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Oil palm ‘slash-and-burn' practice increases post-fire greenhouse gas emissions and nutrient concentrations in burnt regions of an agricultural tropical peatland

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Abstract

Fire is one of the major issues facing Southeast Asian peatlands causing socio-economic, human health and climate crises. Many of these fires in the region are associated with land clearing or management practices for oil palm plantations. Here we study the direct post-fire impacts of slash-and-burn oil palm agriculture on greenhouse gas emissions, peat physico-chemical properties and nutrient concentrations. Greenhouse gas (GHG) emissions were measured using Los Gatos ultraportable greenhouse gas analyser one month after a fire in dry season and five months after the fire event, in wet season. Surface soil samples were collected from each individual GHG measurement points, along with 50 cm cores from both burnt and non-burnt control areas for lab analyses. As an immediate post-fire impact, carbon dioxide (CO_2) and methane (CH_4) emissions, pH, electrical conductivity, and all macronutrient concentrations except nitrogen (N) were increased multi-fold, while the redox potential, carbon (C) and N content were greatly reduced in the burnt region. While some of the properties such as CO_2 emissions, and electrical conductivity reverted to normal after five months, other properties such as CH_4 emissions, pH and nutrient concentrations remained high in the burnt region. This study also found very high loss of surface peat C content in the burnt region post fire, which is irreversible. The results also show that surface peat layers up to 20 cm depth were affected the most by slash-and-burn activity in oil palm agriculture, however the intensity of fire can vary widely between different oil palm management and needs further research to fully understand the long term and regional impacts of such slash-and-burn activity in tropical peatlands.

Keywords: tropical peat fire; oil palm; carbon dioxide; methane; land use change; burnt peatlands.

1. Introduction

One of the most fundamental challenges of the 21st century is to meet the global food and energy needs of the growing population, whilst conserving nature and soil carbon (C) storage to mitigate climate change (Godfray et al., 2010). Oil palm is considered as a crop for the future to serve these global needs, owing to its high productivity and versatility in usage (Abdullah et al., 2009; Corley, 2009; Tan et al., 2009). Oil palm has become the most consumed vegetable oil in the world over the past decade, and already represents 30% of the global usage (Lam et al., 2019). However, as oil palm is an equatorial crop, this has come at the expense of some of the world's most biodiverse and C rich ecosystems (Corley, 2009; Koh and Wilcove, 2008; Murdiyarso et al., 2010; Murdiyarso et al., 2019). For the same reason, oil palm has a higher C footprint than most other vegetable oil crops (Schmidt, 2015), with its expansion into tropical peatlands further increasing its C footprint (Reijnders and Huijbregts, 2008).

Oil palm is native to West Africa, and was first introduced to Malaysia as an ornamental plant in 1875 (Abdullah et al., 2009) and then commercially as a crop of choice for agricultural diversification in 1917 (Rashid et al., 2013). The initial expansion of oil palm plantations was in mineral soil at the expense of other agricultural plantations such as cocoa, rubber and coconut (Basiron, 2007; Dhandapani, 2015). Since then, oil palm has rapidly expanded in Southeast Asia, greatly expanding into peatlands from early 1990s (Miettinen et al., 2012; Shevade and Loboda, 2019). As a consequence, Malaysia had the highest 21st century deforestation rate globally (Hansen et al., 2013). A forested land should be completely cleared of vegetation, drained and levelled to establish an oil palm plantation (Luskin and Potts, 2011). The lowering of water table in peatlands make them highly susceptible for fire, as the dry peat itself is highly flammable (Posa et al., 2011). Unlike contexts involving mineral soils, peat fires can sustain both above and below ground, profoundly affecting surface and subsurface biota and seed bank, damaging the vegetation structure (Posa et al., 2011; Turetsky et al., 2015; Uda et al., 2017).

The forest fires in Southeast Asia are often associated with land clearing for oil palm plantations (Chazdon, 1998; Dennis et al., 2005). An estimated 60,000 peatland fires have occurred in Indonesia between 1997 and 2007, causing harmful haze (Tan et al., 2009). About 2.6 million hectares of land was burned in Indonesia between June and October of 2015, which led Indonesian president to cancel existing concession on agricultural expansion and make conversion of peatlands to agricultural land illegal (World Bank, 2016). However, despite this, fires and the use of fire in peatland agriculture persists in both Malaysia and Indonesia. Furthermore, the use of fire is not just confined to the initial conversion and establishment stage, it is also commonly used in 'slash-and-burn' to burn the waste from previous generation oil palms to clear land for the next generation of crops. Slash-and-burn practice has been used all round the world as a quick short term activity to shift agriculture or for land clearing (Myllyntaus et al., 2002). Even though under certain circumstances in some ecosystems, slash-and-burn practice can be sustainable (Kleinman et al., 1995; Myllyntaus et al., 2002), it is certainly not sustainable in tropical peatlands in any circumstance, as dried peat itself is highly flammable, and fundamentally any agriculture involving drainage itself in tropical peatlands is not sustainable (Evers et al., 2017).

Fires in such tropical peatlands can convert large amount of C stored in peat for millennia into carbon dioxide (CO_2) and cause socio-economic, human health, pollution and climate crises (Cheong et al., 2019; Page et al., 2002; Turetsky et al., 2015; Wiggins et al., 2018). Tropical peatlands in their natural undisturbed state are fire resistant, and historically fire had not played any significant role in tropical peatland ecology (Turetsky et al., 2015). Most of these fires have anthropogenic origin such as clearing of forest land for oil palm or similar agricultural use, and slash-and-burn agricultural practices (Page et al., 2002). As tropical peatlands are naturally acidic, this deliberate use of fire for agricultural practices brings short-term advantages such as increase in pH and reduced cost for land conversion (Islam et al., 2016).

Though there were some research and estimates of direct emission from fire as smoke, haze or CO_2 (Cheong et al., 2019; Hu et al., 2019; Hu et al., 2018; Islam et al., 2016; Smith et al., 2018; Varkkey, 2013; Varkkey, 2016; Wiggins et al., 2018), the subsequent impact of fire on peat physico-chemical properties and long term peat surface GHG emissions are not well documented.

Peat fires can continue for a long time, lasting for months in the form of smouldering, persistent flameless low-heat combustion of organic matter (Ohlemiller, 1985; Rein, 2013). Smouldering in peatlands can be a complex process with interactions between aerobic and anaerobic conditions, where pyrolysis of porous fuel occurs in high temperature at anaerobic conditions, producing char (Ohlemiller, 1985; Rein, 2013) and the produced char is then oxidised when it comes in contact with atmospheric oxygen, simultaneously producing and burning char during the process (Rein, 2013). These complex interactions of aerobic and anaerobic conditions along with other variations in intensity of fire and peat moisture levels can greatly impact peat physico-chemical properties such as pH, electrical conductivity and redox potential, yet these properties are not well documented for fire affected tropical peatlands.

The limited number of studies that do exist, have shown that peat fire significantly reduces the organic matter content of the peat soil (Sazawa et al., 2018), as that very organic matter is lost as C gases during the fire (Wiggins et al., 2018). Sazawa et al. (2018) also found that fire and resultant heat dehydrates and denatures organic matter, which leaves fire affected peat more susceptible to greater C losses, either through oxidation or repeated fire. Fire is generally found to increase both total and available nutrient concentrations in mineral soils due to disintegration of complex forms held in plants, and ash addition (Giardina et al., 2000; Van Reuler and Janssen, 1993). This increase in available nutrients make soils more fertile, which is another motive for the practice of slash-and-burn agriculture (Giardina et al., 2000). There are also instances when total nutrient concentrations increased immediately after fire and then levelled off after few months (Kutiel and Naveh, 1987). The decrease in nutrient concentrations after few months may be because some of the nutrients are highly prone to leaching (Beliveau et al., 2015; Ulery et al., 1993). Similar increase immediately after a fire was also observed for other physico-chemical characteristics such as pH and electrical conductivity because of the addition of ash (Bang-Andreasen et al., 2017; Gay-Des-Combes et al., 2017), before reverting back to normal over time (Kutiel and Naveh, 1987). Fire may also effect increased mineralisation indirectly through soil microbial processes (Gay-Des-Combes et al., 2017). This is especially important in nutrient poor and acidic tropical peatlands, where fire is seen as a short-term and cost-effective solution to make peat more cultivable. Naturally, tropical peat is a very complex soil system and many of the environmental and microbiological interactions are understudied and not well known (Dhandapani et al., 2019c). The interactions of fire in such a complex soil system that is, in itself flammable (Rein, 2013; Uda et al., 2017), needs a more intensive and greater number of research with varying environmental parameters to comprehend and infer a cause and effect pattern.

In this study, we aim to evaluate the direct post-fire impact of slash-and-burn agriculture on peat physico-chemical properties, nutrient concentrations and GHG emissions. We hypothesise that fire increases both CO_2 and methane (CH_4) emission as an immediate post-fire effect. We also hypothesise that fire significantly affects peat physico-chemical properties and nutrient concentrations at surface layers, driven by high heat denaturing organic matter and the addition of ash increasing pH and nutrient concentrations. We postulate that changes in peat physico-chemical properties exhibit significant correlation with GHG emissions.

2. Materials and Methods

2.1. Study site and sampling strategy

The study site (3°25'17.7"N 101°18'44.4"E) is located at Kampong Raja Musa village in North Selangor peatlands, Malaysia (Fig 1). The climatic conditions of the site is tropical, and the soil classification comes under Histosols. The North Selangor peatland complex is the second largest area of peatland in Peninsular Malaysia, and is located adjacent to Thennamaram region, where oil palm was first commercially planted in Malaysia. The site is bordered with oil palm monocropping, polyculture consisting of oil palm, yam and pineapple, pineapple monocropping under an electric pylon trail, and a gravel road on the fourth side. The study site and all the neighbouring land-use type blocks are roughly 2 ha in size each, consistent with other small-holdings in the village (Dhandapani et al., 2019a,b). Two drainage ditches run as two parallel borders with the oil palm monoculture, and the oil palm, yam and pineapple polyculture. There is no drainage ditch within the site itself (Fig 2). The previous generation of oil palm monoculture was cleared and the waste such as dead wood and fronds were stacked in two parallel lines within the site. The stacked piles were burnt on June 2018, but with the fire front extending into the peat itself, and smoke still visible from smouldering of the peat surface for few weeks. The depth of burn was uneven throughout the burnt region, with surface reaching mineral layer in some parts, and some other parts still containing peat to a depth of atleast 50 cm from surface. New young oil palm rows were planted in non-burnt area in July 2018. Alongside this, a pineapple crop was planted in all open area in the non-burnt region and a banana crop was planted in rows in the burnt area, in between dry season (July 2018) and wet season (December 2018) sampling. Complete random sampling was carried out with 20 GHG measurements and surface peat (0-5 cm) collection each for burnt and non-burnt region during August 2018 dry season.

All sampling points were at least 1 metre away from each other. The same method was used for December 2018 wet season sampling with reduced number of measurements to 10 each for burnt and non-burnt region. The dry season measurement points were not the exact measurement points used for the wet season, however they are in the same general area of burnt and non-burnt locations used for the wet season measurements. The measurement points from the first sampling were not marked with collars in order to minimise the disturbances from disturbance from our field measurements, and hence a different set of random measurement points in the same region were used for wet season sampling. Weather information for each sampling period is given in Table 1. During the dry season sampling, 3 peat cores to a depth of 50 cm were collected for each burnt and non-burnt region. In some areas of burnt area peat was completely burnt and mineral layers was reached at the surface. Selective sampling was carried out for core collection, unlike complete random sampling for GHG measurements and associated surface peat collection. The 3 peat cores for burnt region were collected from burnt areas with peat remaining and not the areas with surface mineral exposure, to characterise the impact on leftover peat through the peat depth profile.

2.2. Greenhouse gas 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 measurements were made using closed dynamic chamber method with an inlet and outlet connecting to the gas analyser. The dynamic chamber was inserted up to 1 cm into the peat during each measurement, to seal the chamber to the surface. The chamber was 15 cm high with 27 cm diameter. The Los Gatos gas analyser was set to record the gas flux changes within the chamber every 20 seconds, and measurement was made at each sampling point for 3 minutes, where the measurements from the first minute were ignored allowing the gas concentrations inside the chamber to settle down after initial disturbance. The gas concentrations were then converted to mg CO_2 m^{-2} hr^{-1} and µg CH_4 m^{-2} hr^{-1} for CO_2 and CH_4 respectively, as described in Dhandapani et al. (2019a,b,c).

2.3. Peat analyses

The procedure used for peat analyses were based on Dhandapani et al., (2019a,b,c). Peat temperature was measured *in situ*, using a digital thermometer Cosmark PDT300 (Norwich, UK). Peat samples were collected for measuring gravimetric moisture. For this, fresh peat was dried in an oven at 105°C for 48 hours. The gravimetric moisture was calculated as follows:

Gravimetric moisture (%) = Mass of the water lost in oven drying/ mass of oven dried peat

For pH, redox and electric conductivity measurements, 5 mL volume of peat sample was diluted in 10 mL deionised water in a centrifuge tube and shaken on a table shaker for 2 hours. The pH of the supernatant was then measured using a Eutech pH700 pH meter supplied by Thermo scientific (Loughborough, UK). The redox potential and electrical conductivity were measured using Eutech Ion 2100 (Thermo scientific, Loughborough, UK) and Groline HI98331 probe (Hanna, Leighton Buzzard, UK), respectively.

For analysing total C and nitrogen (N) content, all samples were oven dried (105°C for 48 h) and finely ground using a Fritsch mortar grinder pulveristte 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 C and N content.

2.4. Nutrient analyses

Total nutrient concentrations of phosphorus (P), calcium (Ca), magnesium (Mg), sulphur (S) and potassium (K) in peat 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 were weighed in microwave digestion tubes (MARSXpress vessels, CEM Microwave Technology Ltd., Buckingham, UK.). The digestion tubes are 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., Buckingham, UK.) and run at 1600 W & 100% power with a ramp for 20 minutes and held for 20 minutes at 170°C. The tubes were left overnight in the microwave to cool down. The digested samples were then filtered and made up to 30 mL using milliQ water. Then, 1 mL of each sample were 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. Statistical analyses

All the statistical analyses were carried out using Genstat® 17th edition (VSN international, 2017). The significance of differences between sites for greenhouse gas emissions, nutrient concentrations and other physico-chemical properties were evaluated using linear mixed models with restricted maximum likelihood (REML) incorporating conditions (burnt or non-burnt) and season (August and December 2018) as fixed affects. Similar REML was also performed incorporating condition and depth as fixed effects, to identify the changes with depth. For the data sets that were not normally distributed, the data were log transformed. For data that did not meet normality assumption after log transformation, Boxcox transformation was used. Normality was assessed by visual examination of 4 different residual plots, namely histogram of residuals, fitted-value plot, normal plot and half-normal plot. Backward stepwise multiple regression was performed with CO_2 and CH_4 as response variables and nutrient concentration and other physico-chemical properties as fitted terms. Statistical significance was assessed at $p < 0.05$ for all analyses.

3. Results

3.1. Greenhouse gas emissions

CO_2 emissions in the burnt region were twice as high as the CO_2 emissions from the non-burnt region in the dry season one month after the fire incident (Fig 3a; Table 2). In wet season, five months after the fire incident, CO_2 emissions in the burnt region levelled off to the same level as non-burnt region. The difference between the seasons were significant, while the interactions between regions and season were not significant (Table 2).

CH_4 emissions also varied significantly between the burnt and non-burnt regions (Fig 3b; Table 2). CH_4 emissions were multi-fold higher in the burnt region than in the non-burnt region for both seasons, while the seasonal variations and interaction terms were not significant (Table 2).

3.2. Surface peat/soil properties

Peat surface temperature did not significantly differ between burnt and non-burnt regions, with significantly higher temperature in dry season than in wet season (Fig 4a; Table 2). The wet season temperature was slightly yet significantly different between the regions, resulting in significant interactions terms. Gravimetric moisture did not significantly vary between the burnt and non-burnt regions, while both regions had significantly higher gravimetric moisture content in wet season than in dry season with no significant interaction between region and season (Fig 4b; Table 2). During the dry season, electrical conductivity was more than 3 times higher in the burnt region than in the non-burnt region resulting in significant difference between the regions. Electrical conductivity was greatly reduced in wet season compared to that of the dry season, resulting in significant seasonal variation (Fig 4c; Table 2). During the wet season there was no significant difference in electrical conductivity between the two regions while the difference was significant in dry season, resulting in significant interactions (Fig 4c; Table 2). Both redox potential and pH were significantly higher in the burnt region than in the non-burnt region, with no significant difference between seasons nor significant interactions (Fig 4d,e; Table 2).

3.3. Surface peat/soil C and nutrient content

C content in the non-burnt region was more than double the content in the burnt region, with no significant difference between seasons or interactions (Fig 5a; Table 2). N content was also significantly higher in the non-burnt region than in the burnt region, and both regions had significantly higher N content in wet season than in the dry season, with no significant interactions between region and season (Fig 5b; Table 2). The C:N ratio was higher in the non-burnt region during the dry season and the ratio was higher in the non-burnt region for wet season, resulting in significant seasonal variations and significant interaction terms (Fig 5c; Table 2).

All the rest of the macronutrients except N and S were greater in the burnt region than in the non–burnt region and only S and K varied significantly between seasons with lower concentrations for the burnt region in wet season (Fig 5d-h; Table 2). All macronutrients except K exhibited significant interactions between seasons, as most nutrient concentrations did not significantly differ between seasons in the non-burnt region (Fig 5d-h; Table 2).

3.4. Changes with peat depth

Electrical conductivity and pH were significantly higher in the burnt than in non-burnt region, while the variations with depth and the interactions were not significant (Fig 6a,c; Table 3). Gravimetric moisture in the non-burnt region was significantly higher than that of burnt region in all depths (fig 6b,c; Table 3). The gravimetric moisture increased up to 20-30 cm and 30-40 cm for burnt and non-burnt region respectively (fig 6b; Table 3) and then showed a slight decrease in deepest layers. Redox potential was significantly lower in the burnt region than in the non-burnt region in the top 3 surface layers upto the depth of 30 cm (Fig 6d; Table 3).

Redox potential increased with depth in the burnt region while the redox potential in the surface was slightly lowered in 10-20 cm and stayed at the same level in the deeper layers, resulting in significant seasonal variations and interaction terms (Fig 6d; Table 3).

C content was significantly greater in the non-burnt region than in the burnt region with no significant variations with depth nor interactions (Fig 7a; Table 3). N content and C:N ratio did not significantly vary between regions or depth, with no significant interactions between region and depth (fig 7b,c; Table 3).

All macronutrient concentrations except S and N were significantly greater in the burnt than in the non-burnt region (Fig 7d-h; Table 3). Mg, P and Ca concentrations significantly decreased with depth, which is more pronounced in the burnt region (Table 3). Mg and Ca exhibited significant interactions between region and depth, as the concentration in the burnt region decreased with depth whilst the concentrations in the non-burnt region stayed at the same level throughout the depths. K and S did not show any significant variations with depth, nor any significant interaction between region and depth (Fig 7f,g; Table 3).

3.5. GHG emissions and environmental controls

Backward stepwise multiple regression showed that CO_2 emissions were positively correlated with pH and electrical conductivity and negatively correlated with P and K concentrations (Table 4).

Similar regression for CH_4 emissions showed that the CH_4 emissions were negatively correlated with pH and P concentrations, and positively correlated with Ca concentrations (Table 4).

4. Discussion

Drainage for agriculture in peatlands were known to increase the CO_2 emissions with exposure of peat to aerobic decomposition (Couwenberg et al., 2010; Dhandapani et al., 2019a; 2019c), this study shows that the use of fire in management practices results in further increase in CO_2 emissions post fire (Fig 3a). There are several factors that may have played a part in this increase in emissions in fire affected region, such as increased pH and increased concentrations of macronutrients. It should be noted that the CO_2 emissions decreased and levelled off with that of non-burnt region after few months in the wet season, while the CO_2 emissions from the non-burnt region did not significantly vary between the seasons, suggesting that this artefact was not just seasonal variations of CO_2 emissions, but rather a reverting of emissions along a temporal gradient since the fire. However, while CO_2 emissions of pristine, secondary peat forests and first generation oil palm showing no significant seasonal variations, seasonal variation have been observed in second generation agricultural systems in the area (Dhandapani et al., unpublished; Dhandapani et al., 2019a; 2019c; 2020).

The observed increase in CO_2 emissions post fire may be due to intense disturbance during fire and subsequent changes in peat physicochemical properties such as increased pH, electrical conductivity and nutrient concentrations (Fig 4c-e; Fig 5d-h), along with breakdown of complex organic matter due to fire and new exposure of deeper peat layers to aerobic conditions (Sazawa et al., 2018). However, this increase is short lived as the surface conditions are stabilised over time and also possibly because of greater loss of newly acquired nutrients over time (Fig 4c; Fig 5d-h). This trend of initial increase and consequent decline in CO_2 emissions post fire was previously observed by Astiani et al. (2018) in West Kalimantan peatlands. It should be noted that in Astiani et al. (2018)'s study, the peak in emission was observed in the 9th month post fire, and emissions stabilising at the 11th month post fire. The stabilisation of emissions in 5th month post fire (Fig 3a) in our study may be due to a lower intensity localised fire in our agricultural study site, compared to high intensity fire burning much greater forest biomass in Astiani et al. (2018)'s study that would likely result in greater disturbance, greater nutrient addition from resultant ash, and thus would require greater time to recover and stabilise.

CH_4 emissions were also significantly higher in the burnt region than in the non-burnt region and stayed at similar higher levels even into the wet-season, five months after the fire event (Fig 3b). It was previously observed that fire would make the peat dry and effect lower CH_4 emissions from the burnt areas because of the lack of moisture (Davidson et al., 2019), but this study has shown that at similar moisture levels, burnt peat has a potential for higher CH_4 emissions than the non-burnt peat. This higher CH_4 emissions in the fire-affected region may be due to the availability of more labile C due to the denaturation of peat by fire and resultant heat (Sazawa et al., 2018). Once the moisture level for anaerobic conditions are met, CH_4 emissions are dependent on the availability of labile C in peatlands (Couwenberg, 2009). Fire in peatlands are also known to reduce methanotrophic activity (Danilova et al., 2015), further helping the increase in CH_4 concentration in the burnt areas. However, it should be noted that CH_4 emissions are very low overall, with mean values under 0.1 mg $m^{-2}hr^{-1}$, which is in line with the lower near zero fluxes observed in different oil palm agricultural plantations in the region. Southeast Asian peatlands are naturally low methane emitting landscapes (Dhandapani et al., 2019c; Hatano et al., 2016) compared to peatlands in other regions such as neotropics (Wright et al., 2013), boreal (Kettunen et al., 1996) or temperate regions (Abdalla et al., 2016). This validates our first hypothesis that greenhouse gas emissions are significantly increased in the fire affected burnt region in relation to the non-burnt region.

The surface peat temperature and moisture did not significantly vary between the burnt and non-burnt region, possibly because both regions are open with no ground cover to provide shade and cool down surface peat (Dhandapani et al., 2019a). The significant seasonal changes in both these properties were as expected (Dhandapani et al., 2019a), with higher moisture and lower temperature in both regions during wet season, because of increased rainfall in wet season compared to the dry season (Global Environmental Centre, 2014). Similarly, higher moisture with increasing depth were also as expected, as the top layers in these agricultural peatlands are actively drained, and the surface layers are exposed to the sun, further facilitating increased temperature and evaporation in the surface layers. Most other physico-chemical properties and nutrient concentrations showed that the surface layers such as 0-10cm and 10-20cm showed significant difference between burnt and non-burnt regions before gradually narrowing in on the difference, to the same level in deeper layers starting from 20-30cm layer.

Redox potential is an important soil property which shows the electron exchange capacity for reduction and oxidation reactions that have great impact on nutrient availability and dynamics in soil by changing their electric charges (Niedermeier and Robinson, 2007; Søndergaard, 2009). The reduction in redox potential in the burnt region shows the possible lack of oxidants in the burnt area (Fiedler, 2000). This is likely to be caused by fire, as this difference is observed only in the surface layers, with deeper layers having same level of redox potential in the deepest layers for both burnt and non-burnt regions. Fire were known to accumulate new particulate C forms in mineral soil humus layers that are highly resistant to redox reactions (González-Pérez et al., 2004), a similar trend is observed here in peat soil where fire affected surface layers have low redox potential.

Electrical conductivity and pH increased one month after fire, however electrical conductivity levelled off with that of non-burnt region during wet season, five months after the fire activity. The increase in pH after fire has been widely reported in different soil environments (Chungu et al., 2019; Heydari et al., 2017; Kennard and Gholz, 2001; Scharenbroch et al., 2012; Zaccone et al., 2014), that also holds true for highly acidic tropical peatlands where pH was almost twice as high in the burnt region compared to non-burnt region (Fig 4e). This increase may be directly related to the addition of ash from burning (Bang-Andreasen et al., 2017; Zaccone et al., 2014), as shown by the significant increase only in the top 20 cm surface layers. Electrical conductivity exhibited very similar trend of change with depth as pH, possibly because of the same influence of ash addition in the top layers (Bang-Andreasen et al., 2017; Zaccone et al., 2014). Electrical conductivity indicates the salt content and is considered a rough estimate of soil nutrients that influence important soil processes such as GHG emissions (Visconti and De Paz, 2016). The significant reduction of electrical conductivity and levelling off during the wet season possibly shows that many of the nutrients that are made available after fire (Beest et al., 2019), were leached off in the proceeding few months (Beliveau et al., 2015), aided by heavy rainfall during the wet season (Global Environmental Centre, 2014). This is also evident in reduced concentration of all macronutrients in the wet season (Fig 5).

All of the macronutrients except N increased in the burnt region one month after fire and slightly decreased over time, yet remained higher than the concentrations in the non-burnt region throughout the seasons, except for S that had lower concentration in the burnt region than in the non-burnt region in wet season. The nutrients that are strongly basic and form important salts such as Mg and Ca (Visconti and De Paz, 2016), explicably exhibited the same trend of change with depth as pH and electrical conductivity. P is also widely reported to increase in concentration in burnt peat and soil, as fire causes the release of P from organic materials (Beest et al., 2019; Wang et al., 2015). The increase in Ca, Mg and K concentrations in the burnt region can also be attributed to high content of these nutrient in wood ash that accumulated in the region as a result of burning previous generation oil palm stems (Kennard and Gholz, 2001). These nutrients are also found to be highly susceptible to leaching (Kennard and Gholz, 2001), explaining the lower concentrations in wet season sampling, few months after the fire event. C content was reduced to half in the surface layers, because of the C lost on the burning of organic peat on the surface (Wiggins et al., 2018). The peat cores were selectively collected in areas where the peat is not completely burned off, thus the difference in C content between the surface layers in the cores and high replicate surface samples associated with GHG emission measurements (Fig 5a and 7a). However, it should be noted that lower number of replicate peat cores may also be a factor limiting the usability of these results. This validates our second hypothesis that peat physico-chemical properties and nutrient concentrations were significantly affected by fire, and most of these properties showed significant variations with depth.

These changes in physico-chemical properties were significantly correlated with CO_2 and CH_4 emissions, most visibly CO_2 emissions exhibited the same pattern of change as electrical conductivity and pH of surface peat. Multiple regression analyses showed that peat physico-chemical properties and total nutrient concentrations were strong predictors of change in CO_2 and CH_4 emissions (Table 4). CO_2 emissions from tropical peat of different land uses are known to exhibit positive correlations with pH (Dhandapani et al., 2019a) and our results show that the fire event resulting in sudden and steep increase in pH does not override this relationship. Inversely, CH_4 was negatively related with pH, this negative correlation has also been observed in northern peatlands (Weslien et al., 2009). Acidic condition is a prerequisite to functionalise precursors such as H_2/CO_2, acetic acid, formic acid, methanol and methylamine, for CH_4 production (Qing-Yu et al., 2019), thus explaining this functional relationship between pH and CH_4 emissions in the field.

The positive relationship between electrical conductivity or salinity and CO_2 emissions has been observed in other ecosystems (Capooci et al., 2019), however this is the first time such relationship is explored and reported in tropical peatlands. Though very high or excess salinity can be toxic and can negatively impact microbial activity and reduce CO_2 production (Setia et al., 2013; Yan et al., 2015), tropical peatlands are naturally nutrient poor (Sjögersten et al., 2011) and this increase in electrical conductivity due to fire boosted CO_2 production (Table 4). P concentrations were negatively related with both CO_2 and CH_4 emissions. Additionally, CO_2

emissions were negatively related with K, and CH_4 emissions were positively related with Ca. Nutrient dynamics (with the exception of N) and their interactions with other peat processes such as C cycling were not well documented in agricultural tropical peatlands. Addition of manures containing these macronutrients had different effects on GHG emissions in different soil types (Ren et al., 2017), and their cause and effect pattern in tropical peatlands need more *in situ* research coupled with controlled experiments to understand the interactions, especially considering that they exhibit significant functional correlations with GHG emissions. However, P is known to support methane oxidation reactions in soil (Veraart et al., 2015) and similarly limited addition of Ca compounds were known to support methane production in varied set ups (Khor et al., 2015; Lar et al., 2010), suggesting similar functional relationship in tropical peatlands. In line with this, Murakami et al. (2005) also found CH_4 potential increased with liming ($CaCO_3$ addition) in agricultural tropical peatlands. This validates our third hypothesis that the changes in soil physico-chemical properties and nutrient concentrations correlate with changes in GHG emissions.

As oil palm is a high biomass crop, there is a potential alternative for the biomass removed from previous generation to be used for biochar production, which then could be used to enrich, and return C back to agricultural peatlands, potentially retaining some of the benefits of slash-and-burn practice such as increased pH and nutrient concentrations (Bista et al., 2019; Kong et al., 2014; Liew et al., 2018). Such biochar can be produced using methods ranging from constructing a conical soil pit in the ground, and simple conical or retort kilns to modern microwave pyrolysis equipment (Liew et al., 2018; Arafat Hossain et al., 2017). However socio-economic feasibility, and practicality of such alternatives for biomass management are yet to be explored and researched. There is a need for increased research in understanding the holistic environmental and socio-economic impacts of slash-and-burn practice in tropical peatlands, and other alternative practices for land clearing and biomass management between oil palm generations. This study is a step towards such understanding of the impacts of different practices. Further research addressing these issues will help us make informed suggestions on land use policies and management practices, for rapidly increasing area of agricultural tropical peatlands.

5. Conclusion

The use of fire for slash-and-burn management practice severely alters peat physico-chemical properties and increases post-fire greenhouse gas emissions and peat nutrient concentrations. While some of the properties such as CO_2 emissions, and electrical conductivity reverted back to normal level after few months, other properties such as CH_4 emissions, pH and nutrient concentrations remained high in the burnt region, though nutrient concentrations were significantly reduced over time, possibly due to leaching. This study has shown very high loss of surface peat C content due to fire, which is irreversible. This has important implications if such a loss occurred in all agricultural peatlands in the region through slash-and-burn activity. The practice of intercropping was previously known to prolong defining peat properties and ameliorate environmental impacts of oil palm agriculture in peat, but the current results show that use of fire as a management practice overrides any such benefits from intercropping, because of high C loss. The peat surface physico-chemical properties and nutrient concentrations also exhibited functional correlations with GHG emissions, providing new insights into complex interactions between different biogeochemical processes in tropical peatlands. The results also show that peat layers from surface to 20 cm depth were most affected by this particular slash-and-burn activity in oil palm agriculture. However, the intensity of fire can vary widely between different oil palm management and needs further research to fully understand the long term and regional impacts of such slash-and-burn activity in tropical peatlands.

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Figure Captions

Figure 1: Location of the study site.

Figure 2: Site pictures - a) picture of the study site during smouldering fire July 2018 b) picture of the site during the dry season measurements, one month after the fire event, in August 2018 c) picture of the site during the wet season measurements, five months after the fire event, in December 2018.

Figure 3: Effect of burnt and non-burnt region, and season upon a) CO_2 emissions b) CH_4 emissions, during dry and wet season. Bars denote mean values (for dry season n=20 each region; for wet season n=10 each region). Whiskers denote standard errors.

Figure 4: Effect of burnt and non-burnt region, and season upon a) Peat surface temperature b) gravimetric moisture c) electrical conductivity d) redox potential e) pH during dry and wet season. Bars denote mean values (for dry season n=20 each region; for wet season n=10 each region). Whiskers denote standard errors.

Figure 5: Effect of burnt and non-burnt region, and season upon peat a) C content b) N content c) C:N ratio d) Mg concentrations e) P concentrations f) S concentrations f) K concentrations g) Ca concentrations during dry and wet season. Bars denote mean values (for dry season n=20 each region; for wet season n=10 each region). Whiskers denote standard errors.

Figure 6: Effect of burnt and non-burnt region, and depth upon a) pH b) gravimetric moisture c) electrical conductivity d) redox potential during dry season. Points denote mean values (n=3 for each region). Whiskers denote standard errors.

Figure 7: Effect of burnt and non-burnt region, and depth upon peat a) C content b) N content c) C:N ratio d) Mg concentrations e) P concentrations f) S concentrations f) K concentrations g) Ca concentrations during dry season. Bars denote mean values (n=3 for each region). Whiskers denote standard errors.