significantly in the interaction term (Table 2; Figure 3d). Electrical conductivity was higher in Proximal areas than Distal areas on the Cleared zone, while it was lower in the Proximal than Distal areas in Dead Wood and Understory Ferns zones, resulting in significant interactions between Zones and Areas (Figure 3d; Table 2).

3.2 | Peat elemental analysis

Total carbon varied significantly among sampling zones, and was greater in Proximal than in Distal areas ($p < .001$, Figure 4a). Carbon content was greatest in the Dead Wood zone (471 mg g^{-1}), and lowest in the Canal zone (139 mg g^{-1}). In contrast, while nitrogen content varied significantly among zones ($p < .001$), it did not vary between Proximal and Distal areas (Table 2, Figure 4b). The interaction term, however, was significant (Table 2), as Canal zone had higher nitrogen content in Proximal than Distal areas, while Cleared and Understory Ferns zones had higher nitrogen content in Distal than Proximal areas. Nitrogen was greatest at the Distal area in Understory Ferns zone (21 mg g^{-1}) and was lowest in the Canal zone (8 mg g^{-1}). Phosphorus varied significantly among zones and was consistently higher in the Proximal than Distal areas (Table 2, Figure 4d), as was sulphur (Table 2, Figure 4e). Sulphur content was greatest at the Proximal area in the Canal zone (5 mg g^{-1}) and lowest at the Distal areas in same Canal zone (1 mg g^{-1}). Sulphur content also varied significantly in the interaction term (Table 2), as the Ditch zone exhibited a distinct trend of higher sulphur concentration in Distal than Proximal areas, contradicting all the other zones. Potassium content only varied significantly among zones (Table 2) and was greatest in the Canal zone (1 mg g^{-1}, Figure 4f). Calcium content varied among zones

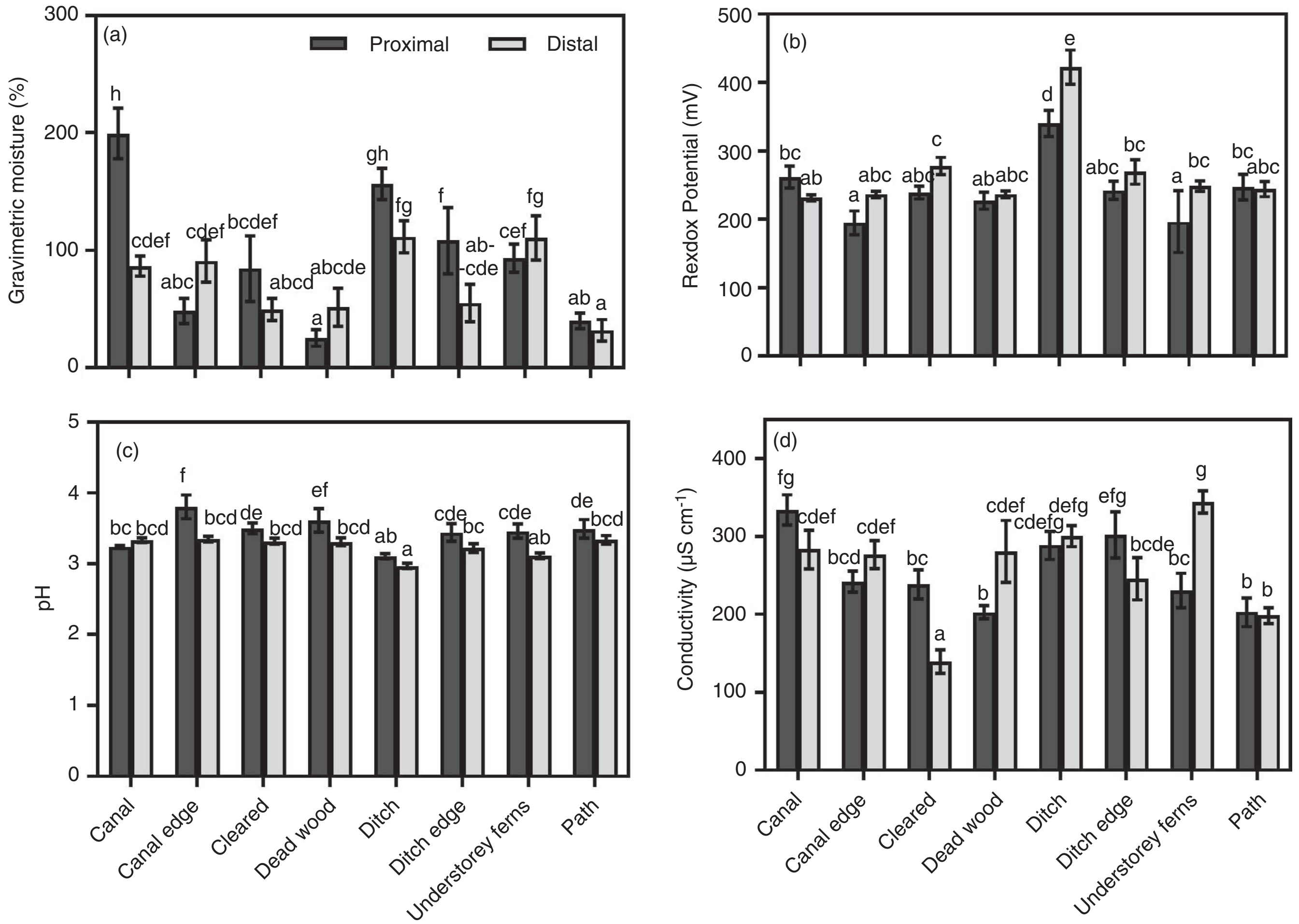


FIGURE 3 (a) Gravimetric moisture (%), (b) redox potential (mV), (c) pH and (d) electrical conductivity (µS cm^{-1}) at Proximal and Distal areas across sampling zones in smallholder oil palm plantation. Means ± 1 SEM. Bars that do not share any letters are significantly different from each other according to Fisher's multiple comparison test

(Table 2, Figure 4g) and was greatest on the Path and Dead Wood zones. Calcium content was generally higher in proximal areas than Distal areas, with no significant interactions between Sampling Zones and Areas (Table 2). Magnesium content varied significantly among sampling zones, and between Distal and Proximal areas, with no significant interactions between Zones and Areas. Magnesium content was notably higher in Proximal areas of Canal Edge and Ditch Edge zones (Table 2; Figure 5h).

3.3 | In situ CO_2 and CH_4 fluxes

Mean CO_2 fluxes varied significantly among sampling zones and between Proximal and Distal areas, but the interaction term was not significant (Table 2, Figure 5a). Fluxes were consistently greater in Proximal areas closer to oil palms, with particularly high fluxes measured in the Proximal area of the Dead Wood zone (1190 mg CO_2 m^{-2} h^{-1}), and in the Path zone (928 mg CO_2 m^{-2} h^{-1}). The mean CO_2 emissions for the site are 620 mg CO_2 m^{-2} h^{-1}. Root-derived CO_2 was calculated only for the Cleared zone, in order to discount effects from other landscape features, for example canals, path compaction or understory vegetation inputs. Root-derived CO_2 was estimated at 189 mg CO_2 m^{-2} h^{-1}, equivalent to c. 28% of total respiration.

CH_4 fluxes exhibited considerable variation, ranging from −32 to 253 µg CH_4 m^{-2} h^{-1} and varied significantly among Zones, with significant interaction between Zones and Areas (Table 2). However, the variation between Distal and Proximal areas was not significant (Table 2, Figure 5b). Proximal areas of Canal Edge and Understorey Ferns had notably higher CH_4 flux, while Proximal areas of Dead Wood had the greatest negative flux. Mean peat temperature varied significantly among the zones, between Distal and Proximal areas, and in the interaction terms (Table 2, Figure 5c). Highest temperatures were recorded in Dead Wood zone (c. 35°C) but were also high around paths. Some Zones such as Cleared, Understory Ferns and Path had higher temperature in Proximal areas, while the rest of the Zones had higher

TABLE 2 Two-way analysis of variance (ANOVA) for peat physico-chemical properties and nutrient concentrations, showing statistical significance of the effects of Area, Zone and the interactions between Area and Zone. Statistically significant figures are presented in bold. The values inside the brackets in subscript indicate numerator and denominator degrees of freedom

Variable	Area	Zone	Area*Zone
Gravimetric moisture	$\mathbf{F_{(1,65)} = 6.02, p = .017}$	$\mathbf{F_{(7,65)} = 11.73, p < .001}$	$\mathbf{F_{(7,65)} = 5.16, p < .001}$
pH	$\mathbf{F_{(1,65)} = 25.19, p < .001}$	$\mathbf{F_{(7,65)} = 6.23, p < .001}$	$F_{(7,65)} = 1.88, p = .087$
Redox	$\mathbf{F_{(1,65)} = 10.93, p = .002}$	$\mathbf{F_{(7,65)} = 17.01, p < .001}$	$F_{(7,65)} = 1.96, p = .074$
Electrical conductivity	$F_{(1,65)} = 0.04, p = .851$	$\mathbf{F_{(7,65)} = 9.18, p < .001}$	$\mathbf{F_{(7,65)} = 5.93, p < .001}$
Carbon	$\mathbf{F_{(1,56)} = 9.07, p < .004}$	$\mathbf{F_{(7,56)} = 9.37, p < .001}$	$F_{(7,56)} = 2.15, p = .053$
Nitrogen	$F_{(1,56)} = 1.96, p = .167$	$\mathbf{F_{(7,56)} = 23.26, p < .001}$	$\mathbf{F_{(7,56)} = 7.22, p < .001}$
C:N	$\mathbf{F_{(1,56)} = 5.87, p = .019}$	$\mathbf{F_{(7,56)} = 7.82, p < .001}$	$\mathbf{F_{(7,56)} = 2.21, p = .047}$
logCalcium	$\mathbf{F_{(1,64)} = 19.60, p < .001}$	$\mathbf{F_{(7,64)} = 5.75, p < .001}$	$\mathbf{F_{(7,64)} = 2.89, p = .011}$
Potassium	$F_{(1,64)} = 1.15, p = .288$	$\mathbf{F_{(7,64)} = 23.62, p < .001}$	$F_{(7,64)} = 1.65, p = .137$
logMagnesium	$\mathbf{F_{(1,63)} = 14.84, p < .001}$	$\mathbf{F_{(7,63)} = 5.7, p < .001}$	$F_{(7,64)} = 2.15, p = .051$
logPhosphorus	$\mathbf{F_{(1,63)} = 38.31, p < .001}$	$\mathbf{F_{(7,63)} = 6.25, p < .001}$	$F_{(7,63)} = 1.10, p = .372$
Sulphur	$\mathbf{F_{(1,64)} = 14.85, p < .001}$	$F_{(7,64)} = 2.01, p = .068$	$\mathbf{F_{(7,64)} = 5.03, p < .001}$
Temperature	$\mathbf{F_{(1,66)} = 9.25, p = .003}$	$\mathbf{F_{(7,66)} = 128.58, p < .001}$	$\mathbf{F_{(7,66)} = 14.96, p = .001}$
boxcoxCH_4	$F_{(1,66)} = 0.21, p = .647$	$\mathbf{F_{(7,66)} = 2.41, p = .029}$	$\mathbf{F_{(7,66)} = 2.17, p = .048}$
logCO_2	$\mathbf{F_{(1,66)} = 7.74, p = .007}$	$\mathbf{F_{(7,66)} = 2.56, p = .021}$	$F_{(7,66)} = 0.87, p = .537$

temperature in Distal areas, resulting in significant interactions between Zones and Areas (Table 2). The mean CH_4 emissions for the site are 39 μg CH_4 m^{-2} h^{-1}.

No significant relationship was found between distal CO_2 fluxes and peat physico-chemical properties. In contrast, distal CH_4 fluxes were significantly correlated with carbon content (Figure 6; 5.2% of variance; p = .030). CH_4 fluxes increased with carbon content.

4 | DISCUSSION

Our results show that the apparent heterogeneity visible within smallholder oil palm plantations (Azhar et al., 2011; Dhandapani et al., 2019a) is reflected by significant variation in peat physico-chemical properties and nutrient content found by sampling across distinct zones. Gravimetric moisture was highest in the Canal and Ditch zones as expected, even though water table was below surface in all zones. Another notable characteristic was the higher moisture content in Proximal areas for most of the zones, in contrast to Dhandapani et al. (2019b), where Proximal areas had the lowest moisture level compared to the Distal areas to oil palm in four different cropping systems. This may be because of the fact that Dhandapani et al. (2019b) included moisture measurements from both wet and dry seasons, whilst our current study only measured moisture in the dry season, when increased shade in Proximal areas may be more important in preventing increased evapotranspiration from the surface peat and maintaining higher moisture levels.

Redox potential and pH are important soil properties for better management of agricultural ecosystems and mitigation of soil GHG emissions (Husson, 2013; Pezeshki & DeLaune, 2012; Wang et al., 2018). Redox potential is lower in Proximal than in Distal areas, which may be related to increased need of oxygen for living cells in oil palm rhizosphere (Husson, 2013). Redox potential in all the sampling zones in this study was higher than have been observed in a pristine tropical peatland in Peninsular Malaysia (Girkin et al., 2020a), and only the Ditch zone had higher redox potential than oil palm and pineapple intercropping system in the same region (Girkin et al., 2020a). The higher Redox potential in the ditch may be because of the higher water and oxygen availability in that zone (Figure 3). pH was in the range previously observed in oil palm plantations in tropical peatlands (Dhandapani et al., 2020; Dhandapani et al., 2019a,b; Tonks et al., 2017). Even though there were significant differences in pH between sampling zones, all the zones were highly acidic with pH under 4. pH was also generally higher in Proximal areas than in Distal areas. This may be because of the influence of oil palm rhizosphere, as plant rhizosphere and their nitrogen uptake mechanisms have been shown to increase the pH in rhizosphere (Nye, 1981). Similar increases in pH closer to tree and plant stems were also observed in Panamanian peatlands (Girkin et al., 2019) and associated with differences in the concentration and composition of root exudates (Girkin et al., 2018a,b) and oxygen (Girkin et al., 2020b).

Electrical conductivity is another important characteristic that influences soil–plant, water and nutrient dynamics, and microbial activity in production of CO_2 and CH_4. Electrical

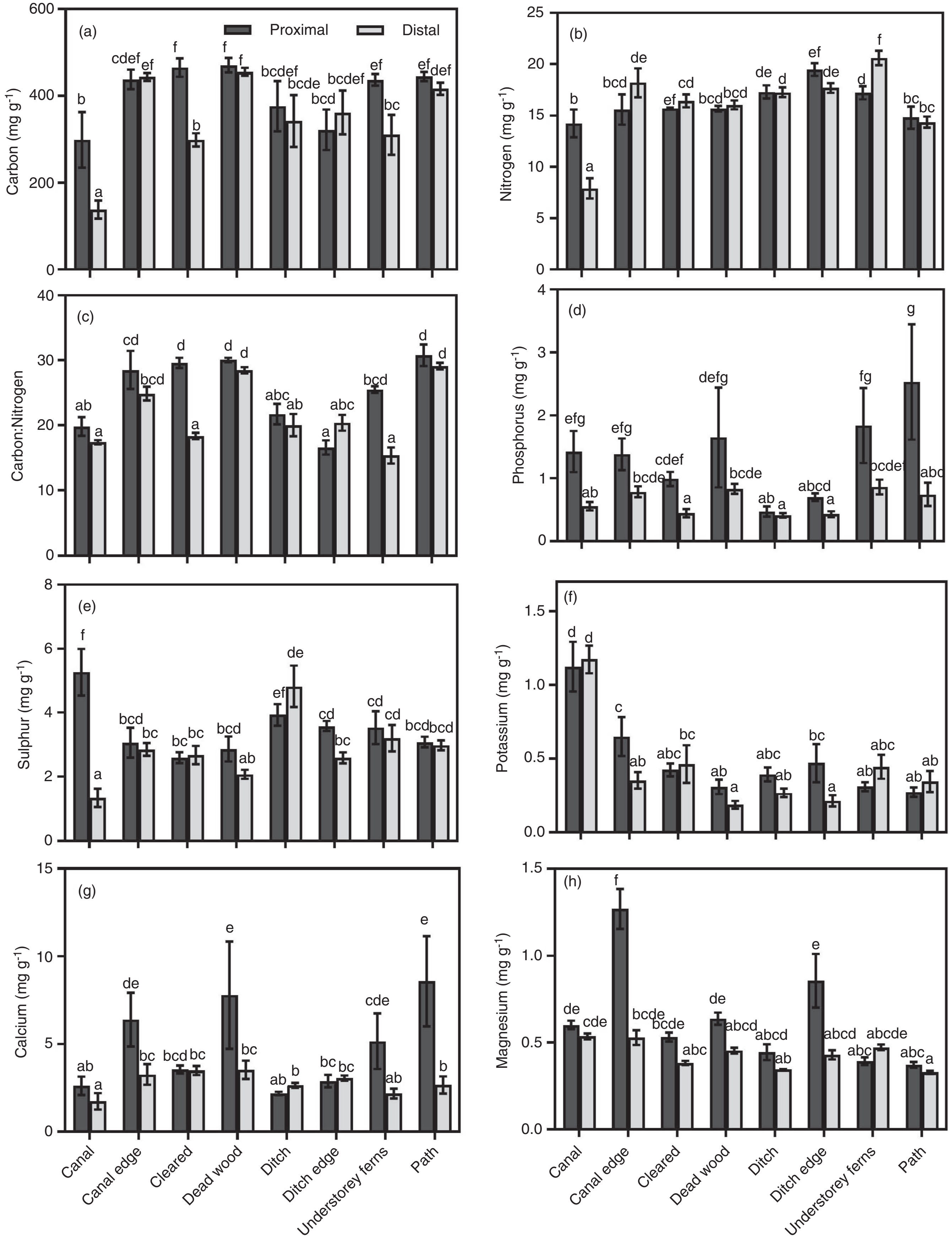


FIGURE 4 (a) Carbon, (b) nitrogen, (c) carbon:nitrogen (d) phosphorus, (e) sulphur, (f) potassium, (g) calcium concentrations and (h) Magnesium (mg g^{-1}) at Proximal and Distal areas across sampling zones in smallholder oil palm plantation. Means ± 1 SEM. Bars that do not share any letters are significantly different from each other according to Fisher's multiple comparison test

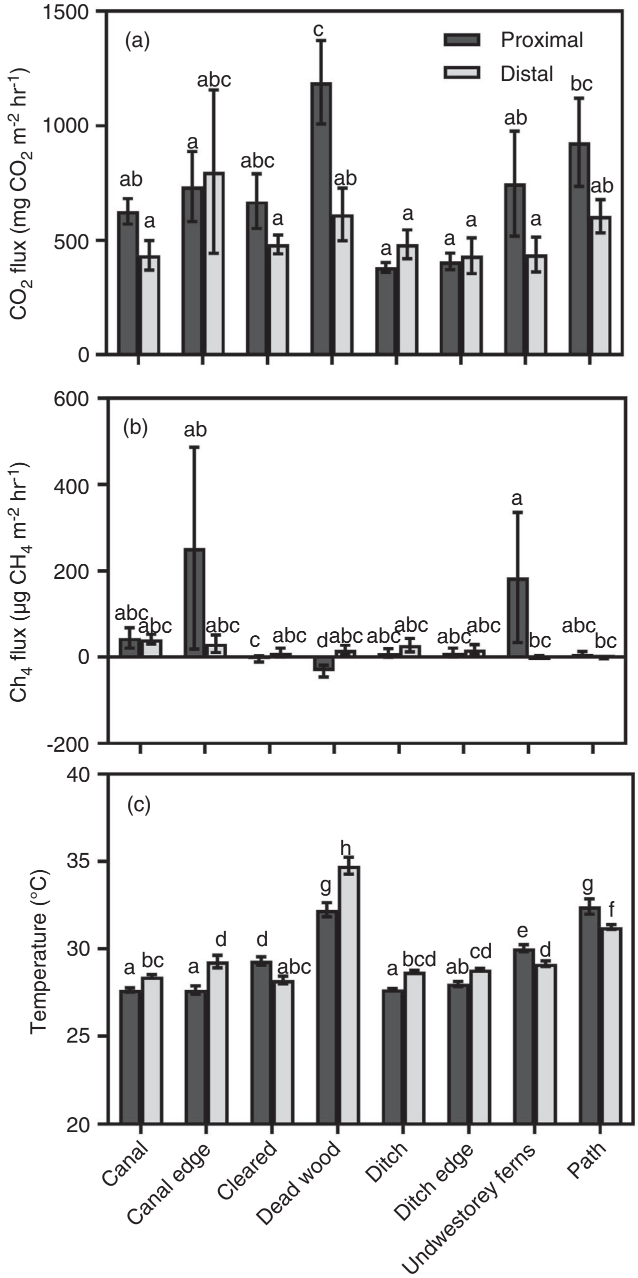


FIGURE 5 (a) CO_2 (mg m^{-2} h^{-1}), (b) CH_4 (μg m^{-2} h^{-1}) and (c) temperature (°C) at Proximal and Distal areas across sampling zones in smallholder oil palm plantation. Means ± 1 SEM. Bars that do not share any letters are significantly different from each other according to Fisher's multiple comparison test

conductivity also significantly varied between sampling zones, but exhibited a different trend of change between Proximal and Distal areas within the zones. Notably, the zones with some understorey ground cover such as Understory Ferns and Dead Woods exhibited higher electrical conductivity in Distal areas than Proximal areas, while it was the opposite in the Cleared zone with no ground cover. This may be because of the surface peat in the open areas such as Cleared zone having more impact of rainfall washing the salts in the surface peat than the zones with some ground cover (Liu et al., 2018). Another factor impacting higher electrical conductivity in Understory Ferns and Dead Wood zones is the additional living and dead roots in the region releasing nutrients into the soil by root exudation and decomposition, respectively (Dhandapani et al., 2019b; Girkin et al., 2018a,b). Moreover, the electrical conductivity in all zones is higher than observations in Panamanian peatlands (Girkin et al., 2019). The difference in rainfall pattern and higher organic content between the studied site and Panamanian peatlands may explain the differences in the electrical conductivity, as Panamanian peat had higher rainfall, and also higher organic content, which is related to lower electrical conductivity in tropical peat (Asadi & Huat, 2009). This may be because the peat in Cleared zone may have undergone a higher degree of decomposition than peat under some ground cover, as electrical conductivity of tropical peat is known to decrease with increased decomposition (Asadi & Huat, 2009). This increased electrical conductivity of surface peat in oil palm plantations may be further aided by additional ionic chemical inputs in preparation for agricultural production, such as liming and fertilizer additions (Azeez & Van Averbeke, 2012).

All the nutrients and total carbon content showed significant variation among sampling zones. Carbon content was noticeably lower in the Canal zone, as expected, as more than a metre of carbon and relatively nitrogen-rich surface peats were displaced by the canal (Tonks et al., 2017). Both the carbon content and nitrogen content of all zones were slightly lower than what was observed in both primary and secondary forests in Peninsular Malaysia (Dhandapani et al., 2019c), possibly because of the lack of leaf litter and other carbon addition in the oil palm monoculture, which may get further reduced with further generation of oil palm monoculture (Dhandapani et al., 2019a; Sayer & Tanner, 2010), as well as continuous oxidative losses (Ishikura et al., 2018) and possible loss through use of fire as a management practice (Astiani et al., 2018; Dhandapani & Evers, 2020).

All the studied macronutrients except sulphur varied among sampling zones, and all macronutrients except potassium varied significantly between Proximal and Distal areas, showing a significant degree of soil heterogeneity in nutrient concentrations. These variations in nutrient concentrations between sampling zones are plausibly influenced by three different factors: (1) legacy effect of peat formation and previous generation forest, (2) fertilizer addition and (3) drainage-associated leaching. Peat, by definition, is partially decomposed organic material, mostly derived from natural vegetation of peat-forming ecosystems, and thus, the above-ground species composition significantly impacts peat properties and nutrient concentrations (Girkin et al., 2019; Sjögersten et al., 2011). North Selangor peatlands are naturally biodiversity-rich ecosystems with wide range of above ground plant and tree species (Dhandapani et al., 2019c;

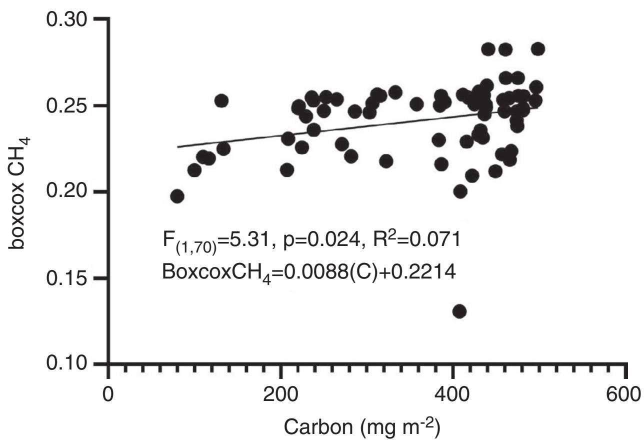


FIGURE 6 Relationship between boxcox CH_4 and carbon content

Yule, 2010). Thus, the spatial variations in this 1st-generation oil palm monoculture is most likely associated with previous generation forest plant species distribution and their varying degree of mineralization. This site is also actively drained and has high potential for nutrient loss through drainage (Dhandapani et al., 2019c). Our recent study has shown consistent decrease in different nutrients over time in different agricultural systems in North Selangor peatlands, further strengthening the theory of nutrient loss through leaching (Dhandapani & Evers, 2020; Dhandapani et al., 2021). This could further add to the spatial variability of these nutrient concentrations. It is unknown if there was any fertilizer usage in this particular agricultural system, which could directly influence changes in macronutrient concentrations in different sampling zones. However, it is clear that these findings validate the first hypothesis that peat physico-chemical properties and nutrient concentrations significantly vary across the plantation.

CO_2 fluxes varied significantly among the sampling zones, but did not significantly correlate with any peat physico-chemical properties or nutrient concentrations. CO_2 emissions were notably higher in Proximal area of the Dead Wood zone. This is possibly because of the higher temperature in the Dead Wood zone (Figure 5c) and availability of extra labile carbon in the form of previous generation's dead wood and root systems (Oertel et al., 2016; Pfeifer et al., 2015). On the other hand, CO_2 emissions were notably lower in the Ditch Edge and Ditch zones, again likely related to lower temperature (Figure 5d). The differences in fluxes between Proximal areas and Distal areas in the Ditch, Ditch Edge and Canal Edge zones were minimal (Figure 5a). This may be because of the removal of surface peat layers, which are needed for the horizontal expansion of oil palm root systems (Safitri et al., 2018), thus reducing fine root biomass which is a significant component of total autotrophic CO_2 emissions (Oertel et al., 2016). As anticipated in the second hypothesis, Dead Wood and Path zones had relatively higher CO_2 emissions compared to other sampling zones. The lack of correlations between measured peat properties and CO_2 emissions indicates that there may be other properties that are not measured such as microbial community structure and activity that may have greater influence on the CO_2 emissions in these ecosystems (Dhandapani, 2018; Dhandapani, Ritz, et al., 2020; Dhandapani et al., 2019c). However, it should also be noted that the lack of temporal data in this study impose limitations on identifying significant correlations between peat properties and GHG emissions.

The mean CO_2 emissions of 620 mg CO_2 m^{-2} h^{-1} for the entire plantation are consistent with CO_2 emissions observed in the site in the previous years using complete random sampling (Dhandapani et al., 2019a). Dhandapani et al. (2019a) consisted of 75 emission measurements from three visits in each season, with 25 measurements made in each visit. This current finding in combination with our previous study suggests that 25 complete random sampling used in our previous research was sufficiently representative of the mean CO_2 emissions from the smallholder oil palm land use. The observed emission levels in this study are also consistent with recent observations in other first- and second-generation smallholder oil palm plantations on peat in the region (S. Dhandapani et al., unpublished).

CH_4 fluxes were very low in comparison to CO_2 fluxes; however, it also significantly varied between sampling zones (Table 2; Figure 5b). The notably higher CH_4 flux in Understorey Ferns zone relates to previous findings that plants with shallow adventitious root systems such as yam and pineapple significantly increased CH_4 emissions from peat surface (Dhandapani et al., 2019b). This is possibly because of different root exudate addition and rhizosphere microbial communities of these plants influencing CH_4 emissions (Girkin et al., 2018a). Similarly, Dhandapani et al. (2019b) also found negative CH_4 flux near dead oil palm stems of previous generation, similar to Dead Wood zone, which also had negative CH_4 flux in this study. This may be because of the fact that previous generation dead wood and stems are usually away from current generation crops, and thus away from shade resulting in higher surface temperature (Figure 5c) and lower moisture (Figure 3a) affecting CH_4 production. Methanotrophic microbial communities were known to be not affected by disturbance in tropical peatlands unlike methanogenic communities (Arai et al., 2014; Jackson et al., 2009), and methane absorption albeit minimal in this zone suggests the dominance of methanotrophs over methanogens. Understorey Ferns also had higher pH than most other sampling zones (Figure 3c), which may also negatively impact CH_4 production (Dhandapani & Evers, 2020) as acidic conditions are required to activate the precursors for CH_4 production (Qing-Yu et al., 2019). It should be noted that mean CH_4 fluxes were minimal in this study and were near zero, even though they significantly varied between sampling zones. It should also be noted that the canals and ditches would be filled with water in wet season, and have, at that point, high potential for CH_4 emissions (Manning et al., 2019).

The net positive mean CH_4 emissions for the site in this study are in contrast to net CH_4 absorption observed in the site in the previous years (Dhandapani et al., 2019a). This may be because of greater emissions in some of the sampling zones such as Understorey Ferns and Canal Edge zones that were not sampled in Dhandapani et al. (2019a). However, low CH_4 flux near zero is consistent with previous studies in Southeast Asian peatlands across land uses (Couwenberg et al., 2010; Dhandapani & Evers, 2020; Dhandapani et al., 2019a,b,c). CH_4 flux also exhibited positive relationship with carbon content. Similar positive relationship between Carbon content and CH_4 flux was previously observed in Malaysian peat swamp forests (Dhandapani et al., 2019c). This is in line with previous conditions that once the required moisture level is met for CH_4 production, their production is dependent on the availability of labile carbon in peatlands (Couwenberg, 2009). This validates part of our second hypothesis that CH_4 emissions are correlated with peat properties and nutrient concentrations; however, another part of the second hypothesis regarding CO_2 flux correlations with measured physico-chemical and nutrient properties is not validated.

The observed c.28% increase in emissions at Proximal areas in Cleared zone compared to Distal areas, corresponding to root-derived autotrophic CO_2 flux, is slightly lower than observations made at the site in 2016–2017 period, which showed 33.5% increase in CO_2 emissions near mature oil palm plants (Dhandapani et al., 2019b). This difference may be because of seasonal variation, as Dhandapani et al. (2019b) reported both wet and dry season emissions, while this study reports only the dry season CO_2 emissions. This is also within the range of other observations made in oil palm plantations in peatlands in other parts of Southeast Asia at 29% and 32.5% autotrophic contribution of mature oil palm to total CO_2 emissions reported by Dariah et al. (2014) and Matysek et al. (2017), respectively. This validated our third hypothesis that autotrophic emissions from mature oil palm trees significantly contribute to total CO_2 emissions.

5 | CONCLUSIONS

Taken together, our study demonstrates a high degree of heterogeneity in peat physico-chemical properties within a smallholder oil palm plantation. The nutrient variation along with small-scale variations of other physico-chemical properties amongst different heterogeneous regions show that intensive sampling is required to characterize a land use in tropical peatlands. The significant variations in many key macronutrients can have functional impact on soil microbial communities and related environmental processes such as nutrient cycling. These results taken alongside with our previous research in the study site (Dhandapani et al., 2019a) suggest that the use of complete random sampling with 25 measurement points was representative of the GHG emissions from the small holder oil palm land use. However, the significant variation among sampling zones in CO_2 emissions, the primary GHG in Southeast Asian tropical peat ecosystems, indicates the importance of accounting for these habitat characteristics in estimating the total emissions for the land use. Notably uncleared previous generation dead wood area in a plantation contribute to greater CO_2 emissions and CH_4 absorption in oil palm monoculture. Similarly, harvesting path and areas near understorey ferns were found to have greater CO_2 and CH_4 emissions, respectively. Future research on the balance between methanogenic and methanotrophic microbial communities in tropical peatlands would help us understand the mechanism behind the changes in CH_4 flux. Consistently higher CO_2 emissions in Proximal than Distal areas across the sampling zones imply the importance of taking the autotrophic contributions of mature oil palm root system into account while reporting total emissions for oil palm land use. Root-derived CO_2 estimates are important and required for any future models to understand carbon cycle and loss in tropical peatlands. There is a need for more research in this area, as oil palm management strategies widely vary from one smallholder to another, in addition to potential seasonal variations in some of these properties and GHG emissions in some heterogeneous zones within a plantation such as canals and ditches.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Selva Dhandapani https://orcid.org/0000-0001-8522-5177

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