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Assessing the role of artificial compaction on physicochemical properties and carbon emissions of tropical peat soils

Marshall Kana Samuel (MEnvSci)

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PhD Supervisory Committee

Dr. Stephanie Evers (Main Supervisor)

School of Natural Sciences and Psychology, Liverpool John Moores University, United Kingdom.

Dr. Matthew Ashfold (Co-supervisor I)

School of Environmental and Geographical Sciences, University of Nottingham Malaysia Campus, Malaysia.

Dr. Thomas Smith (Co-supervisor II)

Department of Geography and Environment, London School of Economics and Political Science, United Kingdom.

Dr. Sofie Sjögersten (Co-supervisor III)

School of Biosciences, University of Nottingham Main Campus, United Kingdom.

PhD Thesis Opponents

Dr. Lim Yin Sze (Internal examiner)
School of Biosciences, University of Nottingham Malaysia Campus, Malaysia.

Dr. Massimo Lupascu (External examiner)
Department of Geography, National University of Singapore, Singapore.

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Abstract

Compaction is undertaken because of claims that confined and restricted peat pores may enhance soil moisture due to the effect of capillary rise. The increase in soil moisture is said to lead to additional benefits of reduced C emissions and reduced risk and extent of peat fires. Nevertheless, information pertaining to induce compaction on peat physicochemical properties and carbon emission seems to be in scarcity. This thesis explored the notion of a misconception in definition of peat compaction in tropical peatland landscape due to confounding factors between (passive) natural compaction by oxidation, shrinkage and compression and (active) artificial compaction- by heavy machinery. This study suggest that this could be a reason for wide interpretation on peat compaction processes. Therefore, the aim of this research project was to assess the impact of artificial compaction on the tropical peat physicochemical properties and carbon emissions from peat surface as well through peat fire.

To make such a contribution, a series of experiments was conducted at matured oil palm plantation (OP) and secondary peat swamp forest (SF) located in Selangor, Peninsular Malaysia. This study first to explore the source of compaction efforts in OP. Holding an assumption that microsites are different in term of bulk density value (compaction) due to agri-management, the findings are inconclusive. Despite fruitless experiment, this study continues to assess the potential and effects of artificial compaction by profile compaction magnitude (induce compaction efforts) on physicochemical properties and carbon emission by implementing *in-situ* and *ex-situ* approaches. The mechanisms of artificial compaction are explored further by measured and determined physicochemical

properties and carbon emission from peat surface and fire. Subsequently, correlations between physicochemical properties and carbon emission were established.

To simplify, this study yielded a number of main key findings: (1) Tropical peat compaction as marked by bulk density (BD) value in matured oil palm plantation relies on the degree of peat oxidation by periodical drainage. (2) It is challenging to achieve artificial compaction on tropical peatland due to labile soil organic matter that leads to self-regulatory mechanism through water table fluctuation. (3) Extremely low water table level and high labile carbon proportion may aid artificial compaction by consolidating varied decomposition degrees between peat horizons from surface and deeper peat. This resulted in average temporary inverse CO_2 and CH_4 emissions by the percentage ratio of *ca.* 1:2, and later, taken over by water table level control. (4) Oxidative or passive compaction leads to higher emission factor (EF) from fire path, owing to peat in advanced decomposition state.

In other words, this study does not recommend applying artificial compaction to either land use type. Primarily this is because: (1) there is no effect from the practice on already drained peatlands; (2) undertaking this in degraded sites as a mechanism to reduce emissions as part of rehabilitation in sites marked for reforestation and rewetting would likely fail due to the fact that compressed peat will return to its original structure due to the increased water table fluctuation or even via rainfall, or any interaction with water sources such that the efforts to induce artificial compaction on tropical peatland are rendered useless; (3) when considered in relation to global warming potential, the results from compacting treatments within the forest soils indicated negligible CH_4 emission in

relation to $CO_{2\text{-eq}}$ though the enhancement is 2-fold greater than the reduction of CO_2. As such the net effect is 41.1 t $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}. However, even if net emissions are reduced by 33%, emissions are still not countered by organic matter inputs so are still net emissions to atmosphere. Furthermore, soils would still be are vulnerable to the "birch effect" when seasonal rewetting does occur. (4) To minimize fires moving forward as well the emissions from future fires, raising water tables will both reduce fire occurrence but will also contribute to decreasing BD value where fires do occur. This result also highlights that any efforts to compact peat as a mitigation measure against fire is in fact more likely to increase EFs overall. Lastly, it is suggested that the terminology of compaction should be differentiated according to the nature of compaction: (1) oxidative or shrinkage compaction or passive compaction —oxidation of peat due to lowered water table, causing peat to collapse and become compressed under its own weight; and (2) artificial or active compaction—induced by horizontal load compression that causes admixture (consolidation) between distinct degrees of decomposition in peat.

Keywords*: bulk density; carbon emission; decomposition degree; peat compaction definition; peat surface and peat fire; physicochemical alteration; tropical peatland; water table level*

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$PV = nRT$ **Eq. (2.10)** 53

$V = \pi r^2 h$ **Eq. (4.1)** 123

$h = \frac{g}{\pi r^2 BD}$ **Eq. (4.2)** 125

$ER_{\frac{i}{y}} = \frac{\Delta[i]}{\Delta[y]} = \frac{[i] - [i]_{background}}{[y] - [y]_{background}}$ **Eq. (5.1)** 166

$EF_i = ER_{i/c0} \times \frac{MM_i}{MM_{co}} \times EF_{CO}$ **Eq. (5.2)** 166

$EF_{CO_2\ or\ CO} = (Fc - PMC) \times 1000 \times \frac{MM_{CO_2\ or\ CO}}{12} \times \frac{\Delta_{CO_2\ or\ CO}}{\sum_{i=1}^{n}(\Delta NCi \times \Delta i)}$ **Eq. (5.3)** 167

$MCE = \frac{\Delta CCO2}{\Delta CCO2 + \Delta CCO}$ **Eq. (5.4)** 167

List of Publications

Matysek, M., Evers, S., **Samuel, M. K.**, & Sjogersten, S. (2018). High heterotrophic CO_2 emissions from a Malaysian oil palm plantation during dry-season. *Wetlands Ecology and Management*, 26 (3), 415–424. https://doi.org/10.1007/s11273-017-9583-6

Wijedasa, L. S., Jauhiainen, J. , Könönen, M. , Lampela, M. , Vasander, H. , Leblanc, M. , Evers, S. , Smith, T. E., Yule, C. M., Varkkey, H. , Lupascu, M. , Parish, F. , Singleton, I. , Clements, G. R., Aziz, S. A., Harrison, M. E., Cheyne, S. , Anshari, G. Z., Meijaard, E. , Goldstein, J. E., Waldron, S. , Hergoualc'h, K. , Dommain, R. , Frolking, S. , Evans, C. D., Posa, M. R., Glaser, P. H., Suryadiputra, N. , Lubis, R. , Santika, T. , Padfield, R. , Kurnianto, S. , Hadisiswoyo, P. , Lim, T. W., Page, S. E., Gauci, V. , Van Der Meer, P. J., Buckland, H. , Garnier, F. , **Samuel, M. K.**, Choo, L. N., O'Reilly, P. , Warren, M. , Suksuwan, S. , Sumarga, E. , Jain, A. , Laurance, W. F., Couwenberg, J. , Joosten, H. , Vernimmen, R. , Hooijer, A. , Malins, C. , Cochrane, M. A., Perumal, B. , Siegert, F. , Peh, K. S., Comeau, L. , Verchot, L. , Harvey, C. F., Cobb, A. , Jaafar, Z. , Wösten, H. , Manuri, S. , Müller, M. , Giesen, W. , Phelps, J. , Yong, D. L., Silvius, M. , Wedeux, B. M., Hoyt, A. , Osaki, M. , Hirano, T. , Takahashi, H. , Kohyama, T. S., Haraguchi, A. , Nugroho, N. P., Coomes, D. A., Quoi, L. P., Dohong, A. , Gunawan, H. , Gaveau, D. L., Langner, A. , Lim, F. K., Edwards, D. P., Giam, X. , Van Der Werf, G. , Carmenta, R. , Verwer, C. C., Gibson, L. , Gandois, L. , Graham, L. L., Regalino, J. , Wich, S. A., Rieley, J. , Kettridge, N. , Brown, C. , Pirard, R. , Moore, S. , Capilla, B. R., Ballhorn, U. , Ho, H. C., Hoscilo, A. , Lohberger, S. , Evans, T. A., Yulianti, N. , Blackham, G. , Onrizal, , Husson, S. , Murdiyarso, D. , Pangala, S. , Cole, L. E., Tacconi, L. , Segah, H. , Tonoto, P. , Lee, J. S., Schmilewski, G. , Wulffraat, S. , Putra, E. I., Cattau, M. E., Clymo, R. S., Morrison, R. , Mujahid, A. , Miettinen, J. , Liew, S. C., Valpola, S. , Wilson, D. , D'Arcy, L. , Gerding, M. , Sundari, S. , Thornton, S. A., Kalisz, B. , Chapman, S. J., Su, A. S., Basuki, I. , Itoh, M. , Traeholt, C. , Sloan, S. , Sayok, A. K. & Andersen, R. (2017). Denial of long-term issues with agriculture on tropical peatlands will have devastating consequences. *Glob Change Biol*, 23: 977-982. Doi:10.1111/gcb.13516

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Samuel, M. K., & Evers, S. (2016). Microsites surface area correction for carbon gas emissions from oil palm plantation, *In International Peat Congress 2016, 15-19 August 2016, Kuching, Sarawak.* Retrieved from https://doi.org/10.13140/ RG.2.2.13063.808

Achievements

1. Best project proposal presentation entitled “Biodegradable Floating Material (BFM) as back to basics planting media of *Macaranga* spp. on tropical peat swamp forest” and ‘Best Overall Group” in *National Workshop on “Domestication of Climax Rainforest Species in Disturbed Sites”* on 14 -17 November 2016. Organised by Forest Research Institute Malaysia (FRIM) and AfoCo (Asian Forest Cooperation Organization).

2. Participant Assistance Programme (PAP) prize to attend *National Workshop on “Domestication of Climax Rainforest Species in Disturbed Sites”* on 14-17 November 2016. Organised by Forest Research Institute Malaysia (FRIM) and AfoCo (Asian Forest Cooperation Organization)

3. Bronze medal (knowledge category) in *MARDI Science and Technology Exhibition (MSTE 2019)* with poster entitled “Does artificial compaction on tropical peatland affects carbon emissions?” on 29-30 October 2019 at Taman Ekspo Pertanian Malaysia Serdang (MAEPS).

Chapter 1. General Introduction

1.1 Overview

Tropical peatlands are very fragile and sensitive ecosystems. Conversion of these areas into agricultural farms demands intensive inputs and management that may affect the ecosystem and subsequently result in land degradation, as well as environmental problems. Tropical peatlands require intensive and proper management for sustainable crop productivity. Drainage of tropical peatland results in changes of soil physicochemical properties and microbial activity, which influence the release of CO_2, CH_4, organic acids, and organic particulates. The rate of carbon loss is also expected to be affected by climate change (e.g. Cooper *et al.,* 2019), particularly from the establishment of oil palm through the drainage and conventional slash-and-burn technique. The compaction method, from a different stance, is currently adopted by Sarawak-based oil palm companies to mitigate the uprising environmental issues. The peat artificial compaction method is claimed to be effective in minimising the risk of fire through enhancement of soil moisture (Busman *et al.,* 2018; Melling & Henson, 2011; Melling & Tang, 2018). In fact, several studies have assessed if peat compaction may positively affect mechanical anchorage for palm stand and nutrients retention (Anuar *et al.,* 2008; Melling & Henson, 2011; Mutert *et al,* 1999). The resultant compressed soil may affect the amount and the nature of both aerobic and anaerobic peat materials, which subsequently can affect the decomposition of peat material. This study investigates the potential impact of compaction practice on tropical peatland. The retrieved information could serve as basic platform to further probe into the highlighted aspects, and may as well function as a guide for management of these sensitive ecosystems, particularly in light of carbon loss mitigation.

1.1.1 Tropical peatlands - background

Peatlands are vital for ecological function as terrestrial carbon sequestration. These ecosystems are characterised by waterlogged, high organic matter environments where reduced oxygen levels in the soil result in slow and only partial decomposition of the organic matter produced by the vegetation growing upon them (Purmalis *et al.,* 2013; Swails *et al.,* 2017; Waldron *et al.,* 2019; Yule & Gomez, 2009). As a result, there is a net gain in in organic matter, high in carbon which accumulates over thousands of years (Carlson *et al.,* 2015; Melling, 2016; Yule & Gomez, 2009). This fragile ecosystem is therefore completely dependent on both the waterlogged (high water table) conditions and the vegetation growing above (Frank *et al.,* 2014; Nahrawi *et al.,* 2011; Yule & Gomez, 2009). In their natural state, peatlands actively sequester carbon and, as such, play a globally significant role in mitigating against climate change (Lal, 2004). Wetland International have estimated that this ecosystem stores up to 550 Gt of the world's carbon pool under, of which approximately 247,778 km^2 or 68.5 Gt distribution across Southeast Asia (Page *et al.,* 2011). In fact, Malaysia alone reported a *ca.* 9.1 Gt carbon pool which contributes approximately 60% to the total forest carbon pool (Page *et al.,* 2011). Nonetheless, these peatland areas have been exploited intensively due to deforestation, drainage, and burning activities. The main driver for this land use change is oil palm (OP).

To date, expansion of OP has increased due to demand from the food industry domain. The United Nations Development Programme (UNDP) (Pacheco *et al.,* 2017) reported that the trend of edible oil demand has escalated exponentially in line with the increasing world population. By the year of 2050, 240 Mt yr^{-1} of edible oil is needed to accommodate 9.2 billion population across the globe. Precisely in Malaysia, the share of

vegetable oil export (crude palm oil is part of vegetable oils) by the year 2024 is been expected to increase by 25%, when compared to other origins and second to Indonesia by 12%. These figures signify high crude palm oil production due to expansion of oil palm across tropical peatland, especially Indonesia and Malaysia with 15.0 Mha and 2.5 Mha of peatland area, respectively (Melling, 2016; Surahman *et al.,* 2018). Until recently, expansion of oil palm took place on mineral soil lowlands (either as previous forms of agriculture - primarily rubber) (Wakhid *et al.,* 2017), or through the deforestation of lowland tropical forest (Austin *et al.,* 2017). However, in the last 15 years or so, much of the expansion of plantations has been undertaken into tropical peatlands. These areas were often considered 'unproductive wastelands' (Evers *et al.,* 2017), ripe for development.

As oil palm cannot grow in waterlogged conditions, to undertake conversion, areas must be cleared of forest (often undertaken using fire) and drained (Zulkefli *et al.,* 2010). This process exposes the soils to oxygen, speeding up decomposition via aerobic microbial activity. This in turn releases vast quantities of GHGs to the atmosphere. The C loss is not then replaced by organic matter inputs as the forest cover has been removed. As such, converted tropical peatlands become enormous net sources of GHGs to the atmosphere, especially CO_2. The present carbon loss due to conversion from peatland to OP, according to Carlson *et al.* (2015) using integration of modelling mass balance at -70.0 cm water table level and based on a number of references (see Comeau *et al.,* 2013; Couwenberg & Hooijer, 2013; Murdiyarso *et al.,* 2010; Page *et al.*, 2011), results in an estimated 13.3 Mt yr^{-1} of carbon loss from 666,038 hectares (year 2009) of oil palm areas in Malaysia alone. Furthermore, this model is solely applicable for carbon loss estimation excluding other carbon loss pathways (i.e. fluvial and soil surface) or other species (i.e.

CO_2 and CH_4). Based on Carlson's *et al.* (2015) estimation, one can conclude that carbon loss from tropical peatland has been underestimated when compared to the estimation made by Intergovernmental Panel of on Climate Change (IPCC) from oil palm land use. Thus, the amount of carbon loss was placed fourth in the 2013 Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories (IPCC, 2013).

While full rehabilitation is in the long-term the only route towards achieving full ecosystem sustainability (Evers *et al.,* 2017), this approach requires rewetting and reforestation of peatlands, meaning agriculture is no longer possible. This approach has proved successful, for example, in a study using validated field inventory and remote sensing to generate 3D models of peat dome hydrology, the rewetting of 590 km^2 was found to mitigated emissions of 1.4 to 1.6 Mt CO_2 yearly (Jaenicke *et al.,* 2010). In contrast, raising water tables in previously developed peatlands to the surface may trigger, in the short term, other adverse effects, such as P and N mobilisation (P-rich water resulted in further eutrophication), algal blooms, and heightened CH_4 (28 times more potent gas than CO_2 based on global warming potential (GWP), CO_2, and dissolved organic emissions (Harpenslager *et al.,* 2015). With many established plantations on peat, it is clear that any changes to management which can decrease the environmental impacts of these developed systems should be explored.

1.2 Peat compaction

A new technique that has been introduced recently during land opening practices for OP establishment on tropical peatland refers to active peat compaction (Busman *et al.,* 2018; Melling & Tang, 2018; Othman *et al.,* 2009). While in the early stage of land preparation, peat compaction occurs 'naturally' by oxidation of peat materials during drainage or by mechanical force of heavy machinery (especially in industrial scale plantations) during timber clearance, this approach seeks to actively increase compaction by additional mechanical exertion with the intention of increasing peat bulk density to a minimum of 0.20 g cm^{-3}. As it will be discussed in greater detail throughout this chapter, the physical alteration that takes place upon changing macropores to micropores has been reported in non-peer reviewed manuscripts to increase soil water holding capacity and bulk density, restrict oxygen concentration, and force habitat stress to pests (Busman *et al.,* 2018; Melling & Tang, 2018; Mutert *et al.,* 1999). This change is thought to result in water-nutrient retention that enhances mechanical anchorage, apart from preventing risk of fire and pest infestation (Melling & Tang, 2018; Mutert *et al.,* 1999; Othman *et al.,* 2010).

However, the effects of peat compaction (either derived passively though conversion or as an active aim) do not only occur at the early stage of oil palm cycle, but continuously throughout the oil palm cycle due to management activities (Melling & Henson, 2011; Mutert *et al.,* 1999; Othman *et al.,* 2011; Yahya *et al.,* 2011). However, it is not known if this effect is more pronounced in specific areas within a plantation (e.g. closer to palms or closer to palm frond piles). These microsites may lead to heterogeneity, particularly in terms of soil properties, which may vary over the life of a plantation cycle.

As such, as while drained tropical peatland under agriculture is susceptible to carbon depletion due to peat oxidation and deposition alteration to soil moisture, bulk density and soil pore size, and other factors associated with compaction have the potential to alter the levels of oxidation, and therefore GHG gas emission extent and signature over both time and space. Proper research-based assessment of these changes is needed before any recommendations of compaction promotion or avoidance are promoted for wiser peat management.

Information on alteration to the quantity and signature of carbon losses due to peat compaction is scarce due to several biotic and abiotic factors that are inter-related. For example, moisture content, oxidation and associated microbial activity, nutrient availability and hydrological connectivity are all likely to be influenced by level of compaction (Agele *et al.,* 2005; Beylich *et al.,* 2010; Breland & Hansen, 1996; Silva *et al.,* 2011). Therefore, compartmentalising its effect to management outcomes is a challenge. Most mitigation options discussed to date on tropical peatland focus only on hydrological restoration as a key mechanism to hinder adverse emission (through air, water, and fire) from drained peat (Jaenicke *et al.,* 2010). However, it must be emphasised here that the present application of peat compaction has become defined within industry practitioners an essential practice for OP establishment (Jelsma *et al.,* 2019), especially to stabilise soils for movement of traffic property of peat soil, but increasingly with the concept that compaction will reduce CO_2 emissions, and reduce fire ignitability risk of dry peat soil (Busman *et al.,* 2018; Melling & Tang, 2018). While theoretically, this technique retains and regains water due to peat pores space restriction that enhance rise of peat capillary. Critically, no study has comprehensively investigated the above-

mentioned claims despite the wide application of the approach across Malaysia (Othman *et al.,* 2009; Wijedasa *et al.,* 2017).

1.2.1 Conversion of peatland – prior to compaction

The two general approaches for land clearing on oil palm are zero burning and slash-and-burn. Land clearance through zero burning has been practised mostly by oil palm companies via manual mechanical vegetation clearance (e.g. pristine forest, secondary forest, bushes dominated by Imperata sp., or conversion from another crop cultivation). This manual mechanical technique incorporates several practices, such as slashing → cutting → chopping → piling/staking (Ismail & Jamaluddin, 2007) or with integration of pesticide spraying. This technique creates an open "wound" to the top soil as the work of pilling does not promote decomposition of woody biomass and results in soil compaction on the peat surface, primarily due to heavy load from the machinery utilised.

Cambi *et al.* (2015) mentioned that the evolution of heavy machinery usage to work efficiently involves heavier and more powerful machinery. This increases the intensity of compaction effort on soil due to traffic flows. Information regarding peat compaction through this clearing method is limited but is mainly due two main factors: shrinkage by lowering water table level, and heavy machinery usage. However, the drawbacks are addressed within certain time period due to plasticity and compressibility properties or rebound effect (Rezanezhad *et al.,* 2016), so long thresholds are not exceeded (Duraisamy *et al.,* 2009) especially on matured peat that consist of collapsed pores structure (Rezanezhad *et al.,* 2016). From the economic stance, this technique is

cost-ineffective, but environmentally less polluting, when compared to burning practice (Zulkefli *et al.,* 2010).

In contrast, slash and burn is conservative as it has been commonly practised by small-holders across the globe for centuries. Typically, this method does not require high-end technology and consumes minimal operational cost. However, it is far less widely practiced and is often banned due to the volatile substances released from fires and escaped fires causing transboundary haze pollution that affects the neighbouring communities and countries (Forsyth, 2014). Yet despite the impacts, several country's policies still allow for this approach where it involves small-scale plantation on their own native land. This clearing technique does not guarantee success due to the massive remaining undecomposed and wet woody materials buried under peat soil or large tree stumps. As a consequence, this may result in unsuitable minor slopes for crops plantation, unless heavy machinery is introduced for land clearance. However, this approach has been considered by oil palm companies as it is potentially beneficial beyond cost reduction, for the reduction of *Ganoderma boninense* Pat., a damaging oil palm fungal disease, and other pests, that threaten palm oil (ASEAN Secretariat, 2003; Integrated Management Plan NSPSF 2014-2023 vol.2, 2014). After clearance, compaction is undertaken. This is addressed below in detail.

1.2.2 Compaction – the process and justification

After clearing has been completed, land preparation for oil palm seedlings is carefully implemented through the compaction approach. First, peat compaction can be induced by heavy machinery usage during land clearance practices (van Asselen *et al.,* 2009; Wösten *et al.,* 1997) (**Figure 1.1**). Specifically, this technique involves land clearing and construction of water canals to control the level of water table (Hooijer *et al.*, 2012; Ritzema *et al.,* 2014) and to prepare the land for oil palm seedling planting (Mutert *et al.,* 1999).

Second, peat compaction continuously occurs within the entire palm cycle due to plantation management activities, such as fertiliser and liming application (Hooijer *et al.,* 2012), as well as harvesting of FFB and frond piling (Yahya *et al.,* 2011) – though these effects may be heterogeneous in their extent across plantation 'microsites'. Third, apart from anthropogenic activities, the impact from abiotic factors (e.g., rainfall, seasonal variation, and peat maturity) may be considered as minor contribution within this process (Díaz-Zorita & Grosso, 2000; Novara *et al.,* 2012)). Based on these potential sources, both the intensity and the magnitude of peat compaction have been expected to rise as time passes (**Figure 1.2**).



Figure 1.1 The use of excavator for land clearing and the preparation of oil palm plantation site in Sibu, Sarawak, Malaysia.

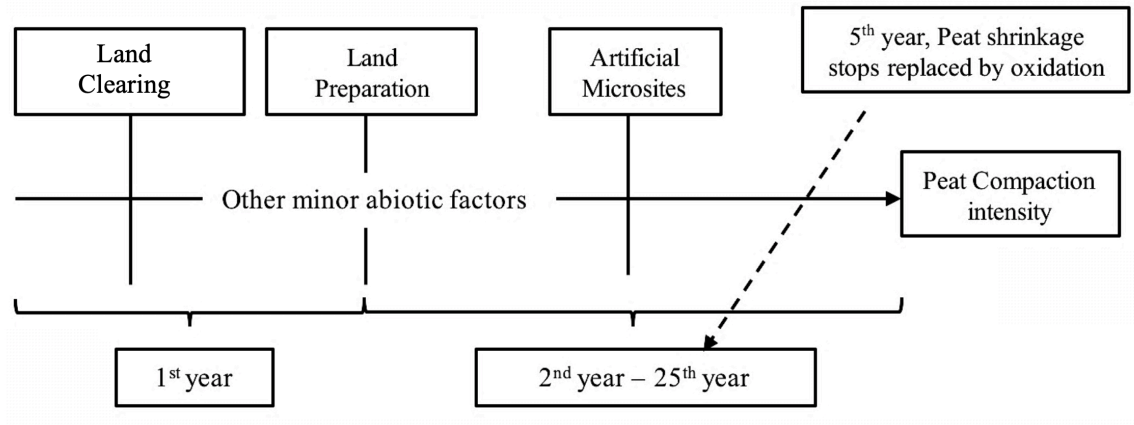


Figure 1.2 Potential peat compaction sources presented by timeline in a cycle of oil palm cultivation for 25 year.

During the past decades, peat compaction across oil palm has become an important practice (Mutert *et al.,* 1999; Othman *et al.,* 2010; Othman *et al.,* 2009). However, this not implicates for small-scaled holder around Malaysia on the usage of heavy machinery due to limited access (Jelsma *et al.,* 2019) than company plantation. Therefore, approximately 36% (*ca.* 874,884 hectares) of tropical peatland in Malaysia is under compaction. This can be estimated by the distribution of agriculture land uses across tropical peatland that reflects soil compaction, wherein 76% (*ca.* 666,038 hectares) were planted with oil palm by large scaled plantation, when compared to other crops, such as pineapple and vegetable crops, on peatlands (Wetland International Malaysia, 2010). The heavy machinery usage for plantation is important as this approach enhances mechanical anchorage for oil palm root system and prevents "love syndrome" among mature palms. Love syndrome refers to the state of oil palm falling over towards each other and resulting in unfavourable growth (**Figure 1.3**).

Further, the compaction approach has also been claimed to increase the available nutrients and water supply by improving capillary rise and water holding capacity (Katimon & Melling, 2007; Kimura *et al.,* 2012; Melling *et al.,* 2013; Melling & Tang, 2018). Limiting nutrients translocation over oil palm vary across a plantation according to water movement and specific microsite heterogeneity (Anuar *et al.,* 2008). In order to maintain and retain nutrients at a specific site, the hole-in-hole practice is applied via peat compaction up to 1.0 m from the initial surface level (Mutert *et al.*, 1999). This practice is an innovative mechanical efforts to initiate direct distribution of agricultural inputs e.g. fertiliser due to the impact of rainwater (Othman *et al.,* 2009). As a result, the fertiliser in oil palm is concentrated around the palm circle with minimal distribution laterally (Anuar *et al.,* 2008)**.**



Figure 1.3 The "love syndrome" among palms at maturity stage (26 years old). Picture was taken (with permission) at drained and shallow tropical peat, Malaysian Oil Palm Board (MPOB) Research Station, Sessang, Sarawak.

As water retention capability is enhance after peat compaction, the risk of fire is stated to be greatly reduced (Melling and Tang, 2018; Mutert *et al.,* 1999; "Prevent peat fires via soil management," - The Borneo Post, 2016). However, no specific research or data towards this conclusion has been undertaken to supported this notion (Wijedasa *et al.,* 2017). Compressed peat is also said to controls pest, such as termites and white ants. This is due to the inducement of habitat stress that targets oxygen availability and food sources. However, according to Beylich *et al.* (2010), the effective compaction threshold to affect soil fauna and microorganism is above 1.70 g cm^{-3}, as measured in bulk density. Yet, attaining such levels of compaction and bulk density in peat soil to that value is

almost impossible due to high organic content (Huat *et al.,* 2011). The maximum bulk density of tropical peat soil in natural and agricultural ecosystems is approximately below 1.0 g cm^{-3} without any amendment of other mineral soil (Firdaus *et al.,* 2011; Kuncoro *et al.,* 2014a; Melling *et al.,* 2013; Ywih *et al.*, 2009). As such, this statement can also be questioned.

The other main claims for this approach are the reduction particularly in CO_2 emissions from sites. As presented in Melling & Tang (2018), during workshop on 'Haze and Biomass in Asia – A Systems Perspective to Reveal Opportunities with Benefits for Long-Term Transformations' at Bandung, Indonesia on 4 to 5th October 2018; who asserted that the increasing of bulk density value by 0.02 gcm^{-3} within the range of 0.13 to 0.15 g cm^{-3}, could reduce CO_2 flux by 15% from the former of un-compacted oil palm plantation (**Table 1.1**). Irony, contradicting with their own finding, the reduction of CO_2 emission will only take effect by the value of bulk density that more than 0.24 g cm^{-3}, but below than that; within the range from 0.14 to 0.22 g cm^{-3}, the CO_2 emissions are not affected (Busman *et al.,* 2018). Beside, although mean water table level at peat swamp forest is obviously higher than that of compacted oil palm plantation by 45.6 cm (**Table 1.1**), the value of water filled pore space (WFPS) is much lower than compacted oil palm plantation, which tentatively in contrast with the results by several authors (Ishikura *et al.,* 2018, 2017; Marwanto *et al.,* 2019; Wakhid *et al.,* 2017) who suggested that the capillary rise will be disconnected when the distance between the water table and the surface ground is too far. Furthermore, the CH_4 and N_2O emissions that considered the second and third important gas of which 28 to 36 and 265 to 298 times more potent gas to global warming potential was not measured- as the impact of CO_2 reduction due to O_2 depletion and water content increases as a result from compaction could lead another

possible effect such as higher CH_4 and N_2O emissions (Torbert & Wood, 1992). Therefore, there is need to understand better the relationship between the CO_2 emissions and bulk density or other parameters that associated with water content, pores condition as well as degree of decomposition.

Table 1.1 Comparison between compacted oil palm plantation (COPP), un-compacted oil palm plantation (UOPP), and peat swamp forest (PSF) in the form of CO_2 and CH_4 emissions (Retrieved from Melling & Tang (2018)).

Parameter	Ecosystem		
	COPP	UOPP	PSF
Mean water table (- cm)	60.7	59.8	15.1
Water-filled pore space (%)	83.3	71.3	75.1
Bulk density ($g.cm^{-3}$)	0.15	0.13	0.11
Soil CO_2 (t C ha^{-1} yr^{-1})	9.5	11.2	12.5
Soil CH_4 flux (t C ha^{-1} yr^{-1})	N/A		

Note: N/A is not available.

1.3 Peat compaction and subsidence

Soil compaction refers to incremental increase of bulk density as a result of macro pores reduction from either single or multidirectional loads. Adapting the theory of tropical peat soil compaction processes initiated by Hooijer *et al.* (2012) and Alakukku (2006), the two main forces that induce peat compaction are external and internal forces. External load is a static and dynamic load that derives from the lateral forces to the soil surface, while internal load refers to the process that occurs due to alteration of soil physical changed by water suction gradient (Horn *et al.,* 1994).

Hooijer *et al.* (2012) explained peat compaction in relation to of peat subsidence. In general, compaction in peat can occur with or without peat oxygen availability (i.e. aerobic and anaerobic) at peat horizons that are divided into three main components (see **Figure 1.4**). The first component (C1) is a combination of compaction and shrinkage, which is considered as an entity of peat subsidence in the aerobic layer beside peat oxidation that can increase the bulk density value. At the unsaturated soil peat layer (aerobic layer), the induced loads may be immediate or temporary. The impact on the peat surface could be caused by several factors, such as heavy machinery wheels (Kuzyakov *et al.,* 2010), rainfall drops (Ball *et al.,*1999), and animal tracks (Hamza & Anderson, 2005). The second and third components are associated within anaerobic layer at saturated peat (anoxic horizon), which are described as primary and secondary consolidation. The primary consolidation (C2) is induced by rapid decrease of moisture regime, whereas the secondary consolidation (C3) is linked with resistance of peat materials to compaction. Since soil consolidation is affected within the saturated soil peat layer or anaerobic horizon (Wösten *et al.,* 1997), the load is applicable over a longer time

period and continuous, for example, over a wetting and drying cycle or with long-term water table fluctuation.

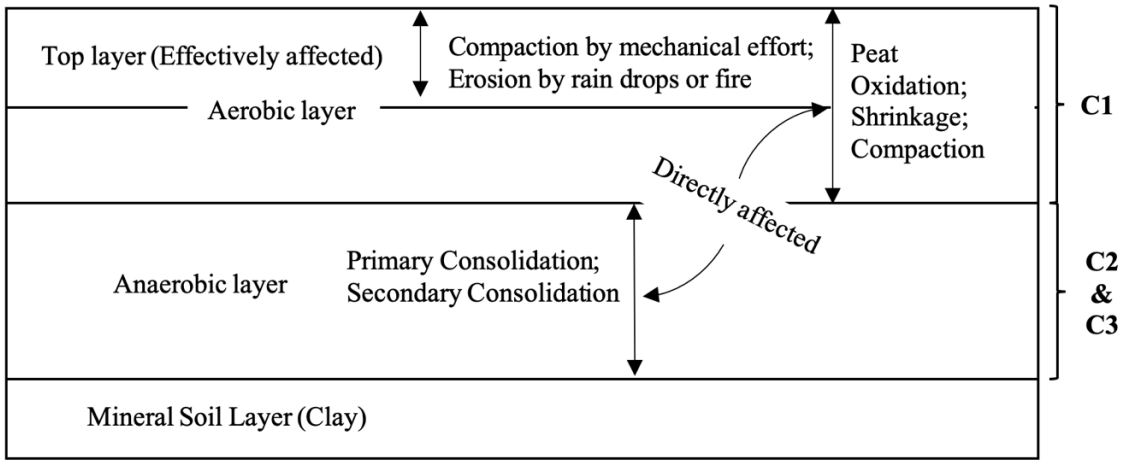


Figure 1.4 Tropical peat subsidence mechanisms or compaction described by Hooijer *et al.* (2012).

Yet grouping subsidence and compaction together has led to some confusion. The application of tropical peatland compaction as a subsidence index has increased. For example, peat subsidence has been used as a measurable indicator to determine carbon loss by observing changes to peat depth (Wakhid *et al.,* 2017). van Asselen *et al.,* (2009) argued that the compaction process of natural peat ecosystems does not always represent peat subsidence. This is because of incompressible layers that dominate peat subsurface, that compaction does not always mean peat loss and the fact that the peat expands and contracts in response to water table fluctuation level due to high porosity and buoyancy characteristics, also independently of carbon loss. As such, data on peat subsidence and surface level growth is heavily depend on water table level and should not be interpreted as a measure of carbon loss without being corrected against soil bulk density.

The complexity underlying compaction magnitude is derived from several factors, such as abiotic, biotic, and anthropogenic factors (man-made compaction). Nevertheless, the combination of compaction and shrinkage as an entity seems very difficult to distinguish. Most literature works (see Hooijer *et al.,* 2012; Melling & Henson, 2011; Mutert *et al.,* 1999; Othman *et al.,* 2009) defined tropical peat compaction based on the nature of the study site. For instance, in logged-over or drained forest ecosystems, peat compaction source is always described as a result from water table fluctuation between seasonal variations (Kennedy & Price, 2005) that causes shrinkage (bulk density increase), or oxidation (by microbial activity), which decreases bulk density (Hooijer *et al.,* 2012). As for developed peatland ecosystems, such as agri-systems, most of the authors (see Hooijer *et al.,* 2012; Melling & Henson, 2011; Othman *et al.,* 2009; Smith *et al.,* 2018) described peat compaction as a coupled process caused by heavy machinery or shrinkage by drainage, which contribute to increased bulk density. This particular landscape-based definition leads to confusion towards the clarity definition mechanism of compaction on tropical peatland among researchers. Therefore, in order to better understand the terminology of 'peat compaction', this research initiate to separate the first component (C1) from oxidation and C loss effects, but rather, considers compaction caused by heavy machinery and shrinkage as a single entity.

1.4 Effects of artificial compaction on tropical peat soil

1.4.1 Physicochemical properties change by artificial compaction

In general, compaction practice on soil affects its integrity by causing forced deformation on the macro structure of the soil. This condition causes reconfiguration of soil pores, reduction in soil volume, restriction on the available oxygen, decreased water infiltration, and increased water content (e.g. gravimetric and volumetric water content and water-filled pore space) (Ball *et al.,* 2000; Horn *et al.,* 1994; Nimmo, 2004; Novara *et al.,* 2012; Yahya *et al.,* 2011). Kuncoro *et al.* (2014a) asserted that deformation of physical structures in compacted soils can affect air and water transportation in various ways, depending on the connectivity of macro pores.

The characteristics of temperate and tropical peats in term of pores distribution are different, mainly depending on the origin plant biomass (Rezanezhad *et al.,* 2016). Hence, the magnitude of compaction towards tropical peats maybe varied. Temperate peats have heterogeneous and anisotropic structures, wherein pores are arranged in vertical and horizontal paths for air-water and solute transportations (Beckwith *et al.,* 2003; Rezanezhad *et al.,* 2016). For the first time, Samuel *et al.* (2014) determined the pore size of peat for Sarawak's tropical peat at MARDI, Saratok, Sarawak (see **Figure 1.5(a)**), within the depth profile of 40 cm using scanning electron microscope (SEM) incorporated with image analyst software [ImageJ; National Institutes of Health (NIH) and the Laboratory for Optical and Computational Instrumentation (LOCI, University of Wisconsin)]. They revealed that the physical configuration of anisotropic pores traits of tropical peat pores is consistent with sphagnum sample across temperate regions (see **Figure 1.5(b)**). This is despite the fact that tropical peat aggregate is somewhat larger,

more clumped, and more amorphous (completely decomposed woody material) than with sphagnum, and there is a large variation in pore diameters (sphagnum is measured between 0.1 and 0.4 mm (Rezanezhad *et al.,* 2016), while tropical peatland between 0.005 and 0.1 mm (Samuel *et al.,* 2014). As such, both systems would have the potential to be differently impacted by compaction in terms of pore deformation. This is also in agreement to the study by Katimon & Melling (2007), who claimed that tropical peat soils differ from those found across temperate regions, with temperate peat behaving more similarly to sand and clay loam, which hold more water by 50 to 60% after treatment with permanent wilting point (-150 kPa). Subsequently, tropical peat maybe successful to compact due to cohesion and adhesive characteristics which are similar to sand and clay loam that susceptible to compaction (Alakukku, 1996a, 1996b).

Overall however, the alteration of tropical peat physicochemical properties by artificial compaction, especially those associated to agriculture activity, is rarely reported (Singh *et al.,* 2015). This is because; most peat is commonly used as soil conditioner to repair and stabilise compacted mineral soil due to its high clay content (Ekwue & Harrilal, 2010; Kuncoro *et al.,* 2014b; Tan & Chang, 2007). Its characteristics as a soil conditioner is derived from the peat itself as peat is formed through the semi- or complete decomposition of botanical material – resulting in high porosity of more than 80% and compressibility of 400% from its initial state (Rezanezhad *et al.,* 2016). Peat is capable to a certain extent of returning to its original state after compression due to plasticity and active pores composition (Huat *et al.,* 2011; Rezanezhad *et al.,* 2016). As such, the methods and concepts used to generalise the porous media properties are based on assessments of mineral soils with peat additions, which may often be insufficient (Caron *et al.,* 2015).

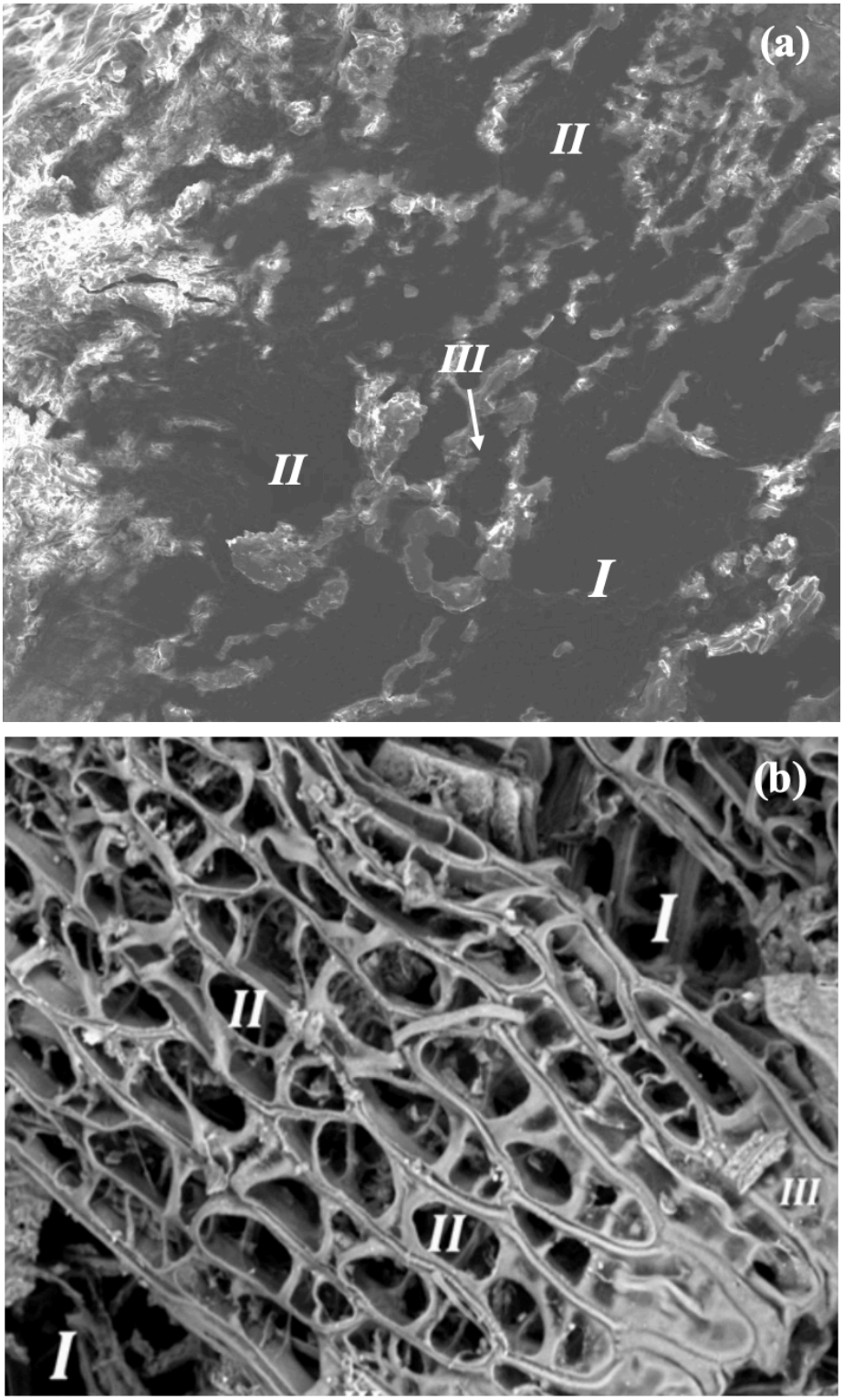


Figure 1.5 (a) The heterogeneous tropical peat configuration in vertical cross-section view. The image shows differentiation of pore path distribution; an evidence of existence of (I) Open and connected macropores, (II) closed or partially closed macropores, (III) dead-end or isolated pores spaces called hyaline cells which consistent with **(b)** temperate peat (Sphagnum) adapted from Rezanezhad *et al.* (2016)

1.4.2 Emissions properties change by artificial compaction (soil emissions)

Changes in physical habitat particularly altered pore-size distribution may lead to restriction of oxygen diffusion in compressed peat. Regulate and induce new conditions or habitable pores to the native peat decomposition microbial communities (Ikeda *et al*., 1997). For instance, during the oxygen depletion that marked by redox potential level (Busman *et al.,* 2018) or water-filled porosity (WFS) of above 60% (Linn & Doran, 1984), the activities of microbes would lead to population succession from which predominated by aerobic to anaerobic communities. Subsequently, the CO_2 production would decrease linearly. In contrast, Shestak & Busse (2005), discovered poor link between physical and biological indices of soil health due to the fact that broad tolerance of microbial communities from contrasting soil textures (mineral soils) to compaction (75 to 3800 Kpa). Thus, the impact of peat pore reconfiguration due to compaction on microbial communities contribute to the ambiguous response, which is another reason for this study to be undertaken.

Compaction mechanism involves in compression of peat and could possibly decrease peat depth although as abovementioned the peat could rebound back due to high plasticity trait unless the pores is inactive due to high decomposition level (Bader *et al.,* 2018). Consequently, the decrease of peat depth may lead to in close proximity to water table level and controlling carbon emission by manipulating aerobic and anaerobic condition within peat horizon. With increment in the oxic level of the peat soil due to water table fluctuation, spontaneous oxidation in terms of CO_2 gas production by peat materials and microbial activities may occur (Moore & Dalva, 1997; Öquist & Sundh, 1998). For instance, the change in compacted peat structure during wetting and drying

influences activity in peat soil, apart from playing crucial roles in the emission and sequestration of carbon in peatlands. Nonetheless, most literature mentions that water table fluctuation is the main control for carbon emission in tropical peatland regardless of compacted or uncompacted peat (see Carlson *et al.*, 2015; Comeau *et al.,* 2013; Hooijer *et al.,* 2012; Jaenicke *et al.,* 2010; Jauhiainen *et al.,* 2005; Wakhid *et al.*, 2017). Altered water levels by drainage leads to continuously fluctuations over time, aside from releasing CO_2 and CH_4 gases (Jauhiainen *et al.,* 2008). This means that gas exchange depends on periodic oxic and anoxic environment, as well as micro-topography within the peat horizon (Miao *et al.,* 2013).

Peat surface respiration is composed of two types of O_2 consumption and release; autotrophic respiration (AR) (by roots) and heterotrophic respiration (HR) (microbial activities). Combined, these two sources make up total soil respiration (SR). To understand the true impact of land use on peat emissions, the peat-only (HR) emissions need to be isolated. There are several techniques to partitioning total soil respiration (SR). For instance, the trenching technique (Hergoualc'h *et al.,* 2017; Jauhiainen *et al.,* 2012; Li *et al.,* 2019; Mäkiranta *et al.,* 2008; Ngao *et al.,* 2007; Varner, 2003; Wakhid *et al.,* 2017) severs active roots from a sampling zone and in doing so isolates HR by measuring CO_2 from soil respiration only. However, this approach when undertaken often then assume that the remaining heterotrophic emissions signature from the soil within a plantation will be fairly uniform in its character and that randomised replication will capture any natural variation in a given area. The common approach at this point is to upscale the average emission by plantation area to give the total HR emissions per hectare. This method does no account for potential consistent variation between microsites within a given area. For example, the results may vary (in a predicable way)

as the peat biophysical itself and other regulatory factors, such as fertiliser input or farming management practices, varied levels of compaction and existence of focal litter piles (Lestariningsih *et al.,* 2013).

However, the specific nature of soil physiological changes and the associated emissions signature may in fact rely on site specific conditions that may be found according to oil palm designated layout and following the planting density. Specifically, each area between the row of palms has a key role based on the management plan with specific perimeter area affected (Luskin & Potts, 2011). For example, the palm circle or 'under canopy' (UC) is usually treated for fertiliser input and hole-in-hole compaction in the first year with a radius of 1.3 m. The frond pile (FP) or frond stack is on average 1.3 m beside UC. The far from palm (FF) is situated beside UC (1.3 m radius) and FP (1.0 m) with passive plantation management activities due to buried plant biomass during the first year of land clearing activity. Lastly, the harvesting path (HP) is located beside other microsites (UC, FP, and FF) and this can be considered as the active path for management activities. As such, these microsites have significant potential to influence the emissions signatures from sites in what would then be a predictable (and critically) up-scalable fashion.

1.4.3 Emissions properties change by artificial compaction (peat fires)

Tropical peatland fire occurrences have recorded huge devastating impacts not only upon environment, but also on human health due to the particulate matter and other hazardous volatile contents (Page *et al.,* 2002). Peat soil after drainage can be hydrophobic due to irreversible drying effects and susceptible to risk of fire. When compared to the process of peat oxidation from peat decomposition, volatile substances from peat fire emissions contain 30% more carbon monoxide (CO), 20% more hydrocarbons, but less CO_2 due to the smouldering nature of peat fires (Filkov *et al.,* 2015).

Peat ignition may occur naturally caused by lightening (Filkov *et al.,* 2015), especially during dry period (April-October) or due to anthropogenic activities, such as the land clearing technique mentioned previously (**Section 1.2.2**). Peat ignitability depends on several characteristics, such as botanical properties that attribute to fuel quality (Wilson *et al.,* 2015). Consequently, affects the spread of smouldering peat fire that ascribed as multidirectional including in-depth vertical and surface lateral distribution (Huang *et al.,* 2016). Peat fire's thermal mechanism reactions play a crucial role during peat utilization processes. Basically, peat fire has three main thermal processes phases of weight loss such as dehydration, oxidative pyrolysis and combustion. The peat burning processes consist of several stages that differentiated by temperature (Leroy- Cancellieri *et al.,* 2014; **Figure 1.6**).

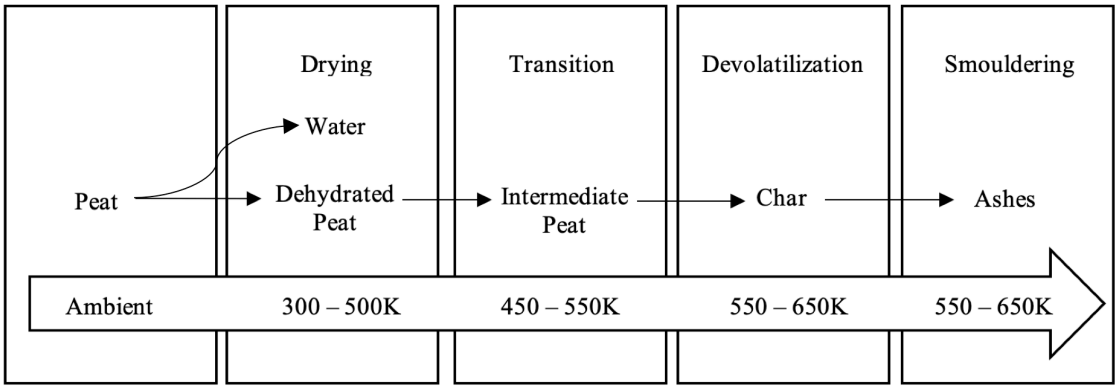


Figure 1.6 Schematic illustration of the decomposition of peat as a function of temperature in Kelvin (K) by Leroy-Cancellieri *et al.* (2014).

However, the temperature threshold between transition of each phases are different between tropical and boreal peats (Leroy-Cancellieri *et al.,* 2014; Usup *et al.,* 2004). This is probably due to the minor components of chemical factors and inorganic compounds present in peat origin; thus, affect the spreading of peat fire once successfully ignited (**Table 1.2**).

Table 1.2 Comparison between boreal and tropical peats on thermal decomposition temperature in Celsius (°C) range between transition phrases.

Peat thermal decomposition phase	Boreal peat	Tropical peat
	Temperature range (°C)	
Dehydration	27 - 226	28 - 210
Oxidative pyrolysis	226 - 377	210 - 350
Combustion	377 - 627	350 - 550

Further, it is important to determine the thermal decomposition properties of peats when talking about peatland fire management. Most of the works have focused on characterising volatile products and evaluating yields from carbon decomposition on boreal, sub-tropic and tropical peats (Christian *et al.,* 2003; Jayarathne *et al.,* 2018; Leroy-

Cancellieri *et al.,* 2014; Paton-Walsh *et al.,* 2014; Setyawati *et al.,* 2017; Smith *et al.,* 2018; Usup *et al.,* 2004). Despite emission factors quantification from peat fire events; only limited information are available on the effects of peat property changes by human intervention on the fuel arrangement such as compaction (Smith *et al.,* 2018; Usup *et al.,* 2008). In addition, the effect of compaction on peat fire is fairly limited (Wijedasa *et al.,* 2017). A recent study on tropical peat in Pahang and Selangor, Peninsular Malaysia suggested a trend of emissions signatures being linked to level of peat compaction, as marked by bulk density value (Smith *et al.,* 2018).

Ground water level, moisture content, and fuel arrangement appear to be the main factors preventing a smouldering fire from burning into deeper layers of peat soil (Huang *et al.,* 2016; Usup *et al.,* 2004). In fact, the overhang thickness formation during fire occurrence is found to increase with moisture and wind speed (oxygen), while the spread rate decreases with moisture and increases with wind speed (Huang *et al.,* 2016). Thus far, water conservation, such as rewetting approach, is essential to mitigate fire risk at drained peatland. Peat fire ignitability can be hindered by manipulating water table level to increase peat moisture content (Putra *et al.,* 2018). A model approach using integrated metadata from Tropical Rainfall Measuring Mission by GES-DISC NOAA, ground water level and historical satellite of fire reoccurrence by NASA-EODIS; suggested that fire reoccurrence can be prevented as long as ground water level be maintained at - 10 cm or higher (Putra *et al.,* 2018). However, the control of ground water level in peatlands is not always possible in dry season periods (especially in tropical countries). This is often due to the over drainage of the peatlands and their reduced capacity to hold water throughout the dry season post conversion as they can develop water repellent or hydrophobicity traits on incessant drought conditions (Perdana *et al.,* 2018; Wirnarna *et al.,* 2016).

According to Akagi *et al.* (2011), during peat fire episode, there are two important transitions that frequently occur simultaneously during a fire such as flaming combustion and smouldering. Flaming combustion converts the C, H, N, and S in the fuel into highly oxidized gases such as CO_2, H_2O, NO_x, and SO_2, respectively, and produces most of the elemental carbon particles. Meanwhile, smouldering produces most of the CO, CH_4, NMOC, and primary organic aerosol. However, this study only focused on the three main peat fire carbon emission by-products in the form of carbon emission (CO_2, CH_4, and CO) or emission factors. The emission factor index value is useful to determine and quantify the impact of peat fire occurrence especially in the IPCC report. These volatile gases can be determined in-situ by using Fourier-transform infrared (FTIR) spectroscopy approach, as described by Smith *et al.* (2018) and Wilson *et al.* (2015) in peat fire investigations on tropical peatland. Emission factor for tropical peatland is one of the most important variables for determining total emission of carbon released by peat fires.

Despite the importance of these fires in terms of environmental, social, economic and political impacts, little is known about what factors control the variability in emissions signatures of quantity. Large-scale modification to soil characteristics (e.g. via compaction) may have a significant impact on future fires. Yet despite this, this practice has been promoted widely without any evidence or empirical investigation to-date into the impact of active compaction and resulting high BD of peats on the signature and quantification of peat fire emissions.

1.5 Concluding remarks

At present, the idea of compaction derives from the personal opinion highlighted by Melling *et al.* (2013), citing presumed capillary rise. Growing momentum and support for this approach (e.g. BorneoPost.com "Prevent peat fires via soil management," 2016) enthusiastically promote this technique to mitigate fire events. However increasing doubts by the scientific community (e.g. Wijedasa *et al.,* 2017) due to the lack of scientific assessment of the impacts of the approach as well as a consideration of the long-term implications to ecosystem function and habitat rehabilitation post OP (in-line with long-term goals suggested by RSPO BMP 2019 and the Indonesian Restoration Agency, BRG) have captured some attention due to limited comprehension pertaining to peat artificial compaction (e.g. JakartaPost.com "Soil compaction puts peatland at risk, agency says"). In general, there is a pressing need to reduce knowledge gaps associated with potential artificial compaction. Better understanding of the impact of physicochemical alteration due to artificial compaction in tropical peatland should consider both the changes in soil physiochemistry and resulting emissions but should also account for the issues associated with the potential permanent loss of unique soil structures and water-sensitive properties of these complex environments.

1.6 Research objectives and hypotheses

The goal of this project is to assess artificial compaction on tropical peat, along with its effects on carbon emissions (both soil decomposition and via fire by-products). The focus of this study lies on shallow to medium deep tropical peat in an oil palm located at Sepang, South Selangor (as described in Matysek *et al.*, 2018) and a secondary peat SF situated at Tanjung Karang, North Selangor (as described in Dhandapani *et al.,* 2019b; Tonks *et al.,* 2017) in Peninsular Malaysia (**Figure 1.7**).

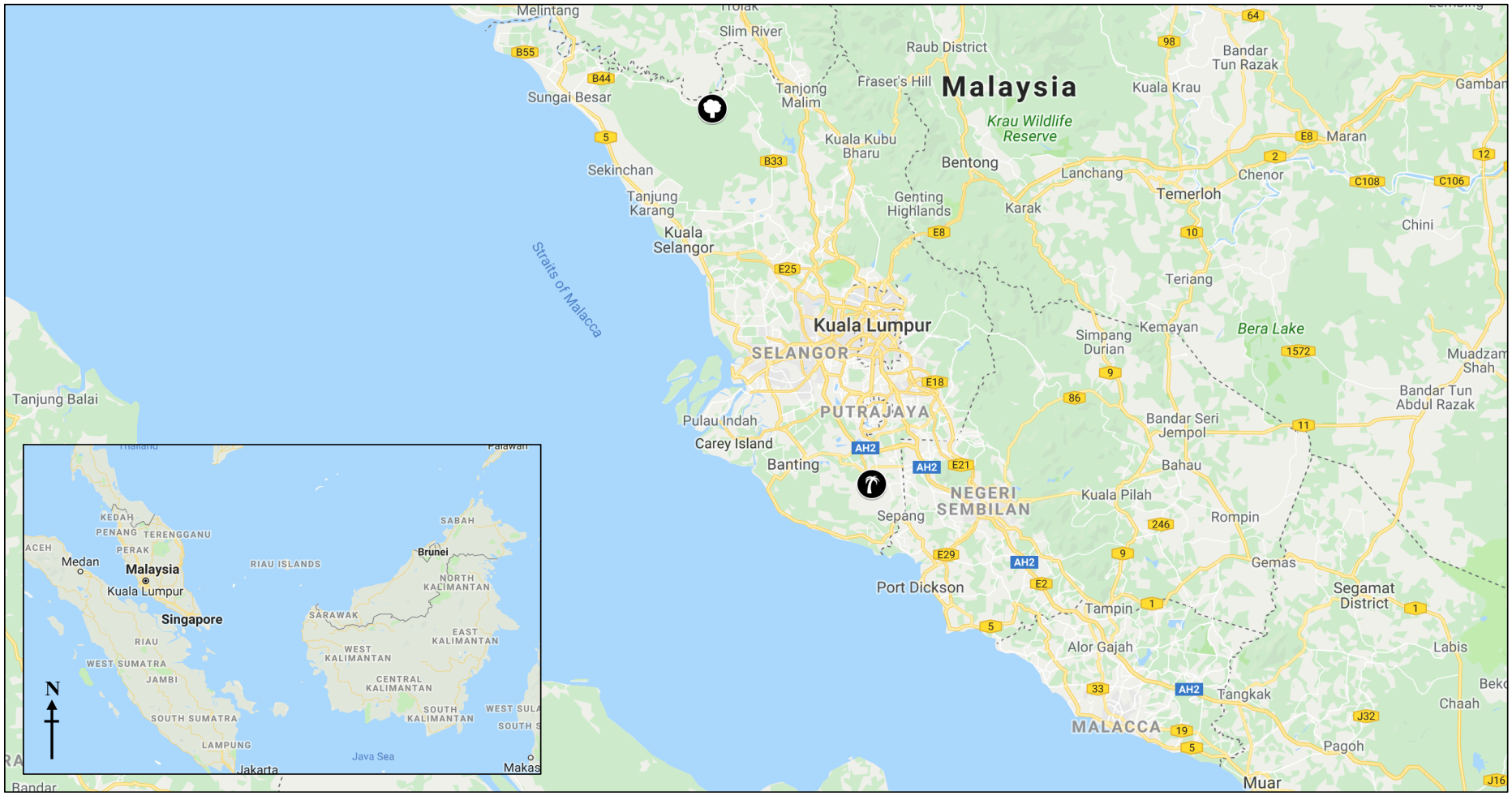


Figure 1.7 Map (retrieved from *Google My Maps 2019*) of Peninsular Malaysia shows the locations of the study in Selangor state marked with representative icons. The Northern part of Selangor is the secondary peat swamp forest (SF) at Tanjung Karang, while in the South; oil palm plantation (OP) at Sepang.

The research questions (RQ) and hypotheses (H) formulated in this study are as follows:

RQ1: Is artificial compaction affected by management practices in OP?

H1: Peat soil compaction magnitude marked by bulk density value and it is hypothesised that this will vary spatiotemporally across a plantation and will influence heterogeneity of moisture content and total porosity of peat. This will affect emission of carbon dioxide and methane from soil surface due to oxygen limitation by constricted peat pores. This study hypothesises that the differing management activities and plantation layout across an OP plantation under a "business-as usual" basis, will result in variation of artificial compaction magnitudes within specified plantation microsites. This variation (over time and space), will result in a predictable (according to the plantation repeated layout) and will result in a patterned response in emissions allowing for more accurate plantation emission accounting.

RQ2: How do physicochemical properties change with peat artificial compaction and do these control carbon emissions?

H2: It is hypothesised that alteration of physicochemical properties by different compaction magnitudes will result in different carbon losses (magnitude and species). This assumption is based on pores condition of compressed peat especially in term of oxygen diffusion or availability. Which later could incorporate modification in microbial activities of initial aerobic to anaerobic or facultative microbes' population. Altered peat properties (especially at affected area of peat compaction – surface, 0 to 10 cm peat depth) in terms of physical (water content) and chemical properties (peat maturity proxies) could

possibly control carbon emission following the level of artificial compaction magnitudes assigned.

RQ3: How does artificial compaction on tropical peat affects fuel quality in terms of pre-combustion physicochemical properties and what is the resulting variation to carbon emission from peat fire?

H3: Peat fire has been frequently practised by small-holder farmers. The assumption holds that the physicochemical properties change due to artificial compaction could possibly affect carbon emission by-product from peat fire. This attribute may be linked with altered oxygen availability and the resulting efficiency of the burning process. Overall, identified the physicochemical properties that may impact fuel quality and thus the signature of carbon emitted.

In order to test these hypotheses, this study adheres to the following four primary objectives:

(i) To assess the extent of tropical peat artificial compaction levels in various conditions and environments.

(ii) To examine the influence of tropical peat artificial compaction on physicochemical properties.

(iii) To examine the influence of tropical peat artificial compaction on carbon losses via peat surface and fire pathways.

(iv) To make recommendations based on findings on the appropriateness of this approach in terms of resulting emission signatures and peat physiochemical

properties resulting from this practice - from the perspectives of a) mitigation of emissions from OP and b) the longer-term implications for any future habitat restoration if matured plantation abandoned.

1.7 Thesis outline

The first part of this thesis, **Chapter 1**, presents the general introduction, as well as the development of research questions and hypotheses. This chapter mainly depicts identification of research gaps from the synthesis of prior studies, which therefore, stems to the goal of this project. As for Chapters 2 until 5, the reports are presented via publication style format.

Chapter 2 describes the outcomes of field assessment at Sepang, South Selangor - matured OP on spatiotemporal variation. This trial was intended to identify the peat artificial compaction potential source. Using bulk density to represent degree of compactness, the measurement was performed from specific microsites namely harvesting path (HP), under canopy (UC), frond pile (FP), and far from palm (FF). Carbon emissions in the form of CO_2 and CH_4 from the microsites were measured. The variation of microsite differentiated by distance is used to explain the source soil respiration (SR), including autotrophic (AR) and heterotrophic respiration (HR) from matured oil palm. By drawing general conclusions on the variability derived from oil palm microsite, total carbon emission on matured oil palm was calculated according to microsite surface area correction (SAC) and compared to existing emission factors described in *Tier 2* IPCC.

Chapter 3 undertakes controlled compaction experiments (as opposed to examining pre-existing BD variation in Chapter 2). This study develops and uses an artificial compaction apparatus that mimicked axle load compression from heavy machinery, which could be controlled and profiled in the field. The *in-situ* experiments were conducted separately at the partially drained secondary peat swamp forest (PSF) at Tanjung Karang (North Selangor) (where a baseline of low BD was expected) and the matured oil palm at Sepang (South Selangor) (where a baseline of high BD was expected). Integrity test was conducted to test the capability of the compaction apparatus to be applied in both ecosystems. Mimicking static compaction efforts by heavy machinery, artificial compaction was profiled based on stratified compressed peat depth in line with compaction component (C1) (**Section 1.3)**. The study considers impacts to CH_4 and CO_2 emissions as well as limitations caused by the apparatus' impact on water table depth (WTD) assessments. Implications are discussed in the context of the present definition of artificial compaction on tropical peatland.

Chapter 4 offers the solution to several confounding factors between water table fluctuation and decomposition proxies in both ecosystems presented in ***Chapter 3***. In discarding the water table fluctuation factor, the experiment was initiated *ex-situ* in a controlled environment (incubation). Intact samples were collected using 40.0 cm high PVC at the same location described in ***Chapter 3***. The artificial compaction treatment based on maximum bulk density value was divided into three parts of volume reduction via peat height alteration and expressed in percentage. The correlations between peat properties and carbon emission within the ecosystem are discussed in detail, arriving at the possible impact of artificial compaction immediate response from drainage

management using standard water table level in adherence to Roundtable Sustainable Palm Oil (2013).

Chapter 5 elaborates the impact of artificial compaction on peat fire smouldering. Intact peat was collected and compacted from matured oil palm to provide a range of BD values. These samples were then air-dried. Samples underwent several series of open-space controlled combustion to determine carbon EF in the form of CO_2, CH_4, and CO via FTIR spectroscopy (as described in Smith *et al.,* 2018). The relationships between pre-combustion peat properties and carbon EFs were tested and represent the first *in-situ* assessment of Malaysian peat soil fire emissions factors from peat under compaction.

Finally, **Chapter 6** presents a general discussion to conclude all significant findings. Datasets in this project were gathered and treated as metadata to discuss the impact of artificial compaction on carbon emission via peat surface and fire across tropical peatland, which is applicable for the Peninsular Malaysia landscape. Using different scenarios of land use shifting that incorporated artificial compaction and usage of fire, this study arrived at explicit carbon EF from peat surface and fire, as well as several recommendations for carbon emission mitigation measures.

1.8 Ethics statement

The application for permission to gain access to the study area was approved by the Forestry Department of Selangor under the National Forestry Act 1984 with Receipt **No. 633141** (**Appendix 1**) and MAB Agriculture-Horticulture Sdn Bhd with reference letter **MN/017173/3017/03** (**Appendix 2**). The field and laboratory studies excluded involvement of endangered or protected species.

Chapter 2. Assessing intra-site variability of carbon emissions in an oil palm plantation on the drained tropical peatland

2.1 Abstract

Change of land use from peat secondary forest (SF) to oil palm plantation (OP) involves several specific practices that may contribute to soil property heterogeneity. Specifically, artificial compaction as marked by increased bulk density value was assessed in relation to repeating microsites identified in standard plantation design, and defined as harvesting path 'HP', under canopy 'UC', frond pile 'FP', and far from tree 'FF'. Along with soil sampling at 25 cm depth, carbon emissions were measured within OP microsites using dynamic closed-chambers. The samples were collected at three different oil palm ages, namely A1 (15 years, 1st generation), A2 (9 years, 2nd generation), and A3 (2 years, second generation and previously burned) between November 2015 and May 2016. Compaction, as indicated by bulk density values, had been comparable among microsites but differed among OP ages. This suggests that compaction source within OP was solely due to period of drainage and the fire event. Meanwhile, CO_2 emission was positively correlated with water proxies and pH, signifying the important of rainfall to dilute soil pH. Here we suggest that this leads to an increase in the solubility of organic matter and subsequently, an increase the availability of labile C to microbes, thus enhancing respiration and CO_2 production. Despite absence of evidence that directly indicated effect of artificial compaction, microsites emission variation was clear and employed to determine Surface Area Correction (SAC) for land use emission factor (EF) calculation. The value retrieved for EF using SAC was between the default value proposed by IPCC (2010) and Environmental Protection Agency (EPA) (2014). The SAC was also applied

to estimate EF reduction by limiting the number of palms per hectare and by converting FP microsites into HP and FF, which resulted in up to 11% of carbon reduction. Hence, identification of microsites emission variability offers data for complementary strategies in managing OP across tropical peatlands.

Keywords: *Agriculture management; Artificial compaction; Bulk density; Carbon emission; Microsites; Oil palm ages*

2.2 Introduction

Peatland is vital ecologically and through their function in terrestrial carbon sequestration. As such, this fragile ecosystem can mitigate adverse climate change (Lal, 2004). The global carbon pool under this ecosystem amounts to 550 Gt (Wetlands International) of which approximately 247,778 km^2 or 68.5 Gt is in Southeast Asia (Page *et al.,* 2011). This includes about 9.1 Gt in Malaysia. However, peatland areas have been massively exploited resulting in deforestation, drainage, and burning. One primary reason is oil palm (OP) plantation establishment. As a result, carbon loss due to conversion from peatland to OP, resulted in approximately 13.3 Mt yr^{-1} carbon loss from 666,038 hectares (in year 2009) of OP areas for Malaysia (Carlson *et al.,* 2015).

In the past decades, the design of OP plantation layout has turned into an important industry topic with the aim of maximising yield and productivity (Mutert *et al.,* 1999). While, the plantation monoculture resulting from conversion of forest ecosystem to plantation adversely affect species richness, subsequent maturation of plantations can also provide unwitting areas of rehabilitation through unwedded microsites within OP (Luskin & Potts, 2011) or frond piling (Henson *et al.,* 2012). Each microsite has distinct characteristics depending on standard planting density and management practices. These attributes are hypothesised to affect site-specific peat property heterogeneity.

The initial land clearance and construction of water canals to control water table level (Hooijer *et al.,* 2012; Ritzema *et al.,* 2014) and land preparation for planting oil palm seedling (Mutert *et al.,* 1999) via the use of heavy machinery, all contribute to

potential peat property heterogeneity, especially in relation to compaction of soil and resulting bulk density. In addition to this, the continuously occurring management practices specific to each microsites (e.g. fertiliser and liming application; Wösten *et al.,* 1997), as well as harvesting of FFB or frond piling (Yahya *et al.,* 2011) throughout an entire palm cycle have the potential to compound this intra-site variation. Indirectly, carbon emission may also affect by these attributes. In general, CO_2 and CH_4 emissions heavily rely on micro-topography, hydro-period, biophysical or above ground plant pool (Jauhiainen *et al.,* 2014; Miao *et al.,* 2013; Moore & Dalva, 1997). However, information on peat bulk density and other peat physico-chemical characteristics across microsite and temporal scales in relation to potential variability in artificial compaction in tropical peat soils is unavailable. In a compaction study of OP at Bernam Series soil a mineral type soil, Yahya *et al.,* (2011) discovered that bulk density and total porosity in HP increased by 10.5% and reduced by 5%, respectively, when compared to FP area after six years of oil palm cultivation. Nevertheless, these outcomes cannot be applied in tropical peatland mainly because peat lacks clay content (Alakukku, 1996b).

While partitioning the heterotrophic and autotrophic contributions of soil respiration (SR) by roots availability has been studied extensively (i.e. Dariah *et al.,* 2014; Jauhiainen *et al.,* 2012; Lim & Ahmed, 2014; Matysek *et al.,* 2018). , these studies do not capture the heterogeneity within these zones, nor are the contribution of these areas accounted for in terms of up-scaled emissions estimated for entire plantations.. The implication for informed policy making is significant; In 2011, the US EPA (EPA, 2014) undertook peer reviews from several experts in tropical peat research to discuss the usage of a default OP on peat emissions factor (EF) value. While this resulted in a determination of 95 t $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}, this remains largely inflated compared to the 40 t $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}

proposed by IPCC 2007. Thus, in order to address uncertainties in calculating the EF of drained OP on tropical peatland, while much of this ambiguity lies in emissions within the first 5 years of conversion, varied peat generation and intra-site heterogeneity also requires full accounting.

Given the information gaps, the objectives of this study are as follows: (1) to quantify peat physical properties, as well as CO_2 and CH_4 emissions, at varied OP ages within described microsites, and (2) to correlate between peat physical properties and carbon emission (3) To use EFs from specific microsites to proportionally upscale (by representative area) total emissions per hectare of OP plantation. This study hypothesised that peat artificial compaction marked by bulk density and other selected physiochemical properties within microsites are affected by oil palm management as defined by specific microsite type. This influences the variation of CO_2 and CH_4 emissions from peat surface.

2.3 Materials and methods

2.3.1 Sampling location and microsites identification

The plantation identified was established in 1970's overlies with a small area of remnant primary forest preserved at the adjacent Kuala Langat South Forest Reserve and surrounds the KLIA airport. This plantation was chosen as it is a well-established field site, providing contextual data and site information for the project (Adeolu *et al.,* 2015; Marshall *et al.,* 2018; Matysek *et al.,* 2018; Waldron *et al.,* 2019). Sites were chosen to represent differing plantation age groups, however specific sites within plantation age blocks were identified randomly. Site A1 established 15 years ago (1st generation), site A2, 34 years ago (9 year old palm, second generation), and site A3 also 34 years ago (2 year old palms, 3rd generation after 9 year old palms burnt) (a cycle OP is 25 years; Zulkifli *et al.,* 2010) (**Figure 2.1**).

Sampling campaign was carried out between wet and dry seasons in November 2015 and June 2016. Although, the number of rain days observed during dry season (30 days) exceeded that of the wet season (20 days), the rainfall average was much lower (i.e. dry season; 4.9 mm/day, and wet season; 15.4 mm/day). Subsequently, water table levels had high ranges that fluctuated between -21.6 cm and -74.3 cm (**Table 2.1**). However, this was due to sampling during a El Nino event which was among the strongest (*Malaysian Meteorological Department (MMD) Annual Report*, 2016). In contrast, previous data from this site shows much greater drainage occurs with water table depths of -70 to -120 cm during dry weather condition of June and August 2014 (Matysek *et al.,* 2018). In this study, peat thickness at sites were 101.5 ± 3.5cm, 84.2 ± 2.1cm, and 82.5 ±

2.8 cm at A1. A2, and A3 sites, which is considered as shallow thick peat in accordance with the Peninsular Malaysia peat classification (Hajon *et al.,* 2018).

Details of these microsites Harvesting Path (HP), Under Canopy (UC), Frond Pile (FP) and Far From palm (FF) are illustrated in **Figure 2.2** and described in **Table 2.2**. Excluding UC microsite (palm centre), all the other microsites (e.g. HP, FP, and FF) and associated samplings were placed more than 3.0 m from the palm trunks based on the distance of potential heterotrophic respiration, as suggested by Dariah *et al.* (2014). A total of 72 soil and gas samples were gathered from two sampling seasons, three OP ages, and four microsites with three replications.

Table 2.1 Mean ± standard error (n =24) of water table level (WTL) at KLIA, Sepang oil palm plantation during wet and dry seasons.

Season	Wet			Dry		
Site	A1	A2	A3	A1	A2	A3
Water table level (cm)	-36.9 ± 1.3	-62.3 ± 3.9	-38.0 ± 2.7	-21.6 ± 4.6	-58.7 ± 2.6	-74.3 ± 3.1

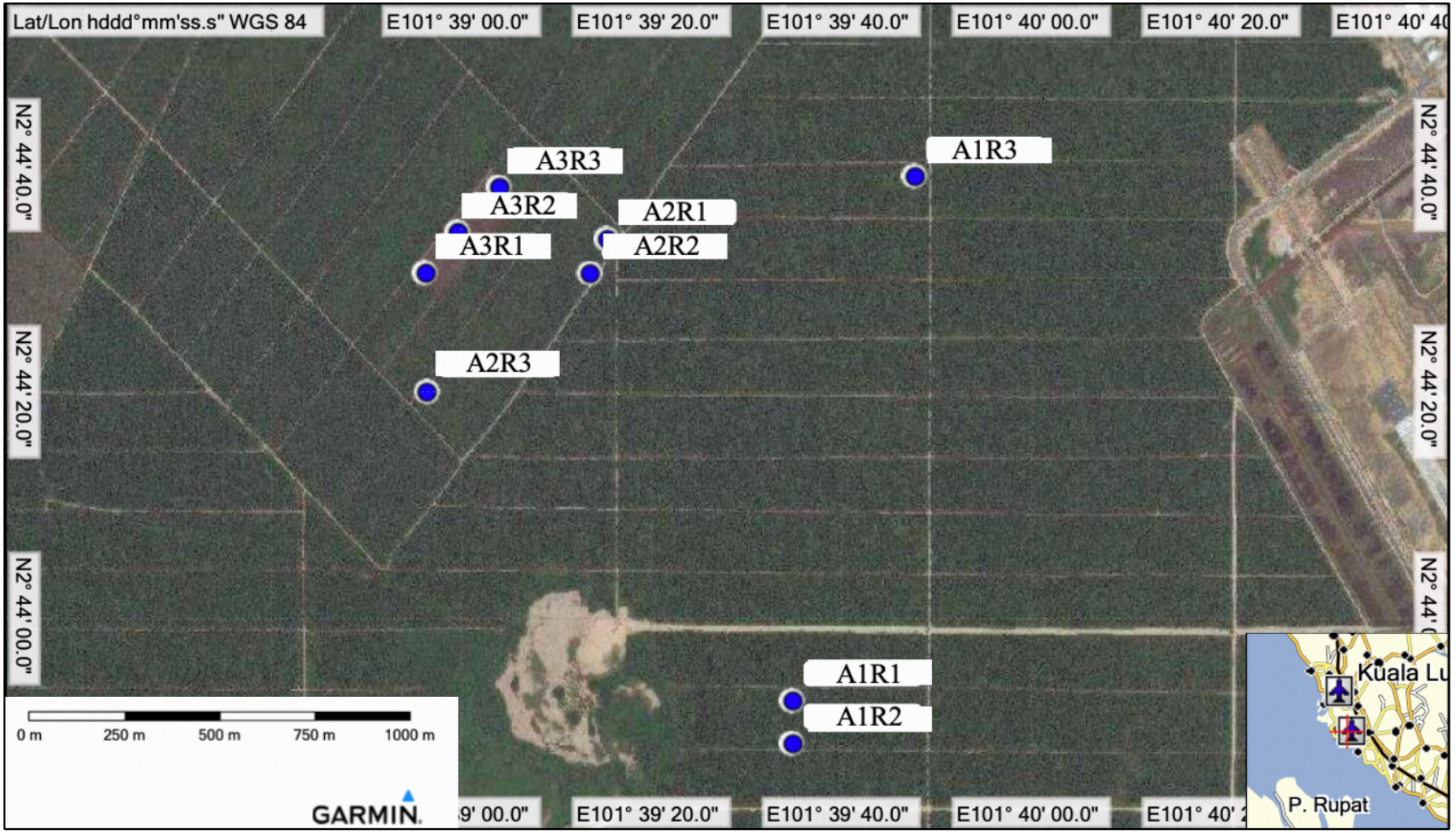


Figure 2.1 Sampling points in oil palm plantation between plantation establishment ages (A) with replication (R).

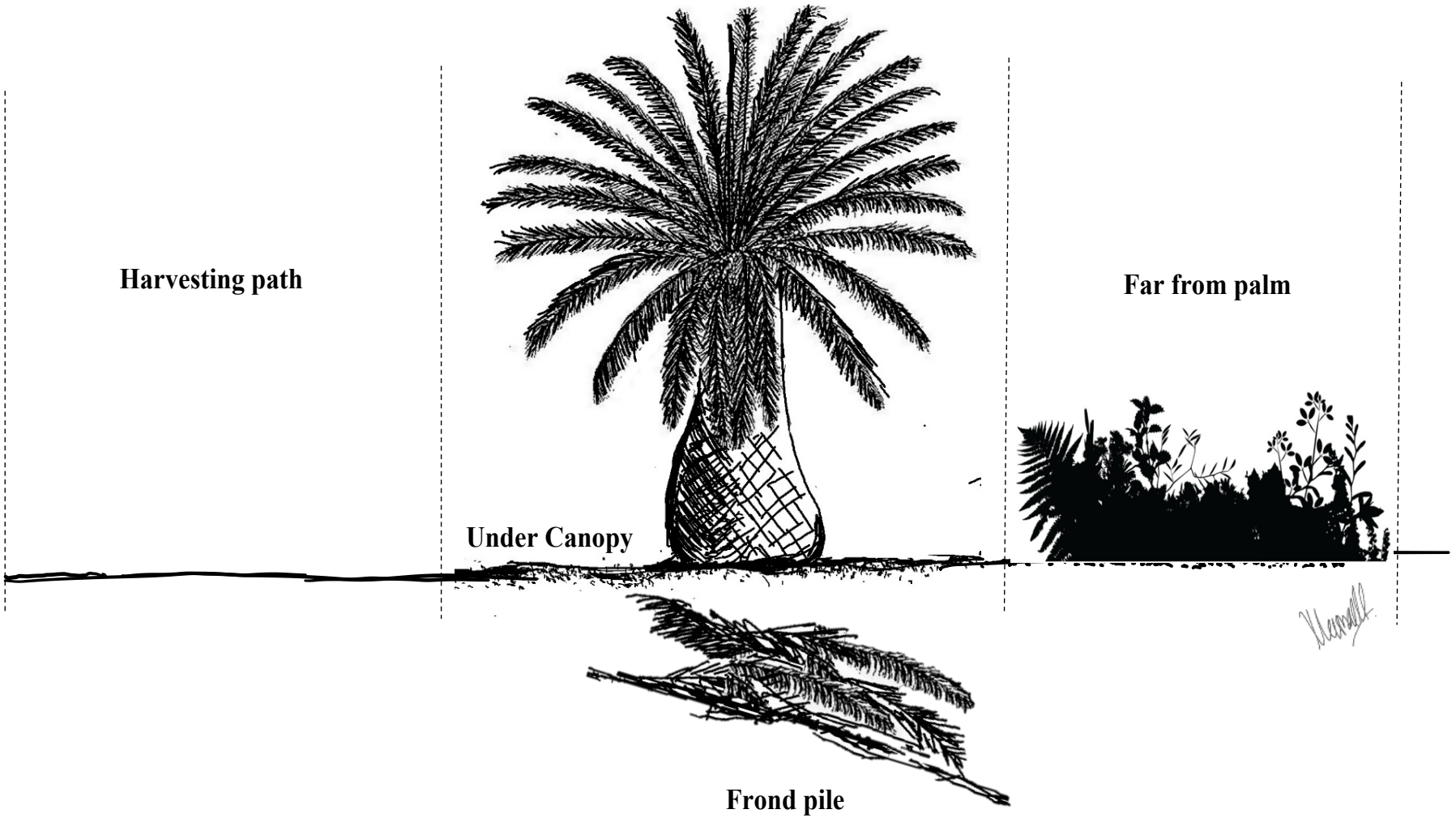


Figure 2.2 Oil palm plantation that classified into different microsites namely Harvesting Path (HP), Under Canopy (UC), Frond Piles (FP) and Far from Palm (FP)

Table 2.2 The main characteristics of microsites within oil palm plantation observed in this study.

Microsites	Main characteristic	References
Harvesting path (HP)	Exposed directly to sunlight and rainfall, may be shaded by palm fronds after five years old. The main path for oil palm plantation activities. May serve as wildlife corridor due to presence of animal tracks (see **Appendix 3**). Compaction intensity was expected to be the highest among others.	Lestariningsih *et al.*, 2013; Shestak & Busse, 2005; Comeau *et al.*, 2013; Mutert *et al.,* 1999; Yahya *et al.,* 2011
Under Canopy (UC)	Almost free from sunlight and rainfall due to shed from palm canopy. Peat surface is mainly dominated by underground palm roots and a focused area for fertiliser and liming application. The compaction intensity is dominated by palm roots distribution and previously during hole in one compaction for planting seedling.	Comeau *et al.,* 2013; Mutert *et al.,* 1999; Yahya *et al.*, 2011;
Frond Pile (FP)	During early stage of establishment, this microsite is exposed directly to sunlight and rainfall, but expected to be covered as a result from the plantation management (pruned fronds). The compaction effort is influenced by the weight of freshly pruned fronds and timely decayed fronds.	Lestariningsih *et al.,* 2013; Yahya *et al.*, 2011
Far from Palm (FF)	A passive microsite, whereby soil surface in this microsite is covered by aboveground pioneer species. Nearby feeder drains. Peat compaction may occur due to roots distribution and weight of decayed plant biomass.	Ariyanti *et al.,* 2016 and by field observation.

2.3.2 Peat depth sampling

Peat thickness was determined by using Russian peat auger with 50.0 cm length (Eijkelkamp Soil and Water, Netherlands) (**Figure 2.3**). Concurrently, peat samples were collected at 25.0 cm depth from after depth measurement. A total of 72 samples were gathered from two sampling campaigns, three OP ages, and four microsites with three replications.



Figure 2.3 Peat depth determined using peat auger by the observation on appearance of distinct coloration between peat and mineral soil (see arrow).

Peat bulk density samples were collected by using fabricated soil core with 173.18 cm^3 volume. Prior to sampling, the peat was dug to make a soil pit of 50.0 cm depth. Peat bulk density sample was collected on the wall of the pit to minimise vertical compaction

(Hooijer *et al.,* 2012). Next, the core was carefully pushed horizontally onto the wall of the pit that displayed minimal amount of semi-decomposed woody materials. The core penetration was assisted by cutting off coarse fragments or palm root with a sharp knife along the cutting edge of the sampler. When the sampler was full, peat around the sampler was cut and carefully taken out from the pit. After that, the sample was trimmed based on the sampler size. In order to hinder evaporation from the fresh peat sample, the sampler was tightly closed with a cap before it was transferred to the laboratory.

2.3.3 Peat physicochemical analysis

On return to the lab, dry bulk density (BD) and moisture content (MC) parameters were analysed by adhering to the methods prescribed by Al-shammary *et al.* (2018). Soil cores containing fresh peat samples were weighed to obtain wet weight (Ww). Next, the samples were oven-dried at 105 °C until constant dry weight (Dw) was attained for 48 hours. The oven-dried peat samples were placed in desiccators for cooling and to prevent moisture absorption. Alongside, the moisture content parameter was obtained as well. Both parameters were calculated using **Eq. (2.1)** and **Eq. (2.2)** and expressed in g.cm^{-3} and percentage (%), respectively.

$$BD = \frac{Dw}{V} \qquad \textbf{Eq. (2.1)}$$

$$MC = \left[\frac{Ww - Dw}{Ww}\right] \times 100\% \qquad \textbf{Eq. (2.2)}$$

Loss on ignition (LOI) was determined from a small fraction of composite oven-dried peat (5.0 g) (Dw) via complete combustion by adhering to the method prescribed by Marwanto *et al.* (2019). After that, the weighed dried peat was transferred to muffle furnace at 550 ºC for 12 hours, including a cooling process to 60 ºC. Next, crucible cups containing ash were placed in the desiccator to gain weighed ash (DA) upon hitting room temperature at 30 ºC. The LOI was calculated using **Eq. (2.3)** and **Eq. (2.4)** and expressed in percentage (%).

$$DA = \left[\left(Dw - \frac{Wa}{Dw}\right)\right] \times 100\% \qquad \textbf{Eq. (2.3)}$$

$$LOI = 100\% - DA \qquad \textbf{Eq. (2.4)}$$

Following the method suggested by Blake (1958), the value of particle density (DS) can be obtained using pycnometer or specific gravity flask. The peat particle density value was calculated using **Eq. (2.5)**. Where (Dw) refers to water density (g cm^{-3}) at the temperature (see **Appendix 5**); (Ws) denotes weight of peat soil sample; (Wsw) represents weight of pycnometer, peat soil, and water, while (Ww) stands for weight of pycnometer and water. The calculation of total porosity (TPS) had been based on peat particle density value using **Eq. (2.6).**

$$DS = \frac{Dw \times Ws}{(Ws) - (Wsw - Ww)}\% \qquad \textbf{Eq. (2.5)}$$

$$TPS = 100 - \left(\left[\frac{BD}{Ds}\right] \times 100\right)$$ **Eq. (2.6)**

Water-filled pore space ($WFPS$) was determined by using gravitational moisture content based on dry weight (GRA) and volume of moisture content (VOL) parameters, as given in **Eq. (2.7)** and **Eq. (2.8)** (Tonks *et al.,* 2017). The calculated values were used to estimate $WFPS$, as shown in **Eq. (2.9)**.

$$GRA = \left[\frac{Ww-Dw}{Dw}\right] \times 100$$ **Eq. (2.7)**

$$VOL = GRA \times BD$$ **Eq. (2.8)**

$$WFPS = (TPS \times VOL) \times 100$$ **Eq. (2.9)**

The composite dry samples from soil core were crushed by mortar and pestle and passed through 2.0 mm sieve to determine their chemical properties (Sakata *et al.,* 2015). The peat pH value was determined by using a benchtop pH meter model (Sartorius pHBasic, Germany) by adding 5.0 g of dried and sieved peat sample into 12.5 ml deionised water (soil-water ratio of 1:2.5) in a 25.0 ml glass beaker.

2.3.4 Gas sampling using dynamic closed-chamber method

Excluding UC microsite (palm centre), all the other microsites and associated chambers were placed more than 3.0 m from the palm trunks based on the distance of potential HR, as suggested by Dariah *et al.,* (2014). Gas emissions sampling was performed from morning until mid-afternoon (1000-1400 hr). Carbon emission was captured by using the dynamic closed-chamber method by following the gas sampling protocols prescribed in *GRACEnet* project (Parkin & Venterea, 2010) involving microsites (**Figure 2.4**). Four square-shaped closed-chambers with open-ended base and sharp edges were fabricated using clear acrylic material measuring 20.0 cm (width) x 20.0 cm (height) x 20.0 cm (length). Next, they were wrapped with aluminium foil to minimise the effect of temperature variance in the chamber. Two sampling ports plugged with rubber septum were fitted on top of the chamber for gas sampling and thermometer installation. Additionally, a battery-operated fan was attached inside the chamber to allow dynamic air flow (Zerva, 2004).

Prior to chamber placement, the existing plant debris on the soil surface was removed as carefully as possible using soft brush until the surface peat was discovered. As for the FF microsite, the aboveground plant was removed two weeks prior to gas sampling. Removal of plant debris was required to homogenise peat surface among the microsites and to prevent leakage on the chamber bottom edge due to uneven placement caused by thick plant biomass resembling a mat (**Appendix 6**). In this study, anchor or soil collar for chamber was neglected because the edge of the chamber was cut with a sharp knife and pushed vertically for lateral diffusion into the soil to the depth of 3.0 cm to avoid gas leakage (Melling *et al.*, 2005). Use of anchor at these sites was unsuitable as

most of the sites are prone to flooding and accumulation of water inside collar was expected. Upon chamber placement, 20.0 mL gas sample was extracted from the chamber from T_0 to T_5 (1, 3, 6, 9, and 12 minutes) time interval by using a polypropylene syringe equipped with a three-way stopcock. The extracted gas was transferred into a 20.0 mL glass vial that had been vacuumed earlier and stored in a box at room temperature (30 ºC) prior to gas analysis using GC. The total gas samples were similar to soil samples collected within microsites (see **Section 2.3.2**).

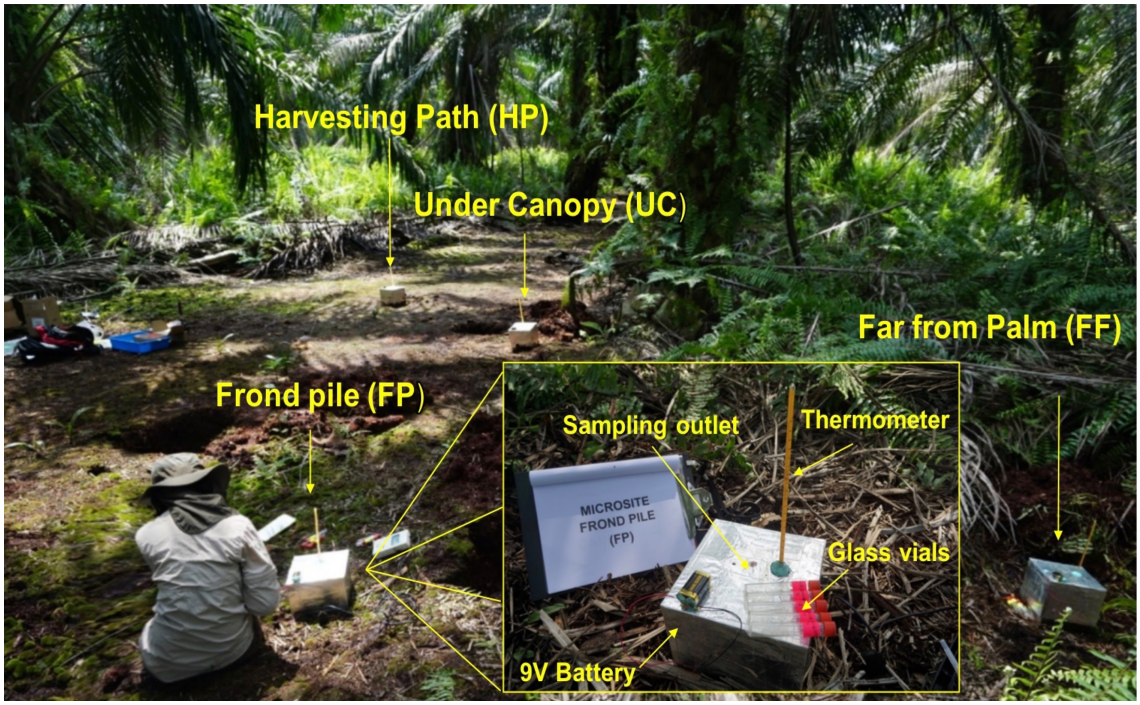


Figure 2.4 Gas emissions were sampled at microsites within oil palm plantation using fabricated dynamic closed-chamber as shows in the sub-figure.

2.3.5 Gas concentration analysis and calculation

Gas samples were analysed using GC (Agilent model 7890A) equipped with thermal conductivity detector (TCD) and flame ionisation detector (FID) to determine CO_2 and CH_4, respectively. The GC was calibrated by using standard mixed gases that consisted of 1.0 ppm of CH_4, 350.0 ppm of CO_2, and 50.0 ppm of N_2O, until it hit 90% of sensitivity value. Gas concentration in ppm was calculated by using ideal gas law, as given in **Eq. (2.10):**

$$PV = nRT \qquad \textbf{Eq. (2.10)}$$

Where: P = Atmospheric pressure (101,325 pa); V = Volume of headspace (m^3); n = Number of moles (mol); R = Universal Gas Constant law (8.314J. $K^{-1}mol^{-1}$) and T = Temperature in kelvin (K) with conversion number of 1 mol of gas to gram, CO_2 = 44.01 g and CH_4 = 16.02 g, respectively.

The increase or decrease in the chamber concentration over time (hour, h^{-1}) by chamber volume (L) from peat surface area covered (m^2) was fitted into LR with at least three sampling points, including T_0 point. The slope from LR denotes the rate of CO_2 or CH_4 emission (+ value) / uptake (-value) and presented in, mg CO_2 m^{-2} hr^{-1} or µg CH_4 m^{-2} hr^{-1}. Any concentration point that observed outlier in LR graph due to sampling time error was omitted from the calculation (retain at least three points of gas concentration). Another prerequisite for LR is that the regression line must exceed R^2=0.60. The

estimation of AR was obtained by subtracting HR rate from the total soil respiration rate (SR) (Melling *et al.,* 2013).

2.3.6 Statistical analyses

Prior to ANOVA, assumptions of data normality and equality of variance were checked by using Ryan-Joiner's method (similar to Shapiro-Wilk method) and Levene's method (Brown & Forsythe, 1974; Shapiro & Wilk, 2006; Yap & Sim, 2011). The effects of spatiotemporal variation (microsites and OP ages) on physicochemical properties and carbon emission had been assessed by employed the general linear model (GLM). Factors with significant difference at $p < 0.05$ reflect further analysis and separation via Tukey's post-hoc analysis (Tukey, 1949) at 95% confidence level. The correlation between peat properties and carbon emission in the form of CO_2 and CH_4 was tested using Pearson's correlation coefficient method with two-tailed at 0.05 probability level. All statistical analyses were performed using MINITAB17® statistical software package, while the graphs were plotted using Sigma Plot version 12.5 software.

2.4 Results

2.4.1 Peat physicochemical properties

The analysis outcomes pertaining to effects of two factors of temporal (OP ages) and spatial (microsites) variation on peat properties are tabulated in **Table 2.3**, while the mean values for the peat parameters are presented in **Table 2.4**. Dry bulk density differed between OP ages ($p = 0.027$) but not microsites ($p = 0.236$). The highest bulk density was measured at A3, followed by A2 and A1 with mean values of 0.188 g. cm^{-3}, 0.184 g cm^{-3}, and 0.155 g cm^{-3}, respectively. Similarly, loss on ignition exhibited variation between plantation ages ($p = 0.001$). The lowest loss on ignition was discovered at A2, followed by A3 and A1 with mean values of 87.59%, 92.7%, and 94.89%, respectively. Meanwhile, the pH value in this study was influenced by microsite variation ($p = 0.024$). The highest pH value was observed at UC, followed by FF, FP, and HP with mean values of 3.75 ± 0.12, 3.63 ± 0.09, 3.51 ± 0.08, and 3.39 ± 0.05, respectively. It was noted that specific gravity, total porosity, volumetric water content, gravimetric water content, and water-filled pore space differed neither between plantation ages nor microsites with mean values of 1.699 ± 0.048 g cm^{-3}, 89.04 ± 0.46%, 41.8 ± 3.1%, 266.3 ± 25%, 46.57 ± 3.34%, and 3.57 ± 0.05, respectively.

Table 2.3 General Linear Model (GLM) analysis for spatial (Micro = microsites) and temporal (Age = oil palm plantation ages) variations factors for peat properties in this study. The bolded *F*-values with *, ** and *** are significant at 0.05, 0.01 and ≤0.001, respectively.

Source	df	Peat properties ANOVA (*F*-value)							
		Bulk density (g cm^{-3})	Loss on ignition (%)	Specific gravity (g cm^{-3})	Total porosity (%)	Volumetric water content (%)	Gravimetric water content (%)	Water-filled pores space (%)	pH value (1:2.5) (Peat:water)
Age	2	**3.84***	**8.43*****	2.45	1.29	1.19	0.84	1.24	0.09
Micro	3	1.45	0.66	0.05	0.65	0.76	0.51	0.88	**3.38***
Age x micro	2	0.89	0.45	0.23	0.56	0.30	0.24	0.34	1.91

Table 2.4 Peat physicochemical properties at 25.0 cm depth. The values presented are mean ± standard error (n = 6).

Age	Micro site	Peat properties							
		Bulk density (g cm^{-3})	Loss on ignition (%)	Specific gravity (g cm^{-3})	Total porosity (%)	Volumetric water content (%)	Gravimetric water content (%)	Water-filled pore space (%)	pH value (1:2.5) (Peat:water)
A1	HP	0.15 ± 0.02	94.59 ± 0.97	1.59 ± 0.11	90.53 ± 1.24	37.57 ± 7.94	291.4 ± 82.3	41.24 ± 4.60	3.44 ± 0.07
	UC	0.16 ± 0.01	91.79 ± 3.23	1.60 ± 0.07	89.85 ± 0.98	30.68 ± 8.79	193.3 ± 55.2	34.50 ± 10.1	3.94 ± 0.28
	FP	0.16 ± 0.01	90.97 ± 4.19	1.55 ± 0.03	89.93 ± 0.98	45.10 ± 10.1	293.1 ± 66.3	50.30 ± 11.4	3.39 ± 0.10
	FF	0.16 ± 0.01	93.42 ± 1.43	1.58 ± 0.08	90.07 ± 0.82	36.50 ± 9.51	239.8 ± 67.6	40.40 ± 10.4	3.46 ± 0.09
A2	HP	0.17 ± 0.02	90.66 ± 1.59	1.58 ± 0.20	88.63 ± 1.60	48.65 ± 6.80	316.3 ± 72.6	54.48 ± 6.89	3.42 ± 0.12
	UC	0.17 ± 0.01	84.53 ± 3.71	1.74 ± 0.15	90.14 ± 0.91	23.95 ± 4.43	153.7 ± 36.4	26.39 ± 4.77	3.76 ± 0.21
	FP	0.21 ± 0.02	88.40 ± 2.78	1.76 ± 0.12	87.82 ± 1.83	40.78 ± 7.73	227.9 ± 59.3	45.79 ± 8.27	3.59 ± 0.13
	FF	0.19 ± 0.01	86.75 ± 3.07	1.62 ± 0.10	88.10 ± 1.06	43.57 ± 9.52	229.7 ± 51.4	49.40 ± 10.7	3.48 ± 0.05
A3	HP	0.20 ± 0.03	94.98 ± 1.48	1.94 ± 0.26	88.52 ± 2.30	53.60 ± 16.4	347.0 ± 148.0	59.10 ± 17.1	3.31 ± 0.08
	UC	0.12 ± 0.02	95.81 ± 0.70	1.75 ± 0.29	88.27 ± 2.28	47.80 ± 17.5	339.0 ± 152.0	52.40 ± 18.3	3.57 ± 0.12
	FP	0.22 ± 0.03	94.23 ± 2.31	1.86 ± 0.22	86.04 ± 2.60	49.90 ± 13.5	261.0 ± 106.0	57.30 ± 14.5	3.56 ± 0.16
	FF	0.16 ± 0.02	93.88 ± 2.16	1.81 ± 0.27	90.63 ± 1.56	43.50 ± 13.1	304.0 ± 105.0	47.50 ± 13.9	3.95 ± 0.20

2.4.2 Carbon emissions from oil palm plantation

Emission of CO_2 at A1, A2, and A3 within microsites ranged from 519 to 1393 mg CO_2 m^{-2} hr^{-1}, 879 to 1421 mg CO_2 m^{-2} hr^{-1}, and 717 to 1018 mg CO_2 m^{-2} hr^{-1}, respectively (**Table 2.5**). No effect of CO_2 emission was noted on two-factor interaction with the total CO_2 emission cumulative of 991 ± 63 mg CO_2 m^{-2} hr^{-1} (p = 0.703). Nevertheless, variance was noted between microsites (**Figure 2.5**; p = 0.018). The greatest CO_2 emission was observed at UC microsite and differed to FP microsite (p = 0.026) with mean values of 1278 mg CO_2 m^{-2} hr^{-1} and 763 mg CO_2 m^{-2} hr^{-1}, respectively. Emission of CO_2 from microsites HP and FF were comparable with other microsites with mean values 1068 mg CO_2 m^{-2} hr^{-1} and 855 mg CO_2 m^{-2} hr^{-1}, respectively. Meanwhile, emissions of CH_4 at A1, A2, and A3 within OP ages ranged from 3.9 to 218 µg CH_4 m^{-2} hr^{-1}, 50 to 246 µg CH_4 m^{-2} hr^{-1}, and 94 to 215 µg CH_4 m^{-2} hr^{-1}, respectively (**Table 2.5**). However, CH_4 emission had no effect on spatiotemporal variation with mean value of 172 ± 27 µg CH_4 m^{-2} hr^{-1} (p = 0.275).

Table 2.5 CO_2 and CH_4 emissions from microsites at different of oil palm plantation ages with mean ± SE values (n = 6).

Oil palm age	Microsite	mg CO_2 m^{-2} hr^{-1}	µg CH_4 m^{-2} hr^{-1}
A1	HP	1052 ± 215	3.9 ± 89.8
	UC	1393 ± 339	391 ± 153
	FP	519 ± 215	208 ± 68
	FF	880 ± 156	218 ± 62
A2	HP	1288 ± 166	50 ± 91
	UC	1421 ± 133	148 ± 92
	FP	879 ± 160	245 ± 77
	FF	968 ± 108	169 ± 93
A3	HP	862 ± 196	195 ± 75
	UC	1018 ± 237	133 ± 80
	FP	892 ± 154	94 ± 70
	FF	717 ± 306	215 ± 137

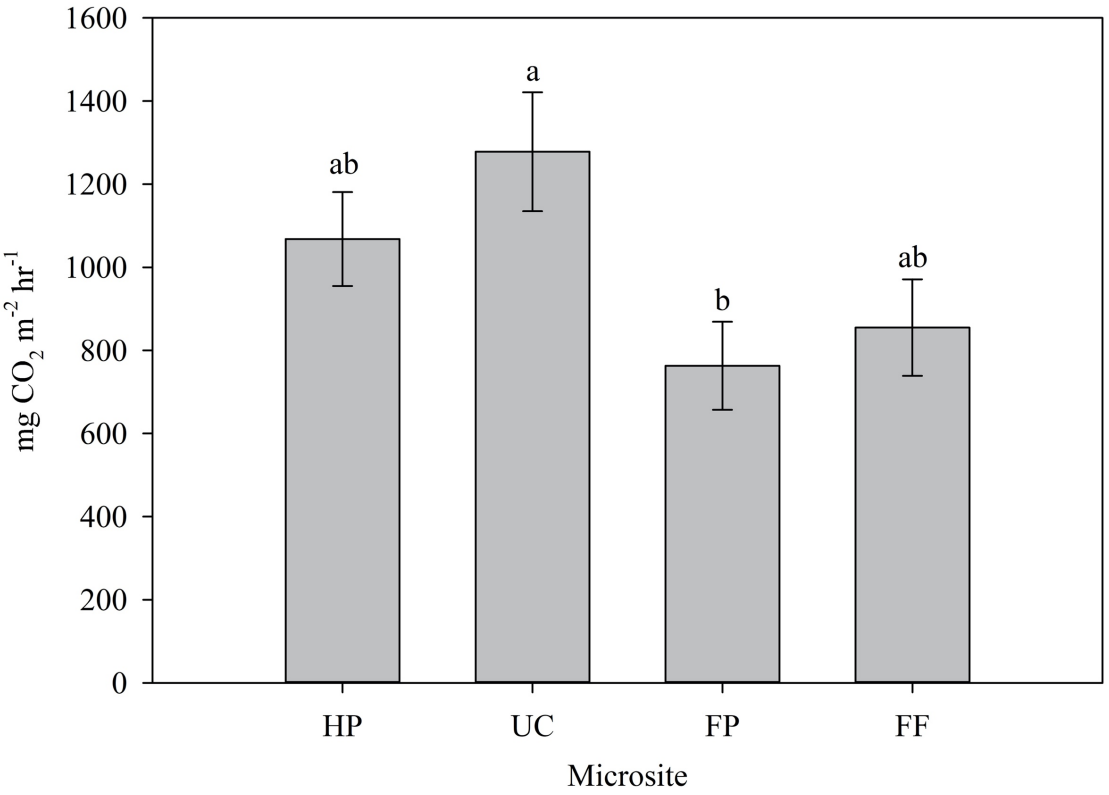


Figure 2.5 CO_2 emission from microsites in oil palm plantation, Sepang, South Selangor. The error bars indicate standard error of means. The different letters signify significant variances between microsites. The means were separated using Tukey's HSD post-hoc test ($\alpha = 0.05$).

2.3.3 Relationship between carbon emissions and physical properties

Pearson's correlation coefficient was performed to determine the correlation between carbon emission and peat physical properties (**Table 2.6**). The results showed that CO_2 emission was positively correlated with volumetric water content ($p = 0.018$), gravimetric water content ($p = 0.020$), water-filled pore space ($p = 0.017$), and pH value ($p < 0.001$), whereas CH_4 emission was positively correlated with pH value ($p < 0.001$).

Table 2.6 Values represent Pearson's correlation coefficient r, between carbon emissions and peat physical properties (n = 72). The bolded r values with *, ** and *** are significant at 0.05, 0.01 and ≤ 0.001, respectively.

Carbon emission	Peat physical properties with Pearson's correlation coefficient (r)							
	Bulk density (g cm^{-3})	Loss of ignition (%)	Specific gravity (g cm^{-3})	Total porosity (%)	Volumetric water content (%)	Gravimetric water content (%)	Water-filled pore space (%)	pH value (1:2.5) (Peat:water)
CO_2	-0.067	-0.135	0.108	0.130	**0.346****	**0.321****	**0.350****	**0.473*****
CH_4	-0.158	-0.135	0.107	0.230	0.184	0.178	0.179	**0.642*****

2.5 Discussion

2.5.1 No clear evidence on artificial compaction within microsites in matured oil palm plantation

A total of 72 peat samples were assessed to identify the effects of spatiotemporal factors on peat physical properties (**Table 2.3**). As mentioned, dry bulk density value is an integral variable that determines the intensity of soil compaction. The hypothesis in this study states that bulk density changes based on plantation management intensity (microsites). This hypothesis is rejected as bulk density is influenced by plantation ages, wherein A3 displayed the highest bulk density. Thus, the assumption that artificial compaction is varied between microsites that marked by bulk density remains uncertain. Results also in disagreement with Yahya *et al.* (2011) which mentioned the bulk density are varied between microsites, and the discrepancy may due to Bernam Series of clay textual as compared to peat which nearly 99.0% of organic matter (Huat *et al.,* 2011). Nevertheless, the change in bulk density between plantation ages is probably due to plantation establishment, which is reflected by drainage period (Hooijer *et al.,* 2012). This suggests that bulk density increases due to the wide range and controlled water table level for a long period (Jauhiainen *et al.,* 2012), hence affecting peat shrinkage (Price, 2003) as a result of distinct wet and dry regimes. Subsequently, increased compression in the oxic peat horizon leads to subsidence, owing to oxidation (Price & Schlotzhauer, 1999; Asselen *et al.,* 2018).

The lowest loss on ignition was observed at A2 site with a mean value of 87%. In this study, A2 site appears to be the oldest among all and have been in operation for oil palm cultivation for 34 years, when compared to A1 (15 years) and A3 (27 years),

indicating that the peat in A2 site was severely oxidised due to the period of drainage. Although peat in A3 site was burned, the loss on ignition value was comparable with A1 site. The negligible of ash on peat surface is probably due to water movement and washed by rainfall. However, according to Hooijer *et al.,* (2012), the function of peat particle in post-fire occurrence to ash movement is limited and subjected to further study. Furthermore, the pH value was significantly higher in the UC microsite, which refers to an area rich in fertiliser and liming (Anuar *et al.,* 2008). Thus, higher pH could be associated with the level of mineralisation (Dariah *et al.,* 2014). Overall, the mean values of bulk density, loss on ignition, specific density, total porosity, volumetric water content, gravimetric water content, water-filled pores space, and pH are 0.176 g cm^{-3}, 91.67%, 1.70 g cm^{-3}, 89.04%, 41.8%, 266.3%, 46.57%, and 3.57, which are in line with those reported by Firdaus *et al.* (2011, 2012), Könönen *et al.* (2015), Matysek *et al.* (2018), Melling *et al.* (2005a), and Tonks *et al.* (2017) across various OP ages on tropical peatland.

2.5.2 Carbon emissions variation in oil palm plantation microsites

The CO_2 emission was varied between microsites (**Figure 2.5**). The highest emission at UC had been expected, being both a combination of AR and HR. However, the remaining sites exhibited interesting trends with fronds pile of decomposed stacked biomass (such as FP), as they resulted in lower emission than the UC site, but HP and FF were not clearly different. Despite FP having no understory biomass due to covered peat surface, poor environment to initiate plant growth is expected (Chalker-Scott, 2007). The stacked fronds may serve as organic mulches that support physical protection and

increase water infiltration from the direct contact of above ground water (e.g. rainfall) (Mancinelli *et al.,* 2015).

Rainfall is linked to momentary CO_2 emission, thus providing an adequate condition for microbial activity (Wakhid *et al.,* 2017). Higher CO_2 emission due to rainfall physical contact is supported by the positive relationship with water-related proxies, such as volumetric water content, gravimetric water content, and water-filled pore space (**Table 2.6**). A positive correlation between CO_2 emission and pH value was also discovered (**Table 2.6**). This suggests that the relationship is due to incorporation of rainfall and nitrate-based fertiliser or liming, particularly observed at UC microsites. Although this association is in agreement with that reported by Ishikura *et al.* (2018), the relationship may inversely change due to seasonal variation as pH is diluted by heavy rainfall (Marwanto *et al.,* 2018). Higher pH leads to increase the solubility of organic matter in wet soils (Pschenyckyj *et al.,* 2019), which may increase the availability of labile C to microbes respiration and enhance CO_2 production (Ye *et al.,* 2012) beside acetate pooling.

No significant variance was observed between OP ages and microsites on CH_4 emission (**Section 2.4.2**). Similarly, a positive association between CH_4 emission and pH value (**Table 2.6**) was found. As discussed, higher pH value was obtained due to fertiliser or liming that potentially increased fermentative activity and thus availability of acetate and dehydrogen that subsequently increase methanogenic substrates that responsible for CH_4 production (Ye *et al.,* 2012). Overall, the cumulative of CO_2 and CH_4 among oil palm ages was from 453 to 1529 mg CO_2 m^{-2} hr^{-1} and from -61 to 406 µg CH_4 m^{-2} hr^{-1},

which shared similar ranges with that reported by Melling *et al.,* (2005a, 2005b) in OP at Sarawak, Malaysia from 168 to 1228 mg CO_2 m^{-2} hr^{-1} and -43.7 to 5.6 μg CH_4 m^{-2} hr^{-1}, respectively.

2.5.3 Microsites attribute to emission factor on oil palm plantation

As mentioned, FP microsite exhibited lower CO_2 emission, when compared to UC. The FP microsite is free from aboveground plant, which represents solely HR signature. The fact that UC is therefore higher than FP, is influenced by rainfall event or HR and AR; suggesting implications to emission from the activities associated with FP practise in plantation management. The reduced C emission from FP microsite demands further investigation in order to decipher the C balance related to organic matter contribution and rainfall physical protection from the reduced C loss from SR. Nonetheless, it has useful implications for optimised management of peat plantations, as discussed later in **Section 2.5.4**, within the context of carbon balance by the fronds-stacking practice.

The contribution of HR was compared using HP, FP, and FF to gain more insight on the wide range of AR/SR%. The AR was estimated by subtracting HR candidates (HP, FP, and FF microsites) from SR (UC microsite) and presented in AR/SR% (**Table 2.7**). Based on the results presented, AR/SR% refers to variation using HR candidates that ranged from 38% to 16% for all land usages. The highest value was calculated at the youngest OP (A1) and within the FP microsite (63%). This signified that the microsite had the lowest HR value that reflected undisturbed area of fronds piles and decomposed biomass, as mentioned earlier. On the contrary, the lowest AR/SR% value was recorded

at A2 within HP microsite (9%). The HP areas were almost free from plants root due to active management practices, except for Bryophyte spp. such as mosses and other non-vascular plants. The impact from rainfall, owing to unprotected area, could add a major setting to higher HR value that indicated severely dry and oxidise site, hence the potential to generate immediate response to the pulse emission in the form of CO_2 (Fraser *et al.,* 2016; Ishikura *et al.,* 2017).

Overall, the estimation of average AR/SR% using all microsites was 29% and fell within the range reported by Dariah *et al.,* (2014), and Melling *et al.,* (2013), of which 58% to 25%. The essential functions from each microsite for AR/SR% estimation are significant to gain more insight on the tropical peat status, instead of focusing on the best approach to quantify the value of HR through estimation of AR/SR%. This is because; the heterogeneity traits within microsites in terms of carbon cycle may alter the HR value, which is likely affected by the management practices.

Table 2.7 Soil autotrophic estimation partitioning using under canopy (UC) microsite as the total soil respiration, while harvesting path (HP), frond pile (FP), and far from palm (FF) microsites as heterotrophic respiration from various land uses in oil palm plantation.

Age	Estimation of AR/SR% using respective microsites as HR candidate		
	HP	FP	FF
A1	24	63	37
A2	9	38	32
A3	15	12	30
Average	16	38	33

2.5.4 Implication to current emission factor in drained tropical peatland default value

The variability of microsites from OP was employed to determine EF. Presently, the estimation of EF from OP on drained peatland seems to have vast uncertainties (EPA, 2014), and a wide range of default values from 40 t CO_2 ha^{-1} yr^{-1} (IPCC, 2010) to 95 t CO_2 ha^{-1} yr^{-1} (EPA, 2014). In this study, the EF from OP was 87 t CO_2 ha^{-1} yr^{-1} and closer to the default value proposed by EPA (2014). It was expected as microsite-based calculation in this study involving the overall SR entities (AR, HR, and both as SR), wide range of water table levels, and emission pulse during wet season, when compared to IPCC 2010, which had been based solely on HR (Drösler *et al.,* 2014; Melling *et al.,* 2005). Nonetheless, the particular interest is towards active areas described by microsites (**Table 2.1**). The proposed method of SAC was calculated based on common planting density of OP across tropical peatland in triangular planting (**Figure 2.6**) in accordance to 160 palms per hectare, which has been commonly exercised on tropical peatland.

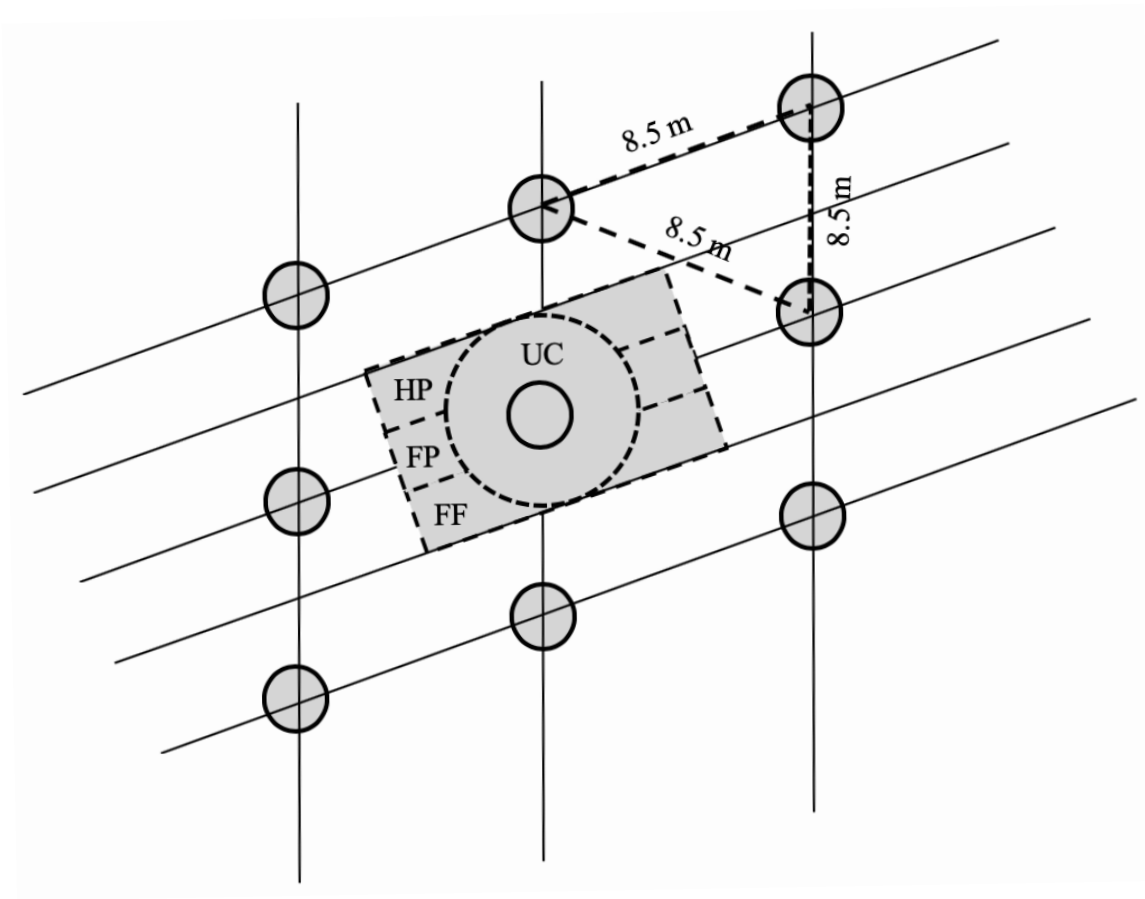


Figure 2.6 Typical planting density of oil palm plantation on tropical peatland in equilateral triangle planting density of 8.5 m x 8.5 m x 8.5 m.

The steps to calculate SAC are as follows: First, calculate the area covered by UC using the area of the circle with radius (Rop) value of 3.0 m that represents effective SR based on oil palm root, as proposed by Dariah *et al.,* (2014). The value of UC was 28.28 m^2 per palm. Next, calculate the FP value by assuming that the fronds piles were located side-by-side to the palm. Assuming FP microsite was rectangular in shape and subtracted by the UC area and given the length of hypotenuse for planting density was 8.5 m and the length of one side was half of UC that of 1.5 m, the other side can be calculated by using Pythagorean Theorem. After that, using UC and FP values, calculations of HP and FF were made by assuming that both microsites shared similar area of rectangular shape.

Therefore, the value of HP was calculated by deducting 10,000 m^2 or 1.0 hectare from UC and FP values and later, divided by two. Hence, the proportion of microsites area were 0.224, 0.452, 0.1, and 0.224 for HP, UC, FP, and FF, respectively, which led to 1.0 or 100% (**Table 2.8**).

Table 2.8 Calculation of palm per microsite area based on oil palm planting density on tropical peat land that of 160 palms per hectare.

Microsites	**Area Calculation (m^2)**	**Surface Area Correction Factor**
Harvesting Path (HP)	[10,000 m^2– 160 (UC + FP)] /2	0.224
Under Canopy (UC)	$\pi 3^2$; Rop = 3.0 m	0.452
Frond Pile (FP)	UC – 2 (1.5 × 7.36) m	0.100
Far from Palm (FF)	HP = FF	0.224
	Total	1.000

The results revealed variances at HP, UC, FP, and FF microsites with 17%, 35%, 72%, and 5%, respectively (**Figure 2.7**). The highest difference was obtained for FP because it involved only a fraction of the entire microsites, when compared to the rest. Here, several strategies have been proposed to reduce EF from OP on drained tropical peatland using SAC. The first approach is to reduce the number of palms. As the SAC had been based on 160 palms per hectare, limiting up to 143 palms per hectare based on 9.0 m x 9.0 m x 9.0 m planting density may enhance the coefficients of FF and HP microsites, while decreasing FP and UC. In explaining the reduction, UC microsite was used due to its greatest CO_2 emission, in comparison to the others. From the calculations, EF decreased by 11% from 157 to 140 t CO_2 ha^{-1} yr^{-1}. This reduction is attributable to the entire entities of SR (AR and HR) in UC, where the SAC factor decreased from 0.452 to

0.404. The second approach is through conversion of FF and HP microsites to FP, whereby FP in this study recorded the lowest CO_2 emission, when compared to other microsites. Hence, if FF, HP or both microsites are converted to FP, reduction of EFs by 1%, 5%, and 6% can be estimated.

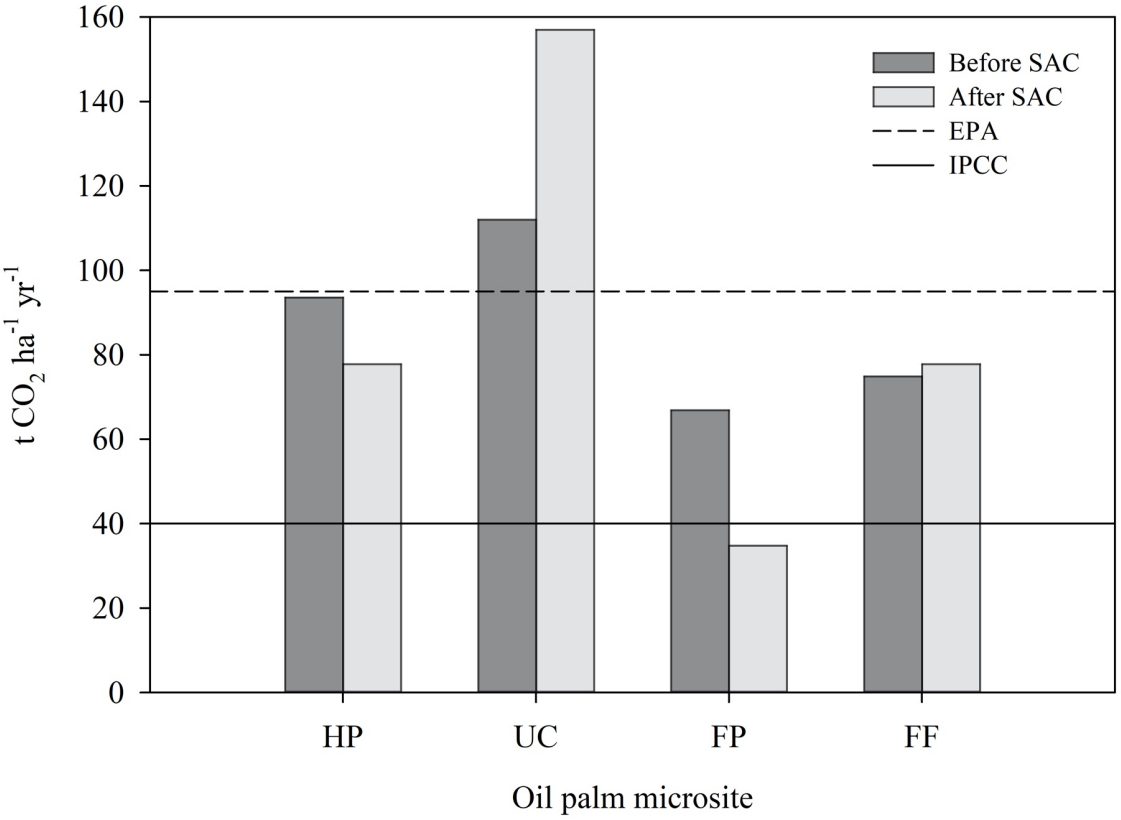


Figure 2.7 CO_2 emissions from study sites with purposed default emissions factor. Dash line represents EPA (2014) purposed default emission factor that of 95 t CO_2 ha^{-1} yr^{-1}, while solid line represents IPCC (2011) purposed default emission factor that of 40 t CO_2 ha^{-1} yr^{-1}.

The calculation using SAC to estimate EF is equitable and represents the entire peat respiration entities (AR, HR or both as total SR) and pulse emission exclusive to OP on drained tropical peatland. Consideration of these microsites with area surface correction is integral and allows one to accurately estimate the amount of gas emission.

Nevertheless, as the estimation from 35 to 157 t CO_2 ha^{-1} yr^{-1} and indeed within to the default value proposed by EPA and IPCC (Hooijer *et al.,* 2012) and (Drösler *et al.,* 2014; Melling *et al.*, 2005a), with two sampling cycles may be insufficient to provide a holistic approach for the overall estimation in light of geographical area, pulse emission, type of peat, peat depth, and water table level (EPA, 2014). Therefore, further measurement in long term is required.

2.6 Concluding remarks

The hypothesis in this work probed into the intensity level of compaction based on bulk density value, mainly because OP management seems to remain ambiguous. Nevertheless, bulk density in this study is associated to peat maturity, which reflects periodical drainage by distinct of establishment OP ages. The heterogeneity of peat quality may lead to a wide range of carbon emissions. In fact, CO_2 emission rates have been linked with volumetric water content, gravimetric water content, water-filled pore space, and pH value. Meanwhile, CH_4 emission rates have been related to pH value. In line with this, the management practices on decayed frond stack at FP microsite offer physical protection and increase water infiltration from raindrops that potentially minimise CO_2 pulse emission. This provides the interim key to information for mitigation measures in reducing carbon emission from matured OP, for example, by using the SAC as proposed in this work. More importantly, future study related to artificial compaction by human-induction in controlled environment is necessary to further comprehend the mechanism behind artificial compaction on the impact of physicochemical properties and carbon gas emission from peat surface. Unfortunately, approach to induce controlled artificial compaction for tropical peatland is presently unavailable.

Chapter 3. The effect of *in-situ* artificial compaction on tropical peat land carbon emissions

3.1 Abstract

Efforts to address the issue of carbon emissions of oil palm plantations have become a major topic of discussion. As a result, application of artificial compaction on peat with the aim of lowering CO_2 through increased moisture level and reduction in soil aeration have been introduced across Malaysia. However, information on the effect of artificial compaction on the carbon emission concentration of tropical peat surfaces is limited. Therefore, this study investigated two ecosystems: a secondary peat swamp forest (SF) and an oil palm plantation (OP). Artificial compaction treatment was based on the compression by a set peat depth at four different magnitudes using a fabricated hybrid compaction apparatus, which also served as a static closed-chamber for gas sampling purposes. The results reveal that the while there was a pre-existing significant difference between SF and OP in terms of a range of physicochemical properties (most pertinently BD), the application of the compression did not result in a significant alteration away from pre-compression levels. Nevertheless, CO_2 and CH_4 emission changes were observed, but only in SF, and showed inverse patterns at a percentage ratio of 1:3 (CO_2 reduction: CH_4; enhancement) based on the different treatments, suggesting that peat depth decreases as a result of compression and thus becomes closer to the water table level. Although the significantly peat decomposition proxies between both ecosystems influenced carbon emissions to less than 28%, water table level was also a key factor that caused CO_2 and CH_4 to exhibit inversely emissions by 61% and 70% from total variation, respectively. However, this was only observed for SF and not OP, owing to substrate

availability in the former. Most importantly, consideration of the confounding factor between decomposition degree and water table fluctuation is important to further understand the effect of artificial compaction on tropical peat.

Keywords**:** *Confounding factor; decomposition degree; hybrid compaction apparatus; self-recovery mechanism; water table level.*

3.2 Introduction

Soil compaction is a perquisite practice for land preparation of tropical peatland, especially for the oil palm plantation (Melling & Tang, 2018). Globally, soil compaction accounts for 4% (68.3 million hectares) of human-made soil degradation (Oldeman, 1994). In Malaysia alone, approximately 57% (1.4 million hectares) of tropical peatland has been compacted, with the agricultural land use reflecting the extensive soil compaction practised in the country (Melling & Tang, 2018; Othman *et al.,* 2010). Soil compaction entails increased bulk density and reduced porosity due to externally- and internally-applied loads (Alakukku, 1996a, 1996b). Peat compaction is a means to provide mechanical anchorage for plant roots, increase the retention of water and nutrient availability for crops, control pests, and mitigate CO_2 emission and fire risk (Melling & Henson, 2011; Mutert *et al.,* 1999). In recent years, this method has also sparked interest from the world's largest producer of palm oil, Indonesia (The Borneo Post, 2016). Even so, the ability of artificial compaction to help reduce the risk of peat fires and lower CO_2 emission is still doubtful because there are limited data to prove this claim (Wijedasa *et al.,* 2017). Furthermore, implications for CH_4 emissions remain unaddressed.

When a plantation area is opened on tropical peatland, land clearing activities such as compaction (done by 2 to 3 tractor passes) could increase the peat dry bulk density value by up to 0.08 g cm^{-3} (Melling *et al.,* 2008). However, prior to mechanical compaction, the water table level will be lowered to the range of 0.5 m to 1.0 m to achieve self-subsidence and to facilitate the peat's trafficability for heavy machinery usage (Mutert *et al.,* 1999; Wakhid *et al.,* 2017). In such cases, two overlapping factors are expected to cause the rise in bulk density value—compaction caused by tractor passes; or

drainage that causes the shrinkage of organic and woody materials as the water is lost (Hooijer *et al.,* 2012; Könönen *et al.,* 2015). To add to this complexity, longer-term dry bulk density value are altered further with long-term oxidation, causing periodic shrinkage, continuous decomposition, and subsequent consolidation and subsidence (Firdaus *et al.,* 2011; Hooijer *et al.,* 2012; Könönen *et al.,* 2015; Rezanezhad *et al.,* 2016). As a result, subsidence values (after the initial conversion period) vary from 2.5 to 10.0 cm per year (Hooijer *et al.,* 2012; Marshall *et al.,* 2018; Mishra *et al.,* 2014; Price, 2003; van Asselen *et al.,* 2018; Wösten *et al.,* 2008).

In a review paper on the terminology of peat compaction, Hooijer *et al.* (2012) mentioned the need for a critical level of understanding of tropical peat compaction due to the coupled processes between oxidative, consolidation, and shrinkage and man-made compaction (also known as artificial compaction). By definition, compaction comprises two coupled elements, compression and consolidation, whereby compression refers to the reduction of material due to the displacement of the oxic phase, and consolidation refers to the increase in mechanical strength of the material due to particle-to-particle interaction resulting from the collapse of peat soil under its own weight (Hooijer *et al.,* 2012). In contrast, the compressibility of peat soil does not make it easy to conduct direct measurements because of the different interrelated parameters such as peat depth, maturity, and bulk density (Price *et al.,* 2005). Most present works that have focused on artificial compaction and peat soil have only considered peat from the context of a soil conditioning agent and an additive for mineral soils (e.g. Ekwue & Harrilal, 2010; Soane, 1990) due to the 99% organic matter content (Huat *et al.,* 2011). Hence, this type of peat soil has a compressibility level of 300% to 400% and a far greater capacity to return to

its original condition (Rezanezhad *et al.,* 2016) – unless the hydrophobicity characteristic is achieved (Perdana *et al.,* 2018; Wirnarna *et al.,* 2016).

While some studies have investigated the effects of soil compaction on carbon emissions and soil water (Ball, 2013; Estop-Aragonés *et al.,* 2012; Ishikura *et al.,* 2018; Wakhid *et al.,* 2017), experimental data related to tropical peat soil-induced compaction or artificial compaction on tropical peat physicochemical properties and carbon emissions is rare. The only available reference by Busman *et al.* (2018) that conducted in laboratory condition using destructive composite sub-surface sample (50 to 70 cm) seems not representative to the nature of peat pedogenesis that vary in decomposition level towards peat depth (Rezanezhad *et al.,* 2016). Hence, this study aims to assess the effect of artificial compaction of tropical peat on the peat physicochemical properties and carbon emissions, as well as to address the concerns of unclear artificial compaction potential sources in **Chapter 2**. The objectives of this study are, therefore: (1) to induce compaction magnitude based on compression according to peat depth using a fabricated compaction apparatus; (2) to determine the peat physicochemical properties and quantify the peat carbon emissions according to the compaction treatment; (3) to establish a relationship between carbon emissions and physicochemical properties. In the end, the results of this study could be used to explain the carbon emission control based on the altered physicochemical properties of artificially compacted tropical peatland

3.3 Materials and methods

3.3.1 Study location

The study was conducted in two tropical peatlands; a drained and logged-over peat swamp forest (SF) in Tanjung Karang (3°41'49.2"N 101°11'06.0"E) at North Selangor (as described in Dhandapani *et al.,* 2019b; Tonks *et al.,* 2017) and a 10-year-old, 2nd generation oil palm plantation (OP), Sepang (2°44'20.4"N 101°39'10.8"E) at South Selangor originally converted in 1978 (as described in Matysek *et al.*, 2018); from December 2016 to April 2017. The peat depth at SF and OP was between 165.4 ± 3.9 (SD) cm, and 95.2 ± 6.5 (SD) cm, considered moderate depth (Hajon *et al.,* 2018). According to USDA soil taxonomy, the peat soils in both areas can be classified as Typic Fibric Tropohemist (Parthiban *et al.,* 2016). In SF, the artificial compaction experiment was established 1.0 km away from the drain edge and entry point. Meanwhile, for OP, the experiment was established in between the palm planting rows (harvesting path) (approximately 20 meters from a main drain; **Figure 2.2**).

3.3.2 Fabrication of hybrid compaction apparatus

The compaction apparatus was fabricated using stainless steel based on a vertical plunger-like compression. This simple apparatus consisted of four important parts, as per **Figure 3.1**: (a) soil collar, (b) piston, (c) piston's ear, and (d) perforated mesh surface. A soil collar cylinder measuring 40.0 cm long with a diameter of 10.16 cm, was used to standardise compaction magnitudes and maintain compaction degree due to the peat's high plasticity and recovery features (Huat e*t al.,* 2011; Rezanezhad *et al.,* 2016). A piston measuring 30.0 cm high and 10.16 cm diameter were used to compress the peat surface to the assigned soil depth. The piston also served as a static closed-chamber for capturing

gas. A cover that fitted two tubing ports was placed on top of the piston to facilitate gas sampling. The size of the piston was intentionally standardised for all treatments of gas concentration calculation (6.5 litres). The piston's ears, attached at various heights in accordance with the compaction treatment, were designed as a stopper during the compaction application. Finally, to address compressibility obstructions such as available water or air from peat removed by the compaction effort (Taylor & Brar, 1991), the piston surface was perforated with 1.0 mm^2 meshes. This also allowed for free transfer of GHGs.

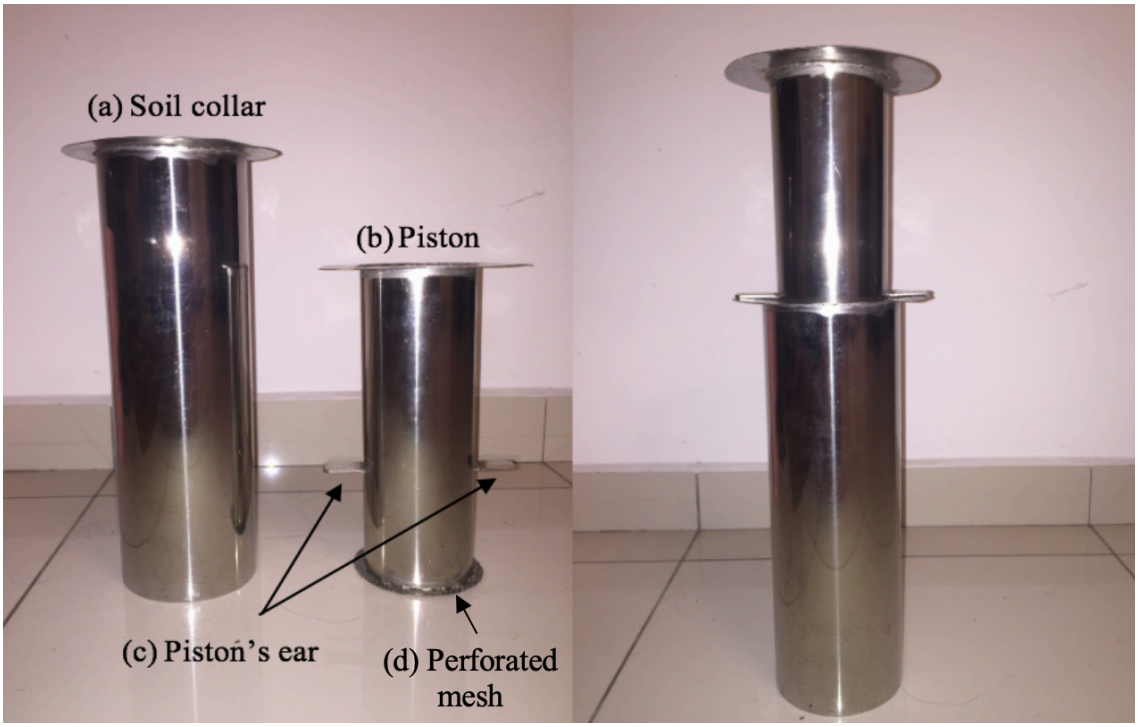


Figure 3.1 The hybrid peat compaction apparatus used in this study.

3.3.3 Artificial compaction using fabricated compaction apparatus

The soil collars were then driven into the peat profile and left for two months to allow resettlement and the root necrosis (Marella *et al.,* 2017) and exclusion of root biomass which would otherwise contribute to additional autotrophic emissions (Melling *et al.,* 2005a). Since flooding inside the soil collar was observed to occur in trials due to rainwater accumulation, the soil collars were covered loosely using a polystyrene plate to prevent direct rain fall while also preventing vapour deficits that could affect gas carbon emission (Gao & Yates, 1998). In addition, the slope of the soil was also considered. For OP, sites used avoided areas within 3.5m of the palm trunk (to avoid the root cycle; Matysek *et al.,* 2018 and reduce microenvironment variability) (see **Chapter 2**). The piston was left inside the soil collar after implementing the proposed depth to emulate static compaction by heavy machinery (Kuncoro *et al.,* 2014) that commonly occur in agricultural fields. To take into account the mesh-perforated surface, which may interrupt the gas diffusion from the surface soil, an integrity test was done to evaluate the compaction apparatus capability in terms of carbon emissions and degree of compactness (i.e. bulk density). The test was performed at the same time as the compaction experiment. Together, the compaction treatments were assigned as Ref (reference for control or no compaction without soil collar); T0 (no compaction with soil collar); T10 (soil compression treatment to 10.0 cm); T20 (20.0 cm); and T30 (30.0 cm), as per **Figure 3.2**. Four replications of the five compaction treatments (including the reference samples for the integrity test) in both ecosystems were established with a total number of samples of $n = 40$.

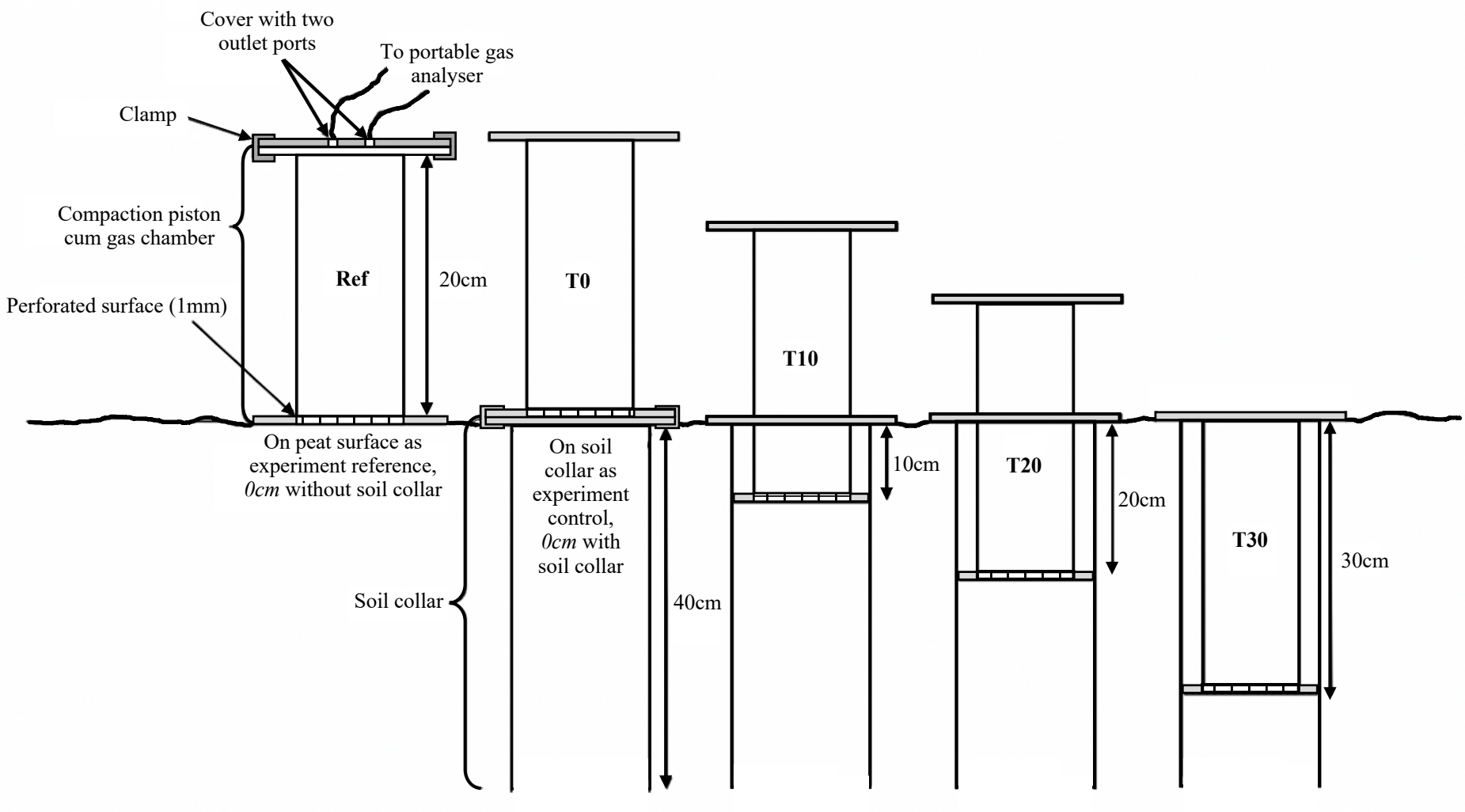


Figure 3.2 Schematic of peat compaction apparatus installation at the peat swamp forest and the oil palm plantation.

3.3.4 Gas sampling and measurement

Gas sampling were implemented in 24 days for SF and 21 days for OP, with three-day interval for one sampling point. Gas carbon emissions were measured using automated gas analyser (Ultraportable gas analyser by Los Gatos Research, USA) (**Figure 3.3**) following protocol as prescribed in the *GRACEnet* project (Parkin & Venterea, 2010). Mixed gas accumulation was analysed in a real time for six minutes and each of gas concentration points represented 20 seconds, which recorded and stored automatically in the analyser's data logger. Three concentration points for the first minute were discounted to account for the lid installation disruption



Figure 3.3 Gas measurement using stainless steel static closed-chamber and automated gas analyser at Tanjung Karang, North Selangor secondary peat swamp forest (SF).

3.3.5 Gas concentration calculation

The gas concentration in ppm was calculated using ideal gas law **Eq. (2.10)** as described in **Section 2.3.6**. The increase or decrease in the head-space concentration over time (hour, h^{-1}) over the head-space volume (L) from peat surface area covered (m^2) were fitted into linear regression (LR) (Parkin *et al.,* 2012; Samuel & Evers, 2016). The slope from LR was considered as the rate of CO_2 emission or CH_4 emission (+ value) / uptake (-value) and presented in, mg CO_2 m^{-2} hr^{-1} or µg CH_4 m^{-2} hr^{-1}.

3.3.6 Water table monitoring

In SF, water table levels were measured from piezometers (1.5 m) installed around the soil collars. However, measuring the water table level using the existing piezometers at OP proved difficult. The existing piezometer installed from a previous project was too deep (>3.5 m) and could not be reached via manual approach (using a ruler or a pole). Therefore, in this study, a technique using a laser distance-measuring application was used instead. With the digital laser distance meter (model GLM50 Bosch Laser Range Finder), the laser was pointed to the surface of a floating polystyrene block securely tied with yarn (**Figure 3.4**). The block thickness was 5.0 cm and used for surface water correction. During gas sampling, all measurements were retrieved from three perforated piezometers and the average measurements calculated.

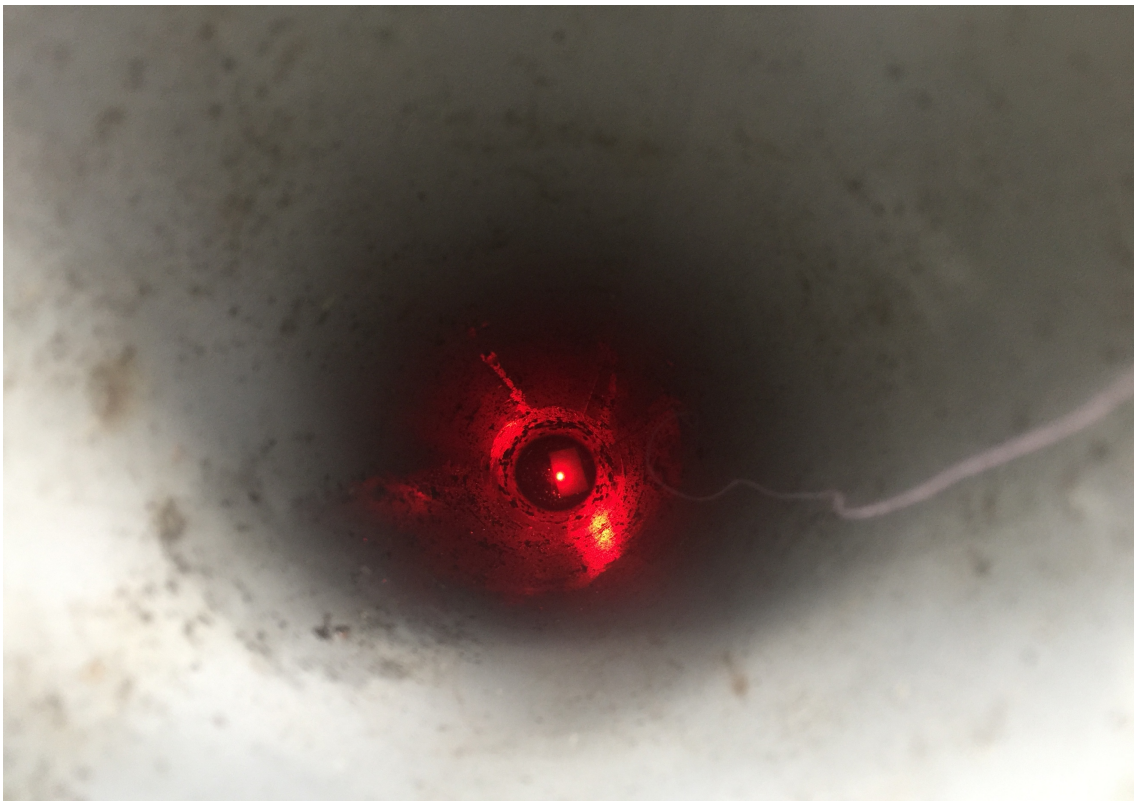


Figure 3.4 The use of a laser distance meter for water table level measurement to address the piezometer depth problem.

3.3.7 Peat sampling and physicochemical properties analysis

The peat and bulk density samples were collected separately from the soil collars at the end of the compaction experiment. The total samples were similar to the gas sample size of n = 40. Considering the small inner diameter of the peat surface inside the soil collar (i.e. 0.127 m diameter; 0.051 m^2 area), a bulk density core with a volume of 50.0 cm^3 at 7.0 cm peat depth was harvested from the soil collar using an open-ended syringe (50.0 ml) modified earlier by cutting off the syringe's Luer part (i.e. 0.027 m diameter with 0.0006 m^2 area). Then, 30.0 g of fresh peat was scooped out using a spatula for selected further peat physicochemical property analysis. In this study, peat surface sampling was emphasised because, within a range of 0 to 10.0 cm, peat soil exerts major

control on CO_2 and CH_4 emissions (Moore & Dalva, 1997) and physicochemical properties (Könönen, 2017), and this range is an effective depth for soil compaction (Kim *et al.,* 2014).

3.3.8 Peat physicochemical analysis

The procedures for the peat physical property analysis were described thoroughly in **Section 2.3.3**.

3.3.9 Determination of total carbon, nitrogen, hydrogen, sulphur and CN ratio using elemental analysis

The total carbon, total nitrogen, hydrogen, sulphur and CN ratio were determined following the standard method of elemental analysis in accordance with ISO 13878:1998. Composite samples were wrapped with a tin capsule. These include standard samples of sulphanilamide, $C_6H_8N_2SO_2$, for calibration purposes. Each sample set contained 16 unknown samples and was incorporated with 3 standard replicates weighing 3.0 mg for accuracy measurements. Meanwhile, for the preparation of the peat samples, composite samples of 10.0 mg were weighed using a microbalance, wrapped in aluminium foil capsules, and transferred into columns in sequence for combustion analysis using a Vario MACRO cube CHNS analyser (Elementary analysis system, Germany).

3.3.10 Statistical analyses

A General Linear Model (GLM) was run to verify the integrity of the fabricated compaction apparatus and to assess the effect of the ecosystems and compaction treatments on the physicochemical properties and carbon emissions of peat. When statistically significant differences between parameters were observed, Tukey's HSD multiple comparison procedure (Tukey, 1949) at $p \leq 0.05$ was performed. In order to identify the relationship between physicochemical properties and water table fluctuation with carbon emissions, Pearson's correlation coefficient method, two-tailed at the 0.05 probability level, was performed. All statistical analyses were calculated and formulated with the help of Minitab software version 18.1 (Penn, USA, 2017) while the graphs were plotted using Sigmaplot 12.5 graphing software (Systat Software Incorporation, UK, 2014).

3.4 Results

3.4.1 Integrity of fabricated compaction apparatus

An apparatus impact test was performed alongside all of the treatments using uncompacted peat samples without a soil collar. This Reference or 'Ref' data was then compared against a treatment control where the apparatus collar was installed but with no compaction ('T0'). This was undertaken for both ecosystems i.e. the secondary peat swamp forest (SF) and the oil palm plantation (OP). To verify if the apparatus was having a significant impact (independently of any treatment) on the results, bulk density and carbon emissions in the form of CO_2 and CH_4 were compared between Ref and T0. Assuming bulk density as an indicator of compactness, no differences in the interaction effects between compaction treatments and ecosystems was observed ($p = 0.260$) with a mean ranging from 0.12 to 0.15 g cm^{-3} and 0.18 to 0.21 g cm^{-3} for SF and OP, respectively (**Figure 3.5**).

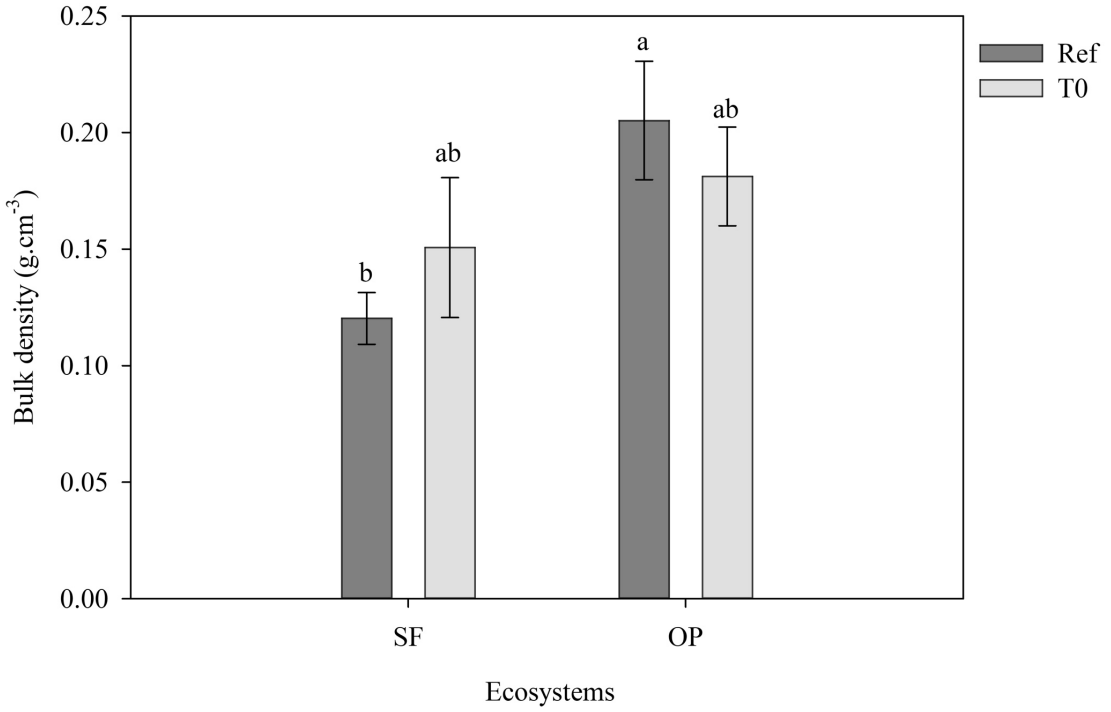


Figure 3.5 The comparison of bulk density (g cm^{-3}) between the reference and T0 samples (n = 4) at the secondary peat swamp forest (SF) and the oil palm plantation (OP). The error bars indicate the standard error of means. The different letters indicate significant differences between treatments and land uses. The means were separated using Tukey's HSD post-hoc test (α = 0.05).

Furthermore, in terms of CO_2 emissions, results also revealed that the reference sample did not differ from the control (p = 0.507) in both ecosystems, with comparable means ranging from 1234.3 to 1294.8 mg CO_2 m^{-2} hr^{-1} and 289.4 to 521.6 mg CO_2 m^{-2} hr^{-1} at SF and OP, respectively (**Figure 3.6 (a)**). A similar trend was also observed for the CH_4 emissions of both ecosystems (p = 0.689), with means ranging from -48.0 to -50.6 µg CH_4 m^{-2} hr^{-1} and -3.9 to -5.3 µg CH_4 m^{-2} hr^{-1} at SF and OP, respectively (**Figure 3.6 (b)**). This result indicates that the fabricated compaction apparatus did not have a significant impact on the reference BD or emissions. Therefore, from here onwards, the results of the physicochemical properties and carbon emissions due to artificial compaction will be presented based on the assigned control, T0 (no compaction with a soil collar).

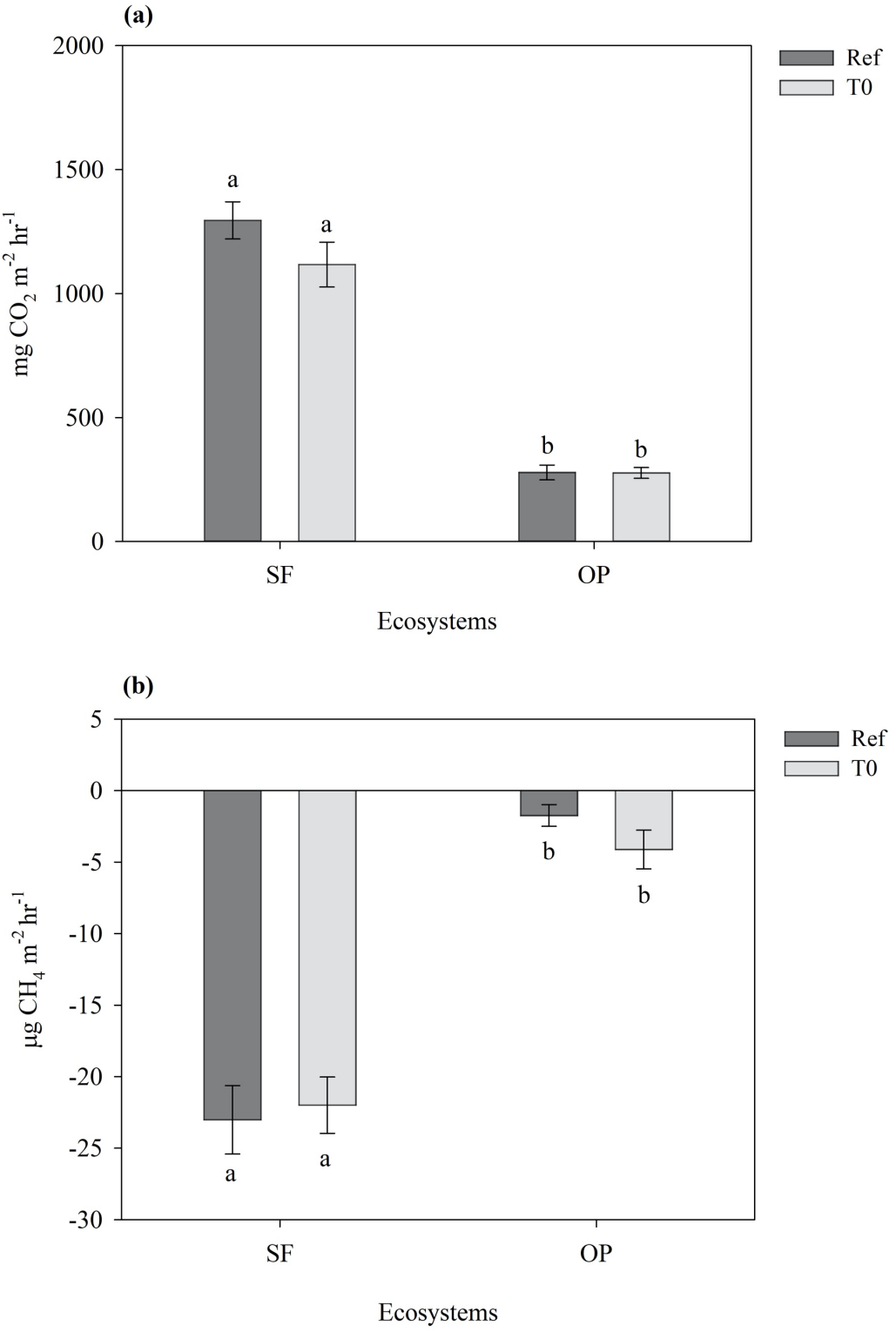


Figure 3.6 The comparison of **(a)** CO_2 and **(b)** CH_4 emissions between the reference and T0 samples at the secondary peat swamp forest (n = 32) and the oil palm plantation (n = 28). The error bars indicate the standard error of means. The different letters indicate significant differences between treatments and land uses. The means were separated using Tukey's HSD post-hoc test (α = 0.05).

3.4.2 Impact of *in-situ* artificial compaction treatments in different ecosystems on physicochemical properties

The change in physicochemical properties of the surface peat samples as a result of compaction treatments is shown in **Table 3.1**. Importantly, despite the compression by depth of the compaction apparatus, there was not a clear relationship between treatment and BD and no significant difference across treatments within each area (**Table 3.2**). Similarly, it is also clear that related to this, the other physicochemical properties such as total porosity, gravimetric water content, total carbon, hydrogen, sulphur, and CN ratio were not affected by the compaction treatments. However, the significant variation in BD between the differing ecosystems is clear with OP having a mean of 0.232 (± 0.020 SE) g cm^{-3} compared to that of SF, at 0.171 (± 0.013 SE) g cm^{-3} ($p = 0.008$). Related to this, peat porosity at OP to be lower than SF, with a mean of 85.5% and 89.7%, respectively ($p = 0.003$). The gravimetric water content was higher at SF compared to OP, with a mean of 225.3% and 175.3% ($p = 0.003$), respectively. At OP, total carbon, hydrogen, and CN ratio were higher than SF, with a mean of 42.5% and 37.4% ($p = 0.017$), 13.8% and 5.7% ($p < 0.001$), and 31.16 and 25.2 ($p < 0.001$), respectively. Conversely, the amount of sulphur at SF was higher than at OP, with a mean of 4.26% and 0.44% ($p = 0.005$), respectively. Meanwhile, loss on ignition, water-filled pore space, volumetric water content, pH, and total nitrogen was not affected by ecosystem or compaction treatment.

Table 3.1 General Linear Model (GLM) analysis between ecosystem and compaction treatment factors for the physicochemical properties of the soil in this study with (n = 16). The F-values in bold with *, **, and *** are significant at 0.05, 0.01, and ≤ 0.001, respectively.

		Physical property					
Source	df	Bulk density (g cm^{-3})	Loss on ignition (%)	Total porosity (%)	Water-filled pore space (%)	Gravimetric water content (%)	Volumetric water content (%)
Ecosystem	1	**6.98***	0.91	**9.12****	1.42	**7.22***	0.39
Treatment	3	1.13	0.47	1.59	2.00	0.25	1.76
Ecosystem X treatment	3	1.00	0.90	0.78	0.94	0.80	1.05
		Chemical property					
Source	df	pH value 1:2.5 (peat : water)	Total carbon (%)	Total nitrogen (%)	Hydrogen (%)	Sulphur (%)	C:N ratio
Ecosystem	1	0.74	**6.64***	1.82	**117.1*****	**9.51****	**19.58*****
Treatment	3	1.52	0.57	0.32	0.08	0.62	0.48
Ecosystem X treatment	3	1.29	0.75	0.04	0.62	0.63	0.99

Table 3.2 Physicochemical properties of the compaction treatments (mean ± standard error, n= 4) between the two ecosystems; namely secondary peat swamp forest (SF) and oil palm plantation (OP). The difference in the uppercase (between ecosystems) and lowercase (interaction effects) letters in bold in the same column indicates significant differences at $p \leq 0.05$.

		Physical property					
Ecosystem	Treatment	Bulk density (g cm^{-3})	Loss on ignition (%)	Total porosity (%)	Water-filled pore space (%)	Gravimetric water content (%)	Volumetric water content (%)
SF	T0	$0.15^{a} \pm 0.03$	$72.8^{a} \pm 9.9$	$91.5^{a} \pm 1.2$	$34.2^{a} \pm 5.9$	$214.9^{a} \pm 22.7$	$31.1^{a} \pm 4.9$
	T10	$0.19^{a} \pm 0.02$	$79.0^{a} \pm 10.2$	$86.4^{a} \pm 0.5$	$45.1^{a} \pm 1.9$	$214.0^{a} \pm 27.7$	$39.9^{a} \pm 1.9$
	T20	$0.15^{a} \pm 0.02$	$85.7^{a} \pm 3.8$	$90.7^{a} \pm 0.8$	$41.5^{a} \pm 2.4$	$257.8^{a} \pm 23.4$	$37.6^{a} \pm 2.1$
	T30	$0.19^{a} \pm 0.03$	$85.1^{a} \pm 1.9$	$88.2^{a} \pm 2.2$	$42.9^{a} \pm 7.1$	$214.5^{a} \pm 37.7$	$37.6^{a} \pm 5.7$
	Mean	**$0.17^{B} \pm 0.01$**	$80.7^{A} \pm 3.6$	**$89.7^{A} \pm 0.7$**	$40.9^{A} \pm 2.4$	**$225.3^{A} \pm 13.6$**	$36.5^{A} \pm 2.0$
OP	T0	$0.18^{a} \pm 0.02$	$85.9^{a} \pm 1.3$	$88.6^{a} \pm 1.3$	$38.7^{a} \pm 3.1$	$195.4^{a} \pm 23.7$	$34.2^{a} \pm 2.7$
	T10	$0.22^{a} \pm 0.04$	$83.8^{a} \pm 0.6$	$86.4^{a} \pm 2.4$	$40.0^{a} \pm 5.7$	$163.7^{a} \pm 15.7$	$34.2^{a} \pm 4.2$
	T20	$0.28^{a} \pm 0.06$	$81.9^{a} \pm 1.1$	$83.2^{a} \pm 3.8$	$47.7^{a} \pm 4.7$	$161.7^{a} \pm 29.2$	$39.2^{a} \pm 2.1$
	T30	$0.25^{a} \pm 0.01$	$85.5^{a} \pm 2.3$	$84.0^{a} \pm 1.2$	$54.5^{a} \pm 7.0$	$180.5^{a} \pm 25.3$	$45.7^{a} \pm 5.8$
	Mean	**$0.23^{A} \pm 0.02$**	$84.3^{A} \pm 0.8$	**$85.5^{B} \pm 1.2$**	$45.2^{A} \pm 2.9$	**$175.3^{B} \pm 11.3$**	$38.3^{A} \pm 2.1$
		Chemical property					
Ecosystem	Treatment	pH value (1:2.5) (Peat:water)	Total carbon (%)	Total Nitrogen (%)	Hydrogen (%)	Sulphur (%)	C:N ratio (%)
SF	T0	$3.06^{a} \pm 0.02$	$33.9^{a} \pm 4.5$	$1.6^{a} \pm 0.3$	$4.7^{a} \pm 0.9$	$7.0^{a} \pm 3.7$	$22.5^{a} \pm 1.8$
	T10	$3.04^{a} \pm 0.04$	$36.1^{a} \pm 4.7$	$1.4^{a} \pm 0.2$	$5.6^{a} \pm 1.0$	$3.7^{a} \pm 2.2$	$26.6^{a} \pm 2.7$
	T20	$3.01^{a} \pm 0.03$	$41.4^{a} \pm 2.2$	$1.6^{a} \pm 0.2$	$6.5^{a} \pm 0.8$	$2.5^{a} \pm 1.0$	$26.9^{a} \pm 3.2$
	T30	$3.07^{a} \pm 0.03$	$38.0^{a} \pm 2.1$	$1.6^{a} \pm 0.1$	$6.0^{a} \pm 0.7$	$3.8^{a} \pm 1.0$	$25.0^{a} \pm 1.7$
	Mean	$3.05^{A} \pm 0.01$	**$37.4^{B} \pm 1.8$**	$1.5^{A} \pm 0.1$	**$5.7^{B} \pm 0.4$**	**$4.3^{A} \pm 1.2$**	**$25.2^{B} \pm 1.2$**
OP	T0	$2.89^{a} \pm 0.1$	$43.2^{a} \pm 1.1$	$1.4^{a} \pm 0.0$	$14.2^{a} \pm 1.1$	$0.4^{a} \pm 0.9$	$31.7^{a} \pm 0.9$
	T10	$2.92^{a} \pm 0.1$	$41.9^{a} \pm 1.6$	$1.3^{a} \pm 0.1$	$13.9^{a} \pm 0.43$	$0.4^{a} \pm 0.1$	$32.2^{a} \pm 1.5$
	T20	$3.01^{a} \pm 0.1$	$42.9^{a} \pm 1.8$	$1.4^{a} \pm 0.1$	$13.1^{a} \pm 0.7$	$0.5^{a} \pm 0.1$	$29.6^{a} \pm 0.8$
	T30	$3.18^{a} \pm 0.2$	$42.4^{a} \pm 2.3$	$1.37^{a} \pm 0.1$	$13.9^{a} \pm 2.0$	$0.5^{a} \pm 0.2$	$31.2^{a} \pm 1.2$
	Mean	$3.00^{A} \pm 0.1$	**$42.5^{A} \pm 0.8$**	$1.37^{A} \pm 0.0$	**$13.8^{A} \pm 0.6$**	**$0.44^{B} \pm 0.1$**	**$31.16^{A} \pm 0.6$**

3.4.3 *In-situ* artificial compaction on carbon emissions

CO_2 emissions were not affected by day after compaction at SF (p=0.649) and OP (p=0.431) (**Figure 3.7 (a)** and **(b)**). However, there were some occasions that against the nature of ground water level after experiencing extreme lowering water level on day after compaction (DAC) 6 at SF specifically at T30. Untypical, during the rising water level from -13.2 cm (DAC 4) to -8.6 cm (DAC 5), the CO_2 emissions were increased gradually from 410.0 mg CO_2 m^{-2} hr^{-1} to 621.9 mg CO_2 m^{-2} hr^{-1}. However, during DAC 21 and DAC 24, the CO_2 emissions at T30 were tend to back to its nature emissions of which following the aerobic space altered by water table level.

The highest cumulative CO_2 emission was observed at SF compared to OP with a mean of 893.7 mg CO_2 m^{-2} hr^{-1} and 328.5 mg CO_2 m^{-2} hr^{-1}, respectively ($p < 0.001$). However, there was a difference between ecosystems and compaction treatments because of combination effects ($p = 0.009$). This result indicates that the cumulative CO_2 emissions from the compaction treatment were influenced by different ecosystems. Through multiple comparisons of simple effect, the reduction in cumulative CO_2 emissions was only effective at SF (**Figure 3.8 (a)**). Compared to T0, the highest cumulative CO_2 emission reduction was observed at T30 followed by T20 with a reduction from 1294.8 to 467.5 mg CO_2 m^{-2} hr^{-1} ($p < 0.001$) and from 1294.8 to 829.6 mg CO_2 m^{-2} hr^{-1} ($p = 0.015$), respectively. However, T10 did not differ from T0 with a comparable mean of 982.7 mg CO_2 m^{-2} hr^{-1} ($p = 0.290$). At OP, cumulative CO_2 emissions remained unchanged for all treatments ($p > 0.05$), with a mean ranging between 231.0 mg CO_2 m^{-2} hr^{-1} and 521.6 mg CO_2 m^{-2} hr^{-1}. (**Figure 3.8(b)**).

Similar to CO_2, CH_4 emissions between compaction treatment and day after compaction were not significant at SF ($p = 0.074$) and OP ($p = 0.203$) (**Figure 3.7 (c)** and **(d)**), also exhibited pulse emission in one replicate sample (caused large standard error) especially on the peat treated with a compaction up to 30 cm depth for SF. The increase of CH_4 emissions was measured on DAC 9 to 15, from 127.2 to 199 and then 151 µg CH_4 m^{-2} hr^{-1}. Even so, the peak emissions only occurred 6 days, after drastic water table level changed from 3.9 cm to -16.2 cm. Overall, CH_4 emissions /drawdown both ecosystems at T0 over the experimental duration were comparable, with means ranging from -6.06 to -1.77 µg CH_4 m^{-2} hr^{-1} ($p = 0.542$) respectively. Nevertheless, similar to CO_2 emissions, CH_4 emissions were found influenced by ecosystems and compaction treatments ($p < 0.001$) and was more profound at SF (**Figure 3.8 (b)**). The highest increment in CH_4 emissions, as compared to the control (T0), was from T30 followed by T20 with increased emissions by 109.6 µg CH_4 m^{-2} hr^{-1} ($p < 0.001$) and 42.2 µg CH_4 m^{-2} hr^{-1} ($p = 0.044$), respectively. However, T10 did not differ from T0 with a comparable mean of −7.5 µg CH_4 m^{-2} hr^{-1} ($p = 0.708$). No changes were observed at OP, with means ranging from −3.93 to -0.49 µg CH_4 m^{-2} hr^{-1} ($p > 0.05$) (**Figure 3.8 (b)**).

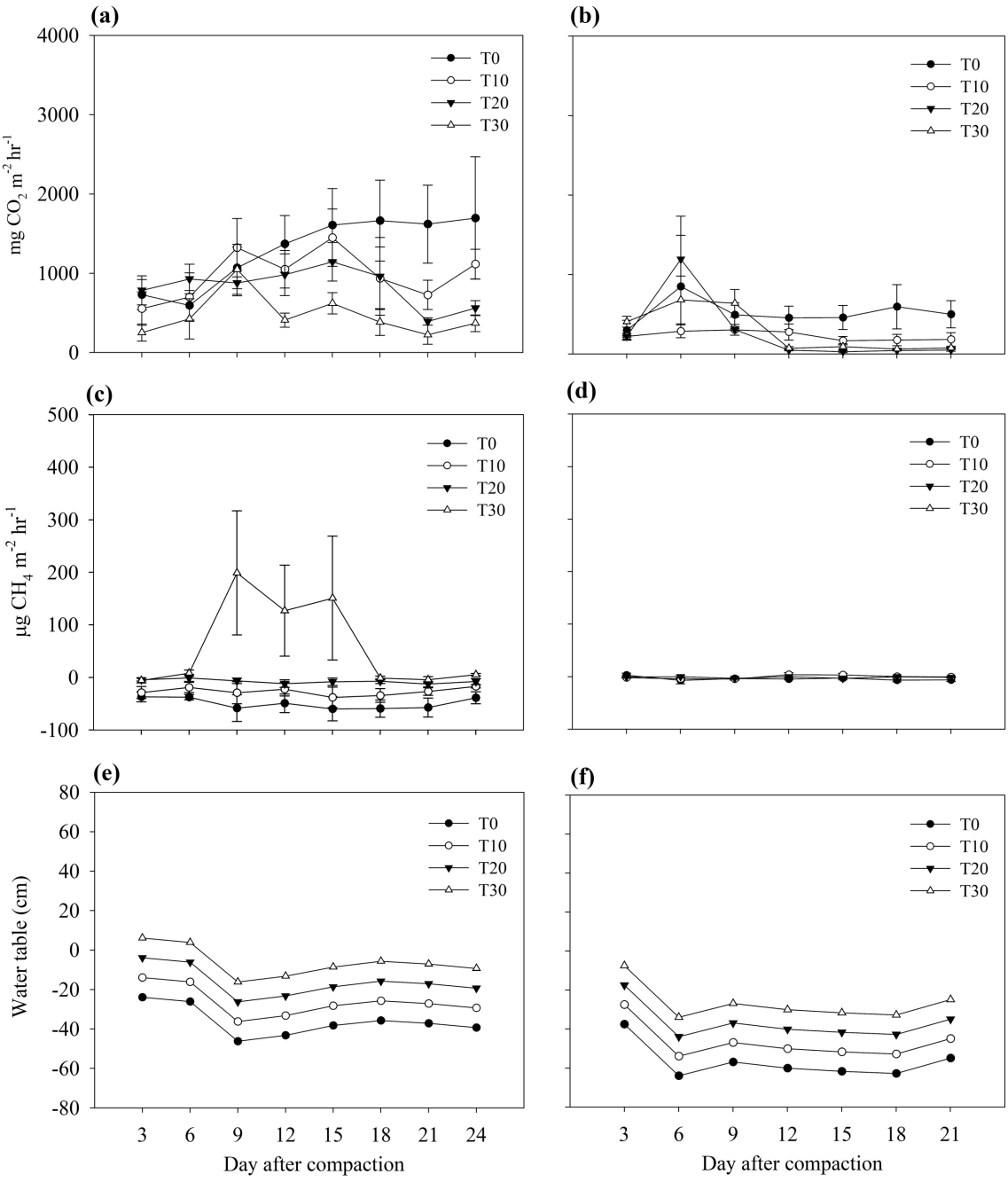


Figure 3.7 CO_2 emissions by day after compaction from compaction treatments at **(a)** SF and **(b)** OP. Meanwhile, CH_4 emissions by day after compaction from compaction treatments at **(c)** SF and **(d)** OP, respectively. Water table level by day after compaction at **(e)** SF and **(f)** OP, respectively. No significant differences were found between compaction treatment and day after compaction ($p \geq 0.05$).

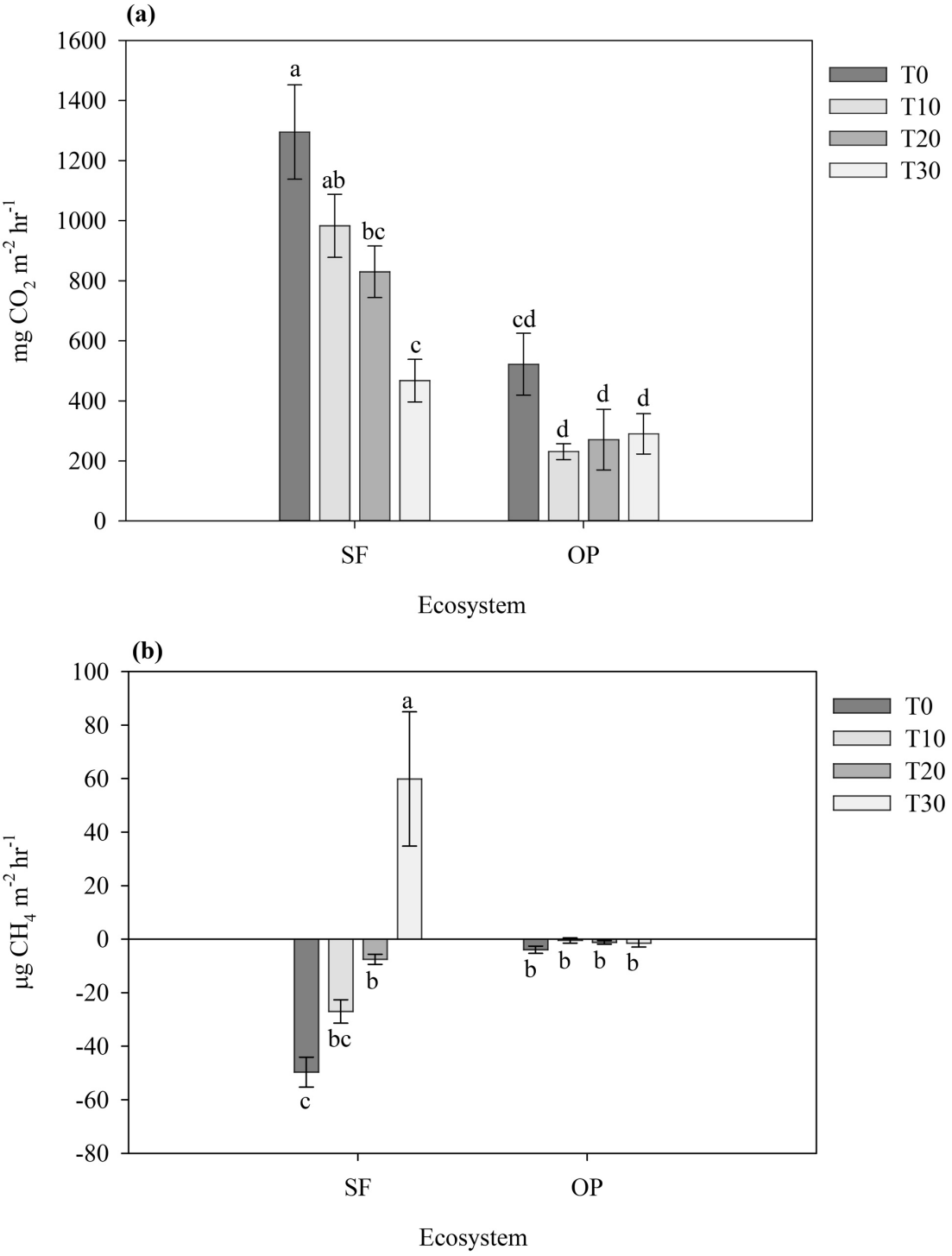


Figure 3.8 The means of cumulative **(a)** CO_2 and **(b)** CH_4 emissions between compaction treatments at SF (n = 32) and OP (n = 28). The error bars indicate the standard error of means. The different letters indicate significant differences between treatments and land uses. The means were separated using Tukey's HSD post-hoc test (α = 0.05).

3.4.4 Water table level due to artificial compaction treatments during study period

As compaction treatments lowered the soil surface compared to surrounding areas, there was a resulting change in relative water table depth compared to the modified surface level (by the distance of the compaction), resulting in the expected significant difference in water table heights between treatments for both ecosystems ($P<0.001$ for both OP and SF) (**Table 3.3**). However, in addition to this, water table level between treatments were different within ecosystem with a mean -21.2 ± 13.4 (SD) cm (n=128) ($p < 0.001$) at SF and -41.8 ± 14.1 (SD) cm (n=112) at OP ($p < 0.001$), respectively.

Table 3.3 Water table fluctuation according to the assigned treatments at the respective ecosystems. Values are presented in mean ± (SD) of water table level at SF (n = 32) and OP (n = 28), respectively.

Treatment	Ecosystem	
	Secondary peat swamp forest (SF)	Oil palm plantation (OP)
T0	-36.21 ± 7.34	-56.84 ± 8.59
T10	-26.21± 7.34	-46.84 ± 8.59
T20	-16.21 ± 7.34	-36.83 ± 8.59
T30	-6.21 ± 7.35	-26.83 ± 8.59

Note: T0 = No compaction with soil collar; T10 = compaction to -10cm peat depth); T20 = compaction to -20cm peat depth; T30 = compaction to -30cm peat depth.

3.4.5 Correlation analysis between carbon emissions with water table fluctuation

Pearson's correlation coefficient was performed to identify correlation between water table level and carbon emissions within ecosystems. The results are presented in **Table 3.4**. The results reveal that the water table at SF was negative correlated to CO_2 emission ($p < 0.001$) and positive correlated with CH_4 emission ($p = 0.008$). For OP, the water table level had no correlation neither with CO_2 emission ($p = 0.119$) nor CH_4 emission ($p = 0.105$).

Table 3.4. Values represent Pearson's correlation coefficient *r*, between carbon emissions and peat physical properties at peat swamp forest ($n = 32$) and oil palm plantation ($n = 28$). The bolded *r* values with *, ** and *** are significant at 0.05, 0.01 and ≤ 0.001, respectively.

Carbon emissions	Secondary peat swamp forest (SF)	Oil palm plantation (OP)
CO_2	**-0.781*** **	-0.302
CH_4	**0.460** **	0.313

3.4.6 Correlation analysis between carbon emissions with physicochemical properties

Soil samples from the last day of gas sampling were used to identify the relationship between physicochemical properties and carbon gas emissions in this study. Pearson's correlation coefficient analysis within ecosystems was performed. The results of this study show that no correlation between carbon emissions and physicochemical properties within the ecosystem was found (**Table 3.5**). Alternatively, pooled data from both ecosystems were used to identify the correlation between carbon emissions and physicochemical properties. Pearson's correlation coefficient analysis was again performed, and the results presented in **Table 3.6** show that CO_2 emission were positively correlated with total porosity (p = 0.010) and total nitrogen (p = 0.024) and negatively correlated with bulk density (p = 0.010), water-filled pore space (p = 0.017), volumetric water content (p = 0.031), hydrogen (p = 0.013), and CN ratio (p = 0.002). Meanwhile, CH_4 emission positively correlated with bulk density (p = 0.026), water-filled pore space (p = 0.025), hydrogen (p = 0.013), and CN ratio (p = 0.011), and negatively correlated with total porosity (p = 0.014).

Table 3.5 Pearson's correlation moment product between CO_2 and CH_4 emissions and physicochemical properties parameters. The values represent Pearson's correlation coefficient, *r*, between carbon emissions and peat physical properties (n = 4) within ecosystems. The *r* value for all parameters **are not** significant differences.

	Secondary peat swamp forest (SF)		Oil palm Plantation (OP)	
Variable	CO_2	CH_4	CO_2	CH_4
Bulk density (g cm^{-3})	-0.380	0.365	-0.415	0.423
Loss on ignition (%)	0.177	0.133	0.219	-0.191
Total porosity (%)	0.378	-0.467	0.407	-0.418
Water-filled pore space (%)	-0.459	0.468	-0.437	0.368
Gravimetric water content (%)	0.043	0.010	0.194	-0.333
Volumetric water content (%)	-0.455	0.455	-0.406	0.331
pH value	-0.074	0.153	-0.471	0.437
Total carbon (%)	0.082	0.072	0.151	-0.261
Total nitrogen (%)	0.372	-0.180	-0.198	0.044
Hydrogen (%)	0.125	0.036	-0.149	0.211
Sulphur (%)	-0.221	0.184	0.139	-0.269
CN ratio	-0.420	0.328	0.418	-0.306

Table 3.6. Pearson's correlation moment product between CO_2 and CH_4 emissions and physicochemical properties. The values represent Pearson's correlation coefficient, *r*, between carbon emissions and peat physical properties ($n = 4$) of pooled data from both ecosystems. The *r* values in bold with *, **, and *** are significant at 0.05, 0.01, and ≤ 0.001, respectively.

	Physical property					
Carbon emission	Bulk density (g cm^{-3})	Loss on ignition (%)	Total porosity (%)	Water-filled pore space (%)	Gravimetric water content (%)	Volumetric water content (%)
CO_2	**-0.447****	-0.151	**0.449****	**-0.419***	0.279	**-0.381***
CH_4	**0.394***	-0.052	**-0.433***	**0.395***	-0.213	**0.363***
	Chemical property					
Carbon emission	pH value (1:2.5) (Peat:water)	Total carbon (%)	Total nitrogen (%)	Hydrogen%	Sulphur%	C:N ratio
CO_2	-0.047	-0.149	**0.398***	**-0.436***	0.173	**-0.528****
CH_4	0.047	0.213	-0.250	**0.387***	0.138	**0.444***

3.5 Discussion

3.5.1 Peat resilience in presence of water table fluctuation

This study successfully developed and applied a hybrid compaction apparatus in a tropical peatland environment. The apparatus impact test conducted showed that the compaction apparatus could be used for both ecosystems and its instillation in itself did not significantly modify bulk density (BD) (**Figure 3.5**) or carbon emissions in the form of CO_2 (**Figure 3.6 (a)**) and CH_4 (**Figure 3.6 (b)**) compared to reference samples. The compaction treatments in this study were focused on vertical load compaction to profile compaction magnitudes according to different peat depths. An assumption that the magnitude of compaction will vary according to the treatments was thus made. However, despite varying magnitudes of vertical compaction, it was found that peat surface physicochemical properties, most significantly bulk density remained unchanged between treatments. Similarly, total porosity, water-filled pore space, volumetric water content, gravimetric water content, pH, loss on ignition, total carbon, nitrogen, hydrogen, sulphur, and CN ratio also remained unchanged between treatments. The only difference perceived was that of an inherent pre-existing difference occurring between ecosystems (OP and SF) in bulk density, total porosity, gravimetric water content, total carbon, hydrogen, sulphur, and CN ratio were different for both ecosystems (**Table 3.2**).

The lack of response of peat properties to the compaction treatments was unexpected and suggested that at the forces applied here at least, the peat in both ecosystems was resilient towards artificial compaction. There are several reasons why the peat from both ecosystems exhibited resilience. First, this effect is a result of water table fluctuation interaction, especially at maximum compaction, T30 (−30.0 cm compression),

where the modified soil surface level was closest to the water table level. The water table level at maximum compaction during the study of SF and OP fluctuated from -6.26 ± 7.35 (SD) cm and -26.8 ± 8.59 (SD) cm, when compaction went above −30.0 cm. Water table level interference was also observed by Baker *et al.* (2004), who suggested that water table level fluctuation in wetting and drying cycles could cause looseness or impaired pore structure or swelling. In addition, Pires *et al.* (2007) also analysed the changes in a pore system using gamma-ray computed tomography (CT) and found that wetting and drying cycles could result in a repair mechanism in the compacted soil structure. This is important when considering potential rebound post compaction but does not account for the continuous compaction which occurred throughout the experimental period.

Second, the ineffectiveness of artificial compaction on peat may be further enhanced by newly decomposed peat, or available labile C from above the peat surface, which has translocated to a deeper depth by vertical compaction and readily has sponge-like features (Campos *et al.,* 2011). Recent dead plant biomass is known as a source of labile C (Jauhiainen *et al.,* 2016). During compaction treatment, labile C from the peat surface could be relocated to the deeper horizon to augment consolidation. However, in this occasion is very difficult to achieve instantly since labile C comprises complex fractions of fresh dead plants that have a firm structure that deters herbivore-like characteristics (Gregorich *et al.,* 2017; Yule & Gomez, 2009). Hence, peat will return to its former state, as the peat pores could still be active and have elastic and plastic properties (Huat *et al.,* 2011; Rezanezhad *et al.,* 2016). Unless the peat pores are inactive due to excessive drying, which will manifest as hydrophobicity (Perdana *et al.,* 2018). Third, peat failure to compress could be a result of a lack of mineral or clay content

(Alakukku, 1996a, 1996b), which serve as a cohesive or macropores filler to stabilise the anisotropic structure of peat. This is because mineral content such fly ash, gypsum, and lime with peat admixtures can promote peat stabilisation and could possibly support more effective compaction (Alakukku, 1996a, 1996b; Kolay & Aminur, 2011; Kolay & Taib, 2018; Kolay & Pui, 2010). However, if this was the case, we may expect more of a response to the compaction treatments in the OP sites where lime application occurs. Finally, and we would propose most likely, is that the compaction effort was insufficient to elicit a response by the physiochemical variables measured. According to Mutert *et al.* (1999), the changes in bulk density may occur when the compaction of peat is drained to 0.50 m to 0.80 cm from the peat surface, allowing self-subsidence to 1.0 m prior to heavy machine passes. Conversely, the induced compaction in this study was kept at a maximum of 30.0 cm depth, and the water table level was not controlled, which might not have been sufficient to initiate changes in physicochemical properties of peat, especially bulk density. Yet, the longer-term drainage of the OP site accounts for the consistently higher BD values found there.

Overall, while not expected, this result points to the impressive resilience of intact peatlands to compaction, and their ability to maintain intact pore structure, water-holding capacity and porosity. These features are key to the hydrological ecosystem services provided by peatlands in terms of flood protection and water storage capacity (Bacon *et al.,* 2017). This result also reinforces the direct role of drainage as the key driver of compaction and consolidation within peatlands (Perdana *et al.,* 2018), with the artificial compaction only compounding the effect. The significant difference between ecosystems corroborate with the findings of several authors (e.g. Firdaus & Gandaseca, 2010; Firdaus *et al.,* 2011, 2012; Ishikura *et al.,* 2017; Melling *et al.,* 2005a, 2005b), who assessed the

physicochemical changes of converted land from a secondary peat swamp forest to an oil palm plantation (**Table 3.7**). These typical changes are based on the origin ecosystem attributes and the different management involving the lowering of water table level by drainage, agricultural input (e.g. fertiliser, pesticide, and agri-implements), and litter input from surrounding plant biomass. Consequently, the distinct traits exhibited at the OP sites will also be associated with the degree of decomposition (e.g. bulk density, total porosity, water-filled pore space, gravimetric, and volumetric water content, and CN ratio) (Firdaus *et al.,* 2011; Tonks *et al.,* 2017).

Therefore, a key question to emerge from this work is if drainage-based compaction is recoverable with rewetting. While the work from Pires *et al.* (2007) suggests that the recovery of natural wet and dry cycles is important to rehabilitation of pore structure, in-situ assessments of BD and pore structure recovery over time will need to be assessed in line with rehabilitation activities. For example, are hydrological ecosystem services are to be recovered at previously drained and converted OP sites?

Table 3.7 Physicochemical properties of peat samples (at 5.0 cm depth) from the artificial compaction treatment of the secondary peat swamp forest (SF) and the matured oil palm plantation (OP) compared with previous studies. The values are mean ± SD (n = 16).

Physicochemical properties	SF	OP	Reported range	References
Bulk density (g cm^{-3})	0.17 ± 0.05	0.23 ± 0.08	0.15 ± 0.00 (SF) 2.0 ± 0.01 (OP)	Melling *et al.* (2005a)
Loss on ignition (%)	80.65 ± 14.37	84.27 ± 3.09	97.3 ± 0.35 (SF) 96.3 ± 0.19 (OP)	Firdaus & Gandaseca (2010)
Total porosity (%)	89.68 ± 2.78	85.54 ± 4.83	91.47 ± 1.82 (SF) 86.41 ± 3.89 (OP)	Firdaus & Gandaseca (2010)
Water-filled pore space (%)	40.91 ± 9.67	45.21 ± 11.55	57.6 (SF) 60.4 (OP)	Melling *et al.* (2005b)
Gravimetric water content (%)	225.3 ± 54.5	175.3 ± 45.2	352.7 ± 25.5 (SF) 348.7 ± 15.9 (OP)	Firdaus & Gandaseca (2010)
Volumetric water content (%)	36.54 ± 7.92	38.3 ± 8.53	55.63 ± 9.63 (SF) 49.7 to 68.98 (OP)	Firdaus *et al.* (2011) Firdaus *et al.* (2012)
pH value (1:2.5) (Peat:water)	3.05 ± 0.06	3.00 ± 0.23	3.60 ± 0.02 (SF) 3.40 ± 0.04 (OP)	Melling *et al.* (2005a)
Total carbon (%)	37.35 ± 7.01	42.48 ± 3.14	47.8 ± 0.87 (SF) 44.7 ± 1.09 (OP)	Melling *et al.* (2005a)
Total nitrogen (%)	1.53 ± 0.42	1.37 ± 0.15	1.77 ± 0.04 (SF) 1.96 ± 0.07 (OP)	Melling *et al.* (2005a)
Hydrogen (%)	5.70 ± 1.66	13.77 ± 2.23	0.20 to 0.7 (TP)*	Rosa *et al.* (2005) therein Botero *et al.* (2010)
Sulphur (%)	4.25 ± 4.75	0.44 ± 0.18	0.04 to 0.64 (RP)	Wakhid *et al.* (2017)
C:N ratio	25.24 ± 4.68	31.16 ± 2.27	27.2 ± 0.96 (SF) 23.4 ± 1.14 (OP)	Melling *et al.* (2005a)

Note: RP = Rubber plantation; TP = Tropical peatland; (* asterisk indicates value of H/C value).

3.5.2 Carbon emission changes due to artificial compaction

Despite physicochemical properties being unaffected by site-specific artificial compaction, carbon emissions in the form of CO_2 and CH_4 from the peat surface showed inverse patterns due to compaction, especially in the SF ecosystem. During compaction, CO_2 emissions decreased according to the treatment, with the greatest reduction measured at T30, by 827.2 mg CO_2 m^{-2} hr^{-1} (64%) and followed by 465.1 mg CO_2 m^{-2} hr^{-1} (36%) at T20 with an average of 50%. Various studies have reported CO_2 emissions from forest and oil palm plantation. The T0 CO_2 emissions in this study ranged from 467.5 to 1294.8 mg CO_2 m^{-2} hr^{-1} and 290.18 to 521.6 mg CO_2 m^{-2} hr^{-1} at SF and OP, respectively, which are similar to Dariah *et al.* (2014), Husnain *et al.* (2014), and Melling *et al.* (2005a). However, compared to many other studies, the value for OP emissions is generally low. For example, Matysek *et al.* (2018) obtained a higher value in their study of the same oil palm plantation during dry season conditions (means up to 1244.7 ± 149.2 (SE) mg m^{-2} h^{-1}; **Table 3.8**), and found the heterotrophic emissions to be dependent on the age of the plantation, with those converted the longest (2^{nd} generation) producing emissions comparable with this study (663.8 ± 102.2 (SE) mg m^{-2} h^{-1}).

Contrary to CO_2, CH_4 emission showed a significant increase in T20 and T30 treatments by 85% and 224% (average 150%), respectively, within the SF ecosystem. Our results found uncompacted (T0) SF to be a strong sink for CH_4 (**Figure 3.7(c))** and OP T0 to be a weak CH_4 sink (**Figure 3.7(d)**). This result conflicted with the CH_4 emissions reported by Melling *et al.* (2005b) (**Table 3.9**) for both ecosystems (where their OP site was a strong sink and the SF was a strong source); but corroborates with Sakabe *et al.,* (2018) for CH_4 emissions in SF and degraded SF. This may have been due to their

OP site being newly converted (4 years) and thus potentially having a higher labile C surface peat content, a source of substrate which has a CH_4 production priming effect (Arai *et al.,* 2014; Girkin *et al.,* 2018), as compared to our matured OP. The effect of the compaction treatments worked to reduce the sink effect at both ecosystems. However only SF T30 became a mean source of CH_4 in this study (**Figure 3.8(b)**). Given that there was no change in the physiochemical variables with treatments, the only significant change between treatments was not the compaction/BD, but rather the increase in relative water table level (-36.21 at T0 and -6.21 at T30).

Table 3.8 Comparison of the CO_2 emissions of this study with previous studies at secondary peat swamp forest (SF) and oil palm plantation (OP).

Ecosystem	Reported range (mg CO_2 m^{-2} hr^{-1})	Reference
SF	1265 ± 110	This study (Integrity test)
OP	405.5 ± 55.5	This study (Integrity test)
SF	467.5 to 1294.8	This study (All treatments)
OP	290.18 to 521.6	This study (All treatments)
SF	366.4 to 1953.1	Melling *et al.* (2005a)
OP	168.6 to 1227.6	Melling *et al.* (2005a)
SF	411.0 to 981.7	Husnain *et al.* (2014)
OP	388.1 to 753.4	Husnain *et al.* (2014)
OP	389.0 to 435.9	Dariah *et al.* (2014)
OP	716 to 909	Matysek *et al.* (2018)

Table 3.9 Comparison of the CH_4 emissions of this study with previous studies at secondary peat swamp forest (SF) and oil palm plantation (OP).

Ecosystem	Reported range ($\mu g\ CH_4\ m^{-2}\ hr^{-1}$)	Reference
SF	-49.3 ± 4.35	This study (Integrity test)
OP	-4.64 ± 1.83	This study (Integrity test)
SF	-48.4 to 59.95	This study (All treatments)
OP	-3.94 to 3.63	This study (All treatments)
SF	-6.03 to 11.19	Melling *et al.,* (2005b)
OP	-43.76 to 5.55	Melling *et al.,* (2005b)
SF	-23.2 to 27.86	Sakabe *et al.,* (2018)
Degraded SF	-9.63 to 10.4	Sakabe *et al.,* (2018)

For this reason, we can use the data here to explore the direct relationship between emissions and WTD from in-situ data. For CO_2 emission, a significant relationship was found in SF ($p < 0.001$; $R^2 = 0.610$) (**Figure 3.9(a)**). The CO_2 predicted emission from SF is equal to – 24.9*WT + 363.05 when CO_2 emission is measured in mg $CO_2\ m^{-2}\ hr^{-1}$. From this established model, the CO_2 emission can be reduced by 6.7 mg $CO_2\ m^{-2}\ hr^{-1}$ for each centimetre of water table level increased. On the other hand, a significant regression between CH_4 emission and water table level (WT) was also found at SF ($p < 0.001$; $R^2 = 0.700$) (**Figure 3.9(b)**) after eliminated pulse emissions (before was CH_4 = 1.981*WT + 35.98 with $p = 0.008$; $R^2 = 0.212$). The predicted CH_4 emission in SF is equal to 1.24*WT + 4.27 in centimetre when CH_4 emission is measured in $\mu g\ CH_4\ m^{-2}\ hr^{-1}$. Thereby, CH_4 emission increased by 1.03 $\mu g\ CH_4\ m^{-2}\ hr^{-1}$ for each centimetre of water table level increased.

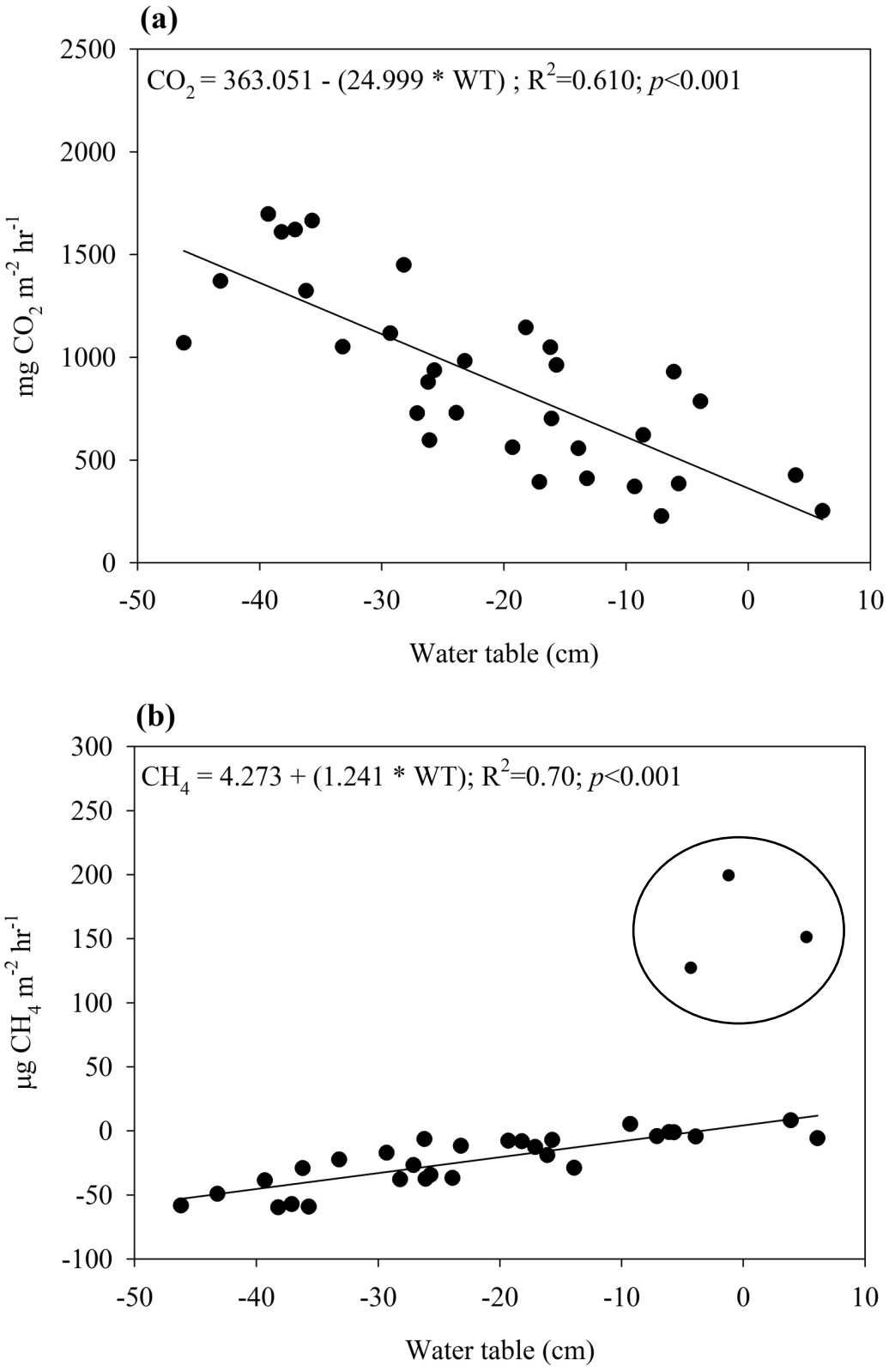


Figure 3.9 Relationship between water table level and **(a)** CO_2 and **(b)** CH_4 emissions at SF (n = 29-32). The point within solid-circle indicates momentary emissions that eliminated from regression analysis. Whereas, solid line indicates regression line between water table level and carbon emission.

Therefore, to further explain the carbon reduction from peat in secondary peat swamp forests, a model illustrating the carbon emission exchange and water table level (**Figure 3.9**) was employed. Thus, high and low water table level scenarios (extreme inter-seasonal effect) were used representing high (-6.21 cm) and low (-66.21cm) water table levels from the initial soil surface height (see **Table 3.3** for water table mean at T0, control). The 30.0 cm value was derived from the effective change in carbon emission due to artificial compaction, which affects peat depth, as mentioned in **Section 3.5.3.** From the estimation presented in **Table 3.10**, 59.1% change in carbon emissions was observed when the water table was raised or lowered (e.g. inter-seasonal) by 30.0 cm.

Interestingly, this estimation is similar to that of Dhandapani *et al.* (2019b), which measured CO_2 and CH_4 in a primary peat swamp forest in Setiu, Terengganu, and in a secondary peat swamp forest in Tanjung Karang, North Selangor. They observed a difference of more than 50% in CO_2 emissions. Thus, there is evidence to suggest that the secondary peat swamp forest in Tanjung Karang shares similar traits with the primary peat swamp forest in Terengganu, Peninsular Malaysia, which has been a protected area since the 1990s (27 years), particularly if the water table level has been raised to +30.0 cm from the initial level. Besides, this is also indicates that rehabilitation of secondary tropical peat forest is progressing splendidly and in agreement with Brühl (2001) that mentioned more than half of the tree species from primary forest can be found after 25 years of logging operations are ceased.

Table 3.10 The estimation of carbon emission changes due to water table level in secondary peat swamp forest of Tanjung Karang, North Selangor.

Scenario	Carbon emission (t CO_{2eq} ha^{-1} yr^{-1})
Initial level (Mean)	111.0
High water table level (+30cm)	45.4
Low water table level (-30cm)	176.6

Hence, this study proposed that the water table level in the secondary peat swamp forest of Tanjung Karang be maintained at 10.0 cm or higher to stabilise or reduce carbon emissions by 51.6%. However, it should be noted that the peat surface of this secondary peat swamp forest will always produce carbon emissions due to the decomposition process of organic materials that are supplied continuously from available trees (Jauhiainen *et al.,* 2016), besides root respiration (Dhandapani *et al.,* 2019b). Therefore, it is expected that approximately 53.7 t CO_{2eq} ha^{-1} yr^{-1} will be emitted naturally by this forest, indicating a 10.0 cm water table depth from the peat surface.

Yet importantly, this relationship only stands for relatively intact (i.e. SF) peatlands. As illustrated, lower water table depths / greater drainage *per se* as found at all the OP treatments did not result in a greater sink potential for CH_4. Indeed, all OP treatments were low CH_4 sinks (**Figure 3.7(d)**) despite having lower water level depths ranging from -56.45 (T0) to -26.83 (T30) (**Table 3.3**). In the OP ecosystem, the litter fall input is undoubtedly limited (Tonks *et al.,* 2017) because of its monoculture system (Dhandapani *et al.,* 2019b). Despite ample oxic and anoxic conditions due to water table fluctuation (**Table 3.3**), insufficient litter input could limit the source of substrate availability that promotes microbial activity (Dhandapani *et al.,* 2019b). Moreover, the

effect of excessive periodical drainage in the matured OP may also affect the water holding capacity resulting from irreversible drying condition (Leng *et al.,* 2018) and an enhanced hydrophobic trait (Perdana *et al.,* 2018) due to disconnecting peat pores from water table level in long period (Ishikura *et al.,* 2017). This phenomenon could explain why CO_2 and CH_4 at OP remain unchanged although the water table fluctuation and through depth alteration by compaction treatment.

Furthermore, consideration of temporal water table fluctuations, of particular interest is at the event of water table exceeds the peat surface on DAC 6 and DAC 9 in SF with a water level difference of 20.1 cm (**Section 3.4.3**) specifically on carbon emissions. Which may reflects the temporary water retention induced by anisotropic deformation (Rezanezhad *et al.,* 2016). In turn, the condition is likely to trigger temporary carbon emissions. Similarly, the CO_2 and CH_4 production also found by Brouns *et al.* (2014) during oxygenation treatment of deep peat layers that had not previously been exposed to air. This pulse and resulting emissions is often discounted in long-term calculations (IPCC) (Ishikura *et al.,* 2017; Wakhid *et al.,* 2017). Therefore, the mechanism of changes in water tables above the ground level accompanied by artificial compaction is important when undertaking a full C cost accounting for the process of palm oil conversion (as opposed to just a comparison of oil palm and forest). This pulse in emissions in association with the process of conversion agrees with that described by Hooijer *et al.* (2012), but is crucially not accounted for in the IPCC 2014 accounting. Nevertheless, the frequency is limited, and further study is needed to verify the reproducibility of the results reported here.

3.5.3 Influence of decomposition current status on carbon emissions from different ecosystems

No correlation between carbon emission and physicochemical properties was found when the data within the ecosystem was analysed. Interestingly, the pooled data of physicochemical properties from both ecosystems showed several associations with carbon emissions (**Table 3.6**). These relationships can be interpreted in regard to the degree of decomposition resulting from oxidation and shrinkage. However, increases in bulk density and its decomposition proxies owing to ecosystem shifting (e.g., from secondary peat swamp forest to oil palm plantation) should not be interpreted as a result of active /artificial compaction, but rather due to oxidation and shrinkage from periodic drainage alone (Hooijer *et al.,* 2012) or passive compaction. These coupled components have given rise to an important question regarding the actual definition of artificial peat compaction. Most works in the literature (e.g., Hooijer *et al.,* 2012; Melling & Henson, 2011; Mutert *et al.,* 1999; Othman *et al.,* 2009; Smith *et al.,* 2018) have unsuccessfully distinguished between artificial compaction and oxidative compaction. This issue could result in the misconception of artificial compaction based on the use of heavy machinery during the opening of the plantation from a forest area. Here, through this study also, it is believed that artificial compaction effectiveness could be deteriorated by the standard water table level from −40.0 cm to −60.0 cm (*Principles and Criteria for the Production of Sustainable Palm Oil*, 2013), provided that the peat has a higher proportion of labile carbon at the early stages of the land opening period.

3.6 Concluding remarks

This study is the first to investigate artificial compaction of tropical peatland in the field by profiling compaction magnitudes based on peat depth, and in two different ecosystems; namely a secondary peat swamp forest (SF) and an oil palm plantation (OP). Apparatus was developed and used in situ to induce compaction and assessed against impacts bulk density and relative water table level and while here it was that exclusively applied to a tropical peat environment, the design is applicable to other peat systems. Our results showed that peat compaction lowers the soil surface level and thus reduces the relative water table depth. In doing so SF sites showed an increase in CH_4 and CO_2 especially during high water table periods. However, the compaction did not actually change any of the other physiochemical parameters at either ecosystem (though pre-existing conditions were significantly different between ecosystems). Through this in-situ experiment, this study was able to determine a strong relationship between water table depth and emissions which can be used for modelling future emissions from SF sites. While pre-existing high bulk density values dominated in the OP, compaction treatments also failed to influence either emissions of peat physio chemistry, suggesting a BD threshold in the effect of compaction and little impact on physiochemical parameters or carbon emissions. Thus, any additional compaction above what 'naturally' occurs as a response to drainage for agricultural conversion has no impact on physiochemical parameters or emissions. As such there seems no beneficial outcomes of this in regard to mitigating against the emissions of drainage-based agriculture on tropical peatlands. As such while more work is required to unpick the effect of compaction from that of water table depth, which is the focus of Chapter 4, the effect in situ compaction is undetectable in existing converted areas and undesirable where there is an impact (i.e. Secondary forest).

Chapter 4. Tropical peat soil artificial compaction in absence of water table level

4.1 Abstract

The artificial compaction of tropical peatland may alter biogeochemical processes and thus affect carbon emissions. The process of compaction occurs naturally due to drainage, shrinkage and peat consolidation, increasingly it is applied via artificial, mechanical compaction as part of peat agricultural conversion and management. While compaction of peat can lead to surface levels being closer to the water table depth (WTD) (**Chapter 3**), understanding the impact of compaction without the compounding effect of WTD is required for adequate assessment of this increasingly widespread approach. Therefore, this study aims to investigate the compaction effect of intact peat soil under laboratory-scale conditions. Fifty intact peat samples were collected using 5.08 cm inner radius and 40.0 cm height PVC tubes from two different locations, namely a secondary peat swamp forest (SF) and a matured oil palm plantation (OP). Artificial compaction treatments were manipulated according to three levels of volume reduction (%) using peat height adjustment based on maximum compaction from reference samples. The intact samples were incubated at room temperature, 30^{o}C, for 9 (at OP) to 10 days (at SF). Carbon dioxide (CO_2) and methane (CH_4) gas samples were sampled at 24-hour intervals using an automated gas analyser. The peat samples were collected at the end of the experiment and their physicochemical properties determined. The physicochemical properties of peat from SF were found to be affected by artificial compaction, but showed an inverse pattern to OP, especially with total nitrogen. Thus, the findings suggests that mechanical consolidation occurs in SF but not in OP due to the labile C composition in the former,

which is associated with peat compressibility and the stratified degree of decomposition from surface to deeper peat. Furthermore, CO_2 (reduction) and CH_4 (emission) according to a percentage ratio of 1:1.6, 1:2, and 1:2.4 for treatments 10%, 20% and 30% compaction were established (average 1:2). However, it is suspected that the effect of compaction on carbon emissions will be temporary since peat with fresh labile C will recover immediately due to water table interference. When considering CO_2 and CH_4 together, global warming potential was 13.9 t $CO_{2\text{-eq}}$ ha^{-1} yr^{-1} in relation to compaction treatment., but later can be undone when water table is introduced. We found that OP plantation sites were unaffected by compaction either in terms of physiochemical properties or emissions suggesting this is an ineffective approach to fire risk reduction in already drained systems.

Keyword: *Artificial compaction; carbon emissions; incubation; intact peat samples; physicochemical properties*

4.2 Introduction

Degradation of tropical peatland is currently receiving widespread criticism from the international community. Although peatland is a fragile and sensitive ecosystem, it is still considered an important filter for water pollution and a buffer for climate change (Cooper *et al.,* 2019; Dhandapani *et al.,* 2019b; McNicol & Silver, 2015; Page & Hooijer, 2016; Urbanová *et al.,* 2011). Currently, about 30% to 40% of 2.4 million ha of peatland in Malaysia has been developed for a variety of agricultural crops, mainly oil palm and pineapple, which have resulted in the degradation of the ecosystem and various environmental problems (Lim & Ahmed, 2014). It is also believed that the drainage of peatland results in greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2) and methane (CH_4), as well as carbon loss through water drainage in the form of organic acids and organic particulates (Evers *et al.,* 2017). As a result, the peatland ecosystem could shift from that of a carbon sink to a carbon source (Miettinen *et al.,* 2017), subsequently expediting the rate of global warming and climate change. Global warming, in turn, could also affect carbon loss in tropical peatland (Leng *et al.,* 2019). Among the imminent effect predicted is the increasing intensity of dry and wet periods, which will result in more extreme fluctuations in the water table, and consequently, accelerating the rate of decomposition and carbon loss in the soil (Girkin *et al.,* 2020).

It is reported that carbon fluxes in a peatland ecosystem are highly influenced by water table depth (Carlson *et al.,* 2015; Wakhid *et al.,* 2017). A high water table depth during the wet season restricts the diffusion of atmospheric oxygen into the peat soil; thereby restraining and limiting microbial activity and decomposition rate (Chimner & Cooper, 2003). The removal of carbon is done by methanogenic microbes that process

organic substrate into CH_4; however, these microbes will be rendered unable to metabolise organic matter into CO_2 due to the limited oxygen (Segers, 1998). A low water table, however, will increase air in the peat soil and remove water from the peat, resulting in shrinkage (Huat *et al.,* 2011). As a result, aerobic decomposition (decreasing the water-filled pore space) will occur in which carbon will be lost in the form of CO_2 when organic matter is metabolised by microbes in an unsaturated zone (Linn & Doran, 1984).

In a peat swamp forest area, the water level is reportedly high and fluctuates according to seasonal variation. However, the secondary peat swamp forest has over 250 km of legacy drainage resulting from left over logging activities (Brown *et al.,* 2018). As such, while natural/vegetative recovery has occurred since 1990, it is likely that there is some remaining hydrological impact via reduced overall WTH and impacts to natural seasonal fluctuations (Hatano *et al.,* 2010; Surahman *et al.,* 2018b). Although, secondary peat swamp forests are now mostly gazetted by the Malaysian State Forestry Department (e.g. Tanjung Karang, peat swamp forest gazetted in 1990 in this study), and drain blocking has occurred, WTH fluctuations observed here show reinstatement of the natural response to changing season and overall this areas of the SF appears to be storing carbon effectively (Waldron *et al.,* 2019). On the other hand, in an oil palm plantation, water table control can be seen as an opportunity to mitigate carbon emissions. According to a recent report (*National Interpretation of RSPO Principles and Criteria for Sustainable Palm Oil Production*, 2015), especially under the National Principle and Criteria number 4.3.4, specific Guidance for Water Table Standard for Existing Plantings On Peat, a water table level of 40.0 cm to 60.0 cm from the peat surface is proposed in order to sustain productivity of the palm oil plantation and at the same time reduce carbon oxidation.

Despite the advantage of high-water table in enabling the control of CO_2 and CH_4 emissions, it is also associated with the formation of pores in peat and thus, the "self-recovery" behaviour of compressed peat (**Chapter 3**). For example, Baker *et al.* (2004) reported that the sub-irrigated soils are not able to develop stable aggregates due to the interference of water, which causes slacking in soil macroaggregates. In general, peat pores decrease from the surface to deeper peat (Rezanezhad *et al.,* 2016) owing to different decomposition levels during peat growth. Subsequently, anisotropic pores that are important for water transportation and geochemical functions are developed (Rezanezhad *et al.,* 2016). On the other hand, compaction causes the reconfiguration of pores dominated by a horizontal laminar structure, which could lead to biogenic gas entrapment and an oxygen-limited environment that favours anaerobic conditions—to the detriment of the general community (Boelter, 1965; Estop-Aragonés *et al.,* 2012; Rezanezhad *et al.,* 2016).

Based on the above rationale, this study aims to investigate the effect of artificial compaction in the absence of water table level on peat physicochemical properties as a result of artificial compaction, as a progression of the work developed in **Chapter 3**. The main objective is the assessment of artificial compaction, as well as the elimination of water table nuisances, using a laboratory-scale experiment (*ex-situ*). It is hypothesised that artificial compaction in the absence of water table fluctuation can change the physicochemical properties of peat and affect the carbon emission from the peat surface. To reiterate, the objectives in this study are: (1) to manipulate bulk density value as a measure of degree of compactness based on reference samples collected alongside intact samples; (2) to determine the changes in physicochemical properties and carbon emission of peat as compared to the sample control, under artificial compaction; (3) to establish a

relationship between the peat physicochemical properties and peat carbon emissions, and finally; (4) to discuss and interpret the results in light of a real case scenario according to the current practice outlined in the Roundtable Sustainable Palm Oil (RSPO) and the Malaysian National Interpretation Task Force (MYNI-TF) (2015).

4.3 Materials and methods

4.3.1 Collection and selection of intact peat sample

Intact peat sample (defined as undisturbed peat cores without peat mixing or structural modification) was collected from two tropical peatland ecosystems, namely logged over or secondary peat swamp forests (SF) in Tanjung Karang, North Selangor, and a 11-year-old oil palm plantation 2nd generation (OP) in Sepang, South Selangor, during the dry season in July 2017. More details of sample locations can be found in **Section 3.3.1**. Intact peat was collected using a PVC tube with a 5.08 cm inner radius and 40.0 cm height (**Figure 4.1**). The sampling site in SF was selected based on aboveground plant biomass, which was covered by a sapling, so the root was young and easy to collect. Meanwhile, in the OP, sampling was performed at the harvesting path (**Figure 2.2**; **Table 2.1**), specifically, more than 3.0 m away from the palms. Water table level during peat sample collection in July 2017 (dry season) ranged between 50.0 cm to 70.0 cm from the peat surface at both locations. Lower water table conditions could facilitate intact peat sampling because peat aggregates are more stable without the interference of water table fluctuations (Baker *et al.*, 2004). A total of 50 intact samples including ten reference samples were extracted from both ecosystems. The reference samples were taken alongside the intact samples to determine the peat moisture content without disturbing the intact samples used for the study. The values of the peat moisture content were used as a standard to manipulate compaction treatments and to estimate initial bulk density.



Figure 4.1 Intact sample was extracted carefully from harvesting path in oil palm plantation in Sepang, South Selangor, Malaysia.

4.3.2 Determination of peat compaction treatments

Prior to conducting the peat compaction treatment, the fresh weight and volume of each intact sample were calculated. The initial peat volume was calculated based on the cylinder volume equation of **Eq. (4.1):**

$$V = \pi r^2 h \qquad \textbf{Eq. (4.1)}$$

Where; V = volume of intact peat in the tube expressed in cm^3, π = 3.142, r = inner radius of PVC tube in cm and h = peat height in cm.

Since each sample has its own height and weight, each sample was treated as an independent sample. Estimation of the initial peat dry bulk density was based on the percentage water loss from the reference samples, which had been dried in an oven at 105°C for 48 hours. While waiting for the reference samples to dry, the water lost from intact peat through evaporation was corrected using gravimetric calculation. Water loss correction was made through the addition of rainwater to mimic the water source from aboveground rainfed peatlands(ombrotrophic), maintain consistent soil moisture contents in daily course. With the reference samples as well, maximum compaction was also tested to assess PVC durability in withstanding extreme pressure.

With the reference samples, maximum compaction was also tested to assess PVC durability in withstanding extreme pressure. From these trials (n = 5 for each land use type), the maximum compression for the peat samples from SF was as high as 30% of the modified soil height. However, OP intact samples could only be compressed by 15%. compared to the SF area. Thus, compaction treatments used were chosen to provide a range of compaction levels (namely 10, 20 and 30% for SF and 5, 10 and 15% for OP). Uncompressed control cylinder samples were also assessed alongside treatments. In addition, to account for the total compaction as a result of cylinder insertion, total height reduction from the original surface (pre cylinder insertion) and the final height after cylinder insertion and compaction treatment was also recorded.

To establish compaction magnitudes according to the assigned treatments, bulk density values were calculated based on altered volume. Here, the height was manipulated

to adjust for the volume of peat. The calculation of altered bulk density value is presented in **Eq. (4.2).**

$$h = \frac{g}{\pi r^2 BD} \qquad \textbf{Eq. (4.2)}$$

Where h = the height of initial peat in the PVC tube in cm with one decimal place; g = initial peat weight in g; π = 3.142; r = the inner radius of the PVC tube in cm; and BD = value of bulk density by an increment from proposed treatment in g cm^{-3}.

The experiment was performed in two phases: a pre-compaction phase (5 days for SF and 4 days for OP) to test for emissions stability and also to act as a control for post compression emissions; and a post-compaction phase (5 days for both samples from SF and OP) to assess compaction effects. In this study, intact samples were maintained at a constant room temperature, at 30.0°C for a total of 9 to 10 days.

4.3.3 Peat sampling and physicochemical properties analysis

Peat sampling and physicochemical properties analysis were performed following the procedures described in **Sections 3.3.7** and **2.3.3**.

4.3.4 Gas sampling, measurement and analysis

A 0.5 L cylindrical chamber made of transparent plastic with two ports for gas exchange was pushed into the peat surface in cylinder as deep as 2.0 cm (**Figure 4.2**). Mixed gas sampling in the form of CO_2 and CH_4 was carried out after accounting for the addition of rainwater gravimetric equilibrium for approximately an hour. To ensure that the chamber was securely sealed, 500 g of ballast was placed above it. Gas concentration measurement and analysis were done using an automated gas analyser (Ultraportable gas analyser by Los Gatos Research, USA) and in accordance with the procedure prescribed in **Sections 3.3.4** and **2.3.6**. In this study, both carbon emissions from peat were presented in mg CO_2 m^{-2} hr^{-1} and µg CH_4 m^{-2} hr^{-1}, instead of per gram of fresh peat (Moore & Dalva, 1997), as the main focus was on the gas emission from the peat surface (Gao & Yates, 1998).

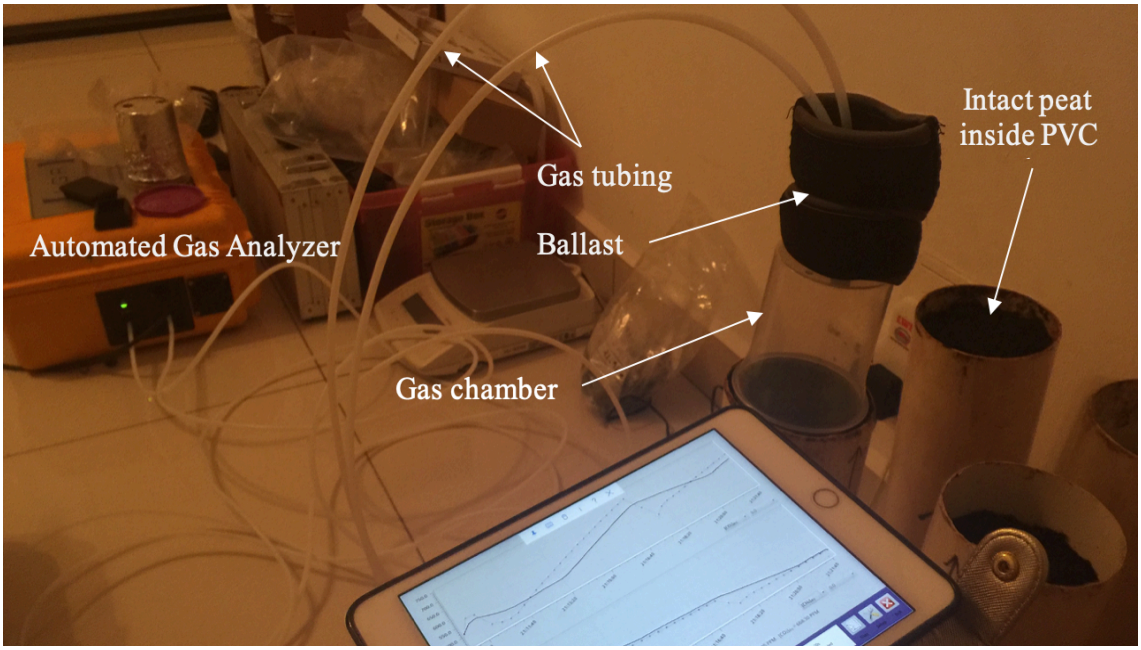


Figure 4.2 Gas sampling and analysis setting in real-time monitored using tablet interfaces during the incubation study.

4.3.5 Statistical analyses

Assumptions of data normality and equality of variance were checked using Ryan-Joiner's method (similar to Shapiro-Wilk's method) and Levene's method (Brown & Forsythe, 1974; Shapiro & Wilk, 2006; Yap & Sim, 2011). The physicochemical properties of peat were analysed using One-Way Analysis of Variance (ANOVA) for the compaction treatments and the control samples of each ecosystem. Any significant effects were further analysed for multiple comparisons of means to the control at $p \leq 0.05$ using Dunnett's post-hoc test (Dunnett, 1955). For carbon emissions, compaction effects at three levels of compaction magnitudes in two incubation phases within the ecosystem were analysed using Two-Way Analysis of Variance (ANOVA). Any significant effects were further analysed using the multiple comparisons of means at $p \leq 0.05$, as per Tukey's HSD post-hoc analysis (Tukey, 1949). The correlation between each gas carbon species with the peat physicochemical properties were investigated using Pearson's correlation moment. Significant correlation, r, was further analysed using an R^2 regression model, at $p \leq 0.05$, unless stated otherwise. All statistical analyses were calculated and formulated with the help of Minitab software version 18.1 (Penn, USA, 2017) while the graphs were plotted using *Sigmaplot 12.5* graphical software (Systat Software Incorporation, UK, 2014).

4.4 Results

4.4.1 Comparison between targeted bulk density value with reference sample

The compaction treatments in this study were assigned based on the maximum compression of the reference samples, then sub-divided into three levels of compaction treatment for each land use type (10, 20 and 30% for SF and 5, 10 and 15% for OP). The compaction treatment was manipulated via the volume reduction approach; however, these treatments did not yield bulk density increments comparable to expected values (**Table 4.1**). There was no clear relationship between the proportional compaction by volume and the resulting bulk density despite low variance in the reference and control sample BDs used as a basis for compression treatments (i.e., starting BDs were unlikely to be significantly variable within land-use type soil samples). In the majority of SF samples, there was an increase in BD where treatment was applied (though not proportional). This was not the case with the OP samples, where reference BD was in many cases higher than treatments, and again no clear proportional relationship was observed.

Table 4.1 Comparison of bulk density between reference sample (Ref) and after actual compaction treatment (mean ± standard error) (n=5) of secondary peat swamp forest (SF) and oil palm plantation (OP) samples. Means were distinguished by Dunnett's test ($\alpha = 0.05$).

Secondary forest (SF)						
Volume reduction	Mean peat depth after alteration (cm)	Bulk density (g cm^{-3})	t-value	p-value	Actual increased (%)	Expected increased (%)
SF Ref		0.15 ± 0.02				
0, control	-4.52	0.17 ± 0.01	0.51	0.959	9.31	0
10%	-5.02	0.14 ± 0.02	-0.43	0.978	-7.87	10
20%	-6.17	0.23 ± 0.03	2.71	0.045	49.08	20
30%	-9.50	0.20 ± 0.02	1.85	0.229	33.5	30 (max)
Oil palm plantation (OP)						
OP Ref	-14.16	0.31 ± 0.03				
0, control	-14.88	0.31 ± 0.03	0.12	1.000	1.60	0
5%	-17.36	0.28 ± 0.03	-0.76	0.860	-9.77	5
10%	-18.89	0.34 ± 0.03	0.80	0.838	10.29	10
15%	-14.16	0.28 ± 0.03	-0.79	0.847	-10.09	15 (max)

4.4.2 Alteration of physicochemical properties by artificial compaction

A total of 20 samples at 10 cm depth were extracted from intact samples to determine the physicochemical properties of peat as a result of compaction treatments. The effects of different compaction magnitudes (in the incubation experiment) on the peat physicochemical properties are presented in **Table 4.2**. The physical properties of the samples from SF observed a change in the water-filled pore space and volumetric water content, notably with the T30% compaction treatment, with the values being higher than the control by 17.92% (p = 0.026) and 15.09% (p = 0.024), respectively. Significantly however, the compaction treatments did not affect bulk density (mean of 0.184 ± 0.012 g cm^{-3}; p = 0.081). Further, there was no impact on loss on ignition, total porosity, or gravimetric water content with a mean of 79.64 ± 3.56% (p = 0.129), 88.97 ± 0.56% (p = 0.058), 261.8 ± 11.4% (p = 0.424), respectively.

Consideration of chemical variation (**Table 4.2**) with treatment showed that while there was no alteration to pH, which ranged from pH 2.69 to pH 2.77 (p = 0.650), compared to the control, total carbon after the T20% treatment was lower by 9.6% (p = 0.019), while no difference was observed for other treatments, with means ranging from 31.0% to 33.2%. The total nitrogen increased with treatment intensity, but only significantly (compared to the control) at T30% to 3.46%, while less intense treatments ranged from 2.21% to 2.59%. Meanwhile, T20% and T30% had reduced hydrogen in the samples, with concentrations decreasing by 2.4% (p = 0.001) and 1.4% (p = 0.040), respectively. Interestingly, sulphur decreased significantly according to the following order of compaction treatments: T10% > T20% > T30%, with a mean reduction of 0.7% (p = 0.038), 0.9% (p = 0.004), and 1.4% (p < 0.001), respectively. Similarly, CN ratio

also decreased at T20% and T30% with a mean reduction of 8.4 ($p < 0.001$) and 10.1 ($p < 0.001$), except for T10%, which was 15.5, comparable to the control, which was 19.0 ($p = 0.085$).

The physicochemical properties of the samples sub-core from OP showed a change in loss on ignition, and total carbon, nitrogen, and sulphur as a result of compaction treatments whereby at T15%, a decrease in loss on ignition of 7.2% ($p = 0.001$) was observed compared to the control. Meanwhile, total carbon was decreased after the T10% and T15% treatments by 4.4% ($p = 0.001$) and 7.7% ($p < 0.001$), respectively. Total nitrogen was also decreased after the T15% treatment ($p = 0.025$) with a mean reduction of 0.25% sulphur at T5% whereas T15% samples showed a mean reduction of 0.2% ($p = 0.031$) and 0.3% ($p = 0.004$), respectively. Conversely, bulk density, total porosity, water-filled pore space, gravimetric water content, volumetric water content, pH, hydrogen, and CN ratio did not change as a result of artificial compaction with a mean of 0.30 ± 0.02 g cm^{-3} ($p = 0.035$), 81.2 ± 0.8% ($p = 0.334$), 51.8 ±1.7% ($p = 0.311$), 146.5 ± 8.7% ($p = 0.411$), 42.0 ± 1.3% ($p = 0.309$), 2.89 ± 0.05 ($p = 0.444$), 13.8 ± 0.45% ($p = 0.092$), and 31.0 ± 0.52% ($p = 0.949$), respectively.

Table 4.2 Physicochemical properties of intact samples from compaction treatments in two ecosystems (Eco): secondary peat swamp forest (SF) and oil palm plantation (OP). The compaction treatments (Trt) were based on altering the height in the volume of peat inside the PVC tube of the reference samples expressed in percentage of reduction. The values are the mean of two independent experiments (n= 5) with a standard error (SE) at a 95% confidence interval. Statistically significant differences within the ecosystem are indicated with the asterisk *, **, and *** to denote significance at 0.05, 0.01 and ≤ 0.001, while ^{ns} is not significant differences. Treatment means were compared with the control, T0, within the ecosystem using Dunnett's test (α = 0.05).

		Physical property					
Eco	Trt	Bulk density (g cm^{-3})	Loss on ignition (%)	Total porosity (%)	Water-filled pore space (%)	Gravimetric water content (%)	Volumetric water content (%)
SF	T0	0.17 ± 0.01	88.11 ± 2.830	89.30 ± 0.85	47.38 ± 4.18	252.5 ± 9.30	42.18 ± 3.45
	T10%	0.14^{ns} ± 0.02	84.35^{ns} ± 2.88	91.24^{ns} ± 1.01	40.88^{ns} ± 4.03	269.1^{ns} ± 13.7	37.15^{ns} ± 3.29
	T20%	0.23^{ns} ± 0.03	66.00^{ns} ± 10.6	87.61^{ns} ± 1.21	57.72^{ns} ± 6.2	236.3^{ns} ± 32.6	50.41^{ns} ± 5.18
	T30%	0.20^{ns} ± 0.02	80.09^{ns} ± 6.44	87.71^{ns} ± 0.77	**65.3* ± 1.84**	289.1^{ns} ± 27.3	**57.26* ± 1.58**
OP	T0	0.31 ± 0.030	87.69 ± 1.50	80.20 ± 1.77	48.54 ± 3.88	128.6 ± 12.8	38.78 ± 2.68
	T5%	0.28^{ns} ± 0.03	88.67^{ns} ± 0.62	82.28^{ns} ± 1.61	54.77^{ns} ± 3.01	166.9^{ns} ± 12.5	44.93^{ns} ± 2.06
	T10%	0.39^{ns} ± 0.03	84.00^{ns} ± 0.90	79.06^{ns} ± 1.63	55.14^{ns} ± 3.34	136.0^{ns} ± 22.5	43.66^{ns} ± 3.09
	T15%	0.28^{ns} ± 0.03	**80.5*** ± 1.43**	83.27^{ns} ± 1.92	48.65^{ns} ± 2.54	154.8^{ns} ± 19.4	40.43^{ns} ± 1.95
		Chemical property					
Eco	Trt	pH value (1:2.5) (Peat:water)	Total carbon (%)	Total Nitrogen (%)	Hydrogen (%)	Sulphur (%)	C:N ratio
SF	T0	2.71 ± 0.03	34.14 ± 1.44	1.81 ± 0.09	7.84 ± 0.42	2.21 ± 0.24	19.00 ± 0.86
	T10%	2.69^{ns} ± 0.08	33.22^{ns} ± 0.76	2.21^{ns} ± 0.22	8.06^{ns} ± 0.21	**1.54* ± 0.08**	15.52^{ns} ± 1.29
	T20%	2.77^{ns} ± 0.03	**24.59* ± 2.47**	2.59^{ns} ± 0.53	**5.47*** ± 0.40**	**1.27** ± 0.23**	**10.6*** ± 1.43**
	T30%	2.72^{ns} ± 0.01	30.96^{ns} ± 3.24	**3.46** ± 0.33**	**6.40* ± 0.44**	**0.82*** ± 0.09**	**8.94*** ± 0.28**
OP	T0	2.98 ± 0.10	46.14 ± 0.57	1.49 ± 0.08	13.26 ± 0.92	0.63 ± 0.10	31.22 ± 1.22
	T5%	2.75^{ns} ± 0.10	44.62^{ns} ± 0.79	1.47^{ns} ± 0.05	15.68^{ns} ± 1.26	**0.40* ± 0.06**	30.40^{ns} ± 0.95
	T10%	2.91^{ns} ± 0.10	**41.7*** ± 0.52**	1.36^{ns} ± 0.07	12.92^{ns} ± 0.32	0.43^{ns} ± 0.02	31.01^{ns} ± 1.46
	T15%	2.90^{ns} ± 0.10	**38.5*** ± 0.84**	**1.24* ± 0.04**	13.25^{ns} ± 0.16	**0.31** ± 0.02**	31.19^{ns} ± 0.70

4.4.3 CO_2 emissions due to artificial compaction in absence of water table

CO_2 emissions from the intact samples taken from the SF and OP ecosystems between compaction phases (pre- and post-compaction) are presented in **Figure 4.3 (a)** and **(b)**. Changes in terms of gas emission patterns between the two phases can be seen especially in the SF samples. On the other hand, the OP samples showed consistent uneven emissions from the beginning until the end of the experiment. The effect of peat compaction at different phases on the cumulative CO_2 emissions from both ecosystems are presented in **Figure 4.4 (a)** and **(b)**. During the pre-compaction phase, intact samples from SF and OP exhibited a cumulative mean of 276.3 ± 5.4 mg CO_2 m^{-2} hr^{-1} and 226.4 ± 12.6 mg CO_2 m^{-2} hr^{-1}, respectively. Meanwhile, the CO_2 emissions in the post-compaction phase of the intact SF and OP samples were 199.4 ± 4.7 mg CO_2 m^{-2} hr^{-1} and 204.6 ± 15.0 mg CO_2 m^{-2} hr^{-1}, respectively. Analysis of Variance (ANOVA) between compaction phases (pre- and post-compaction) and compaction treatments had a significant interaction effect on CO_2 emissions. Hence, only intact samples from SF (p = 0.001) were changed but the OP (p = 0.178) (**Figure 4.4 (a)** and **(b)**). Compared to pre-compaction within each treatment of the SF intact samples, the highest CO_2 reduction was observed at T30% followed by T10% and T20% with a decrease of 115.9 mg CO_2 m^{-2} hr^{-1} ($p < 0.001$), 84.4 mg CO_2 m^{-2} hr^{-1} ($p < 0.001$) and 79.7 mg CO_2 m^{-2} hr^{-1} ($p < 0.001$), respectively. The control sample, however, exhibited no changes with a mean ranging from 251.5–279.1 mg CO_2 m^{-2} hr^{-1} (p = 0.362). Meanwhile, samples from OP showed comparable means ranging from 195.1– 265.85 mg CO_2 m^{-2} hr^{-1}.

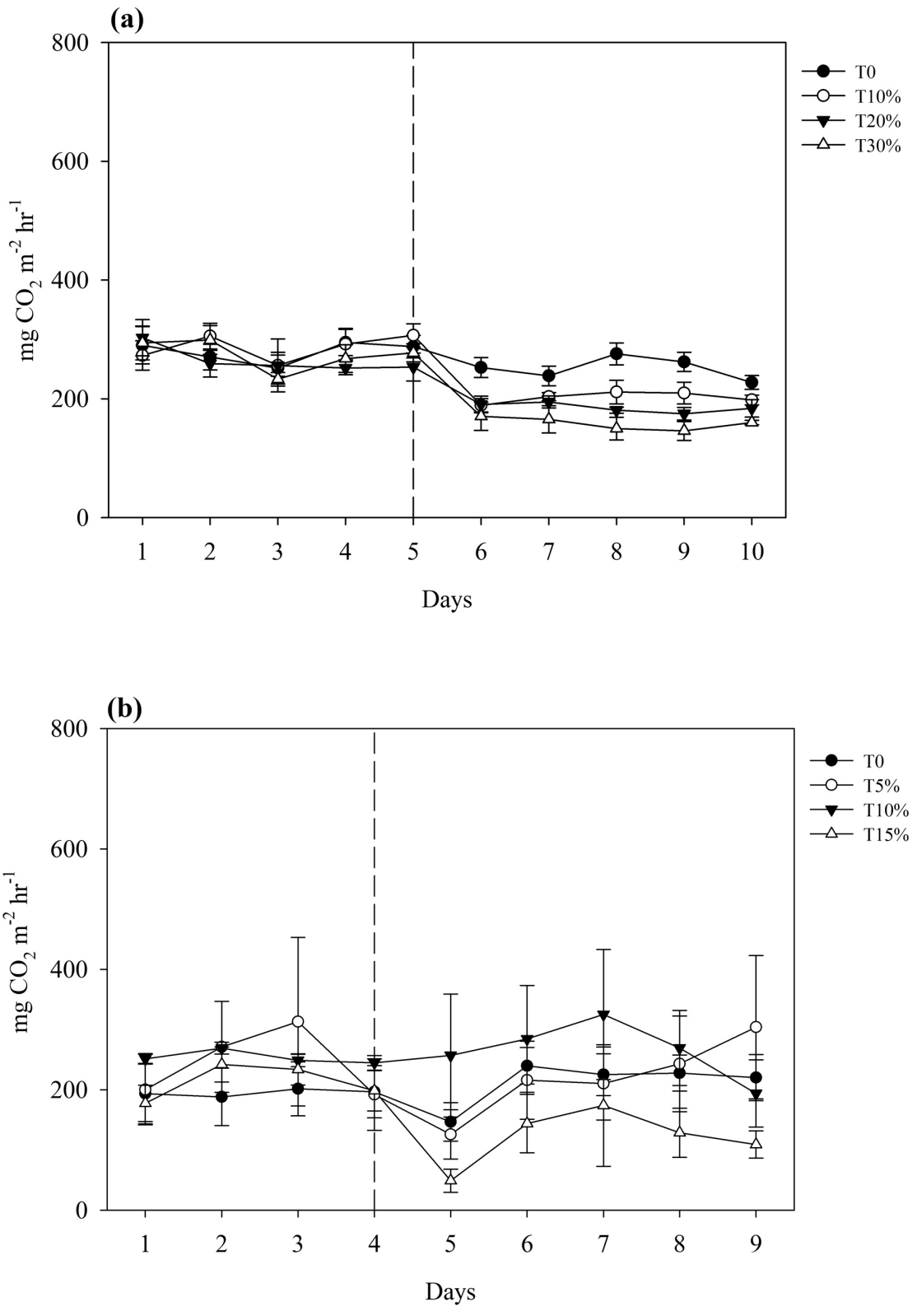


Figure 4.3 CO_2 emissions between compaction treatments and phases within intact samples from **(a)** SF (10 days) and **(b)** OP (9 days). The error bars indicate the standard error of means (n = 5). Meanwhile, the medium dash line within the ecosystems indicates that artificial compaction was applied.

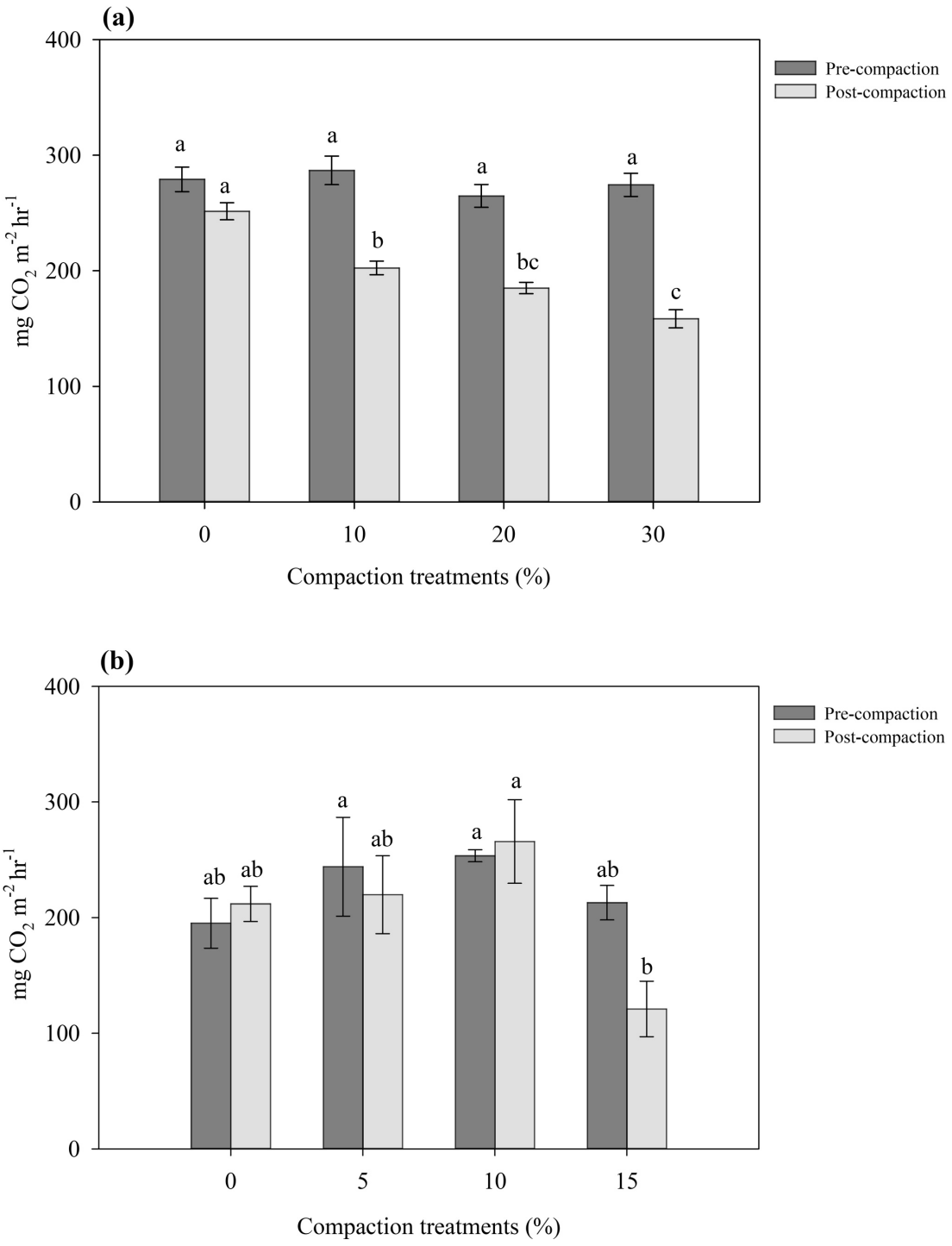


Figure 4.4 CO_2 emissions of intact samples from: **(a)** secondary peat swamp forest, SF; and **(b)** oil palm plantation, OP, in different phases; pre- and post- artificial compaction. The error bars indicate the standard error of means. The different letters indicate significant differences between treatments within different phases. The means were separated using Tukey's HSD post-hoc test ($\alpha = 0.05$).

4.4.4 CH_4 emissions due to artificial compaction in absence of water table

The CH_4 emissions of the intact samples obtained from the SF and OP ecosystems between phases are presented in **Figure 4.5 (a)** and **(b)**. Similar to CO_2, greater changes in CH_4 emissions can be observed in the SF samples, while the sample from OP exhibited consistent CH_4 emissions until the end of the experiment. The effect of peat soil compaction at different phases on the cumulative CH_4 emissions from both ecosystems are presented in **Figure 4.6 (a)** and **(b)**. During the pre-compaction phase, the intact samples from SF and OP exhibited a cumulative mean of −16.6 ± 1.22 μg CH_4 m^{-2} hr^{-1} and −3.6 ± 0.7 μg CH_4 m^{-2} hr^{-1}, respectively. Meanwhile, CH_4 emissions in the post-compaction phase for the intact samples of SF and OP were −7.2 ± 0.8 μg CH_4 m^{-2} hr^{-1} and -1.0 ± 0.6 μg CH_4 m^{-2} hr^{-1}, respectively. Similar to CO_2 emissions, Analysis of Variance (ANOVA) was conducted between the compaction phases (pre- and post-compaction) and compaction treatments; a significant interaction effect was observed on the CH_4 emissions of samples from SF ($p < 0.001$) but not OP ($p = 0.441$). In the SF intact samples, all compaction treatments were found to have increased CH_4 emissions, as per **Figure 4.6 (a)**. Compared to the pre-compaction phase, the highest increment in CH_4 emissions was at 30% treatment followed by 20% and 10% with a mean increase of 18.7 μg CH_4 m^{-2} hr^{-1} ($p < 0.001$), 10.7 μg CH_4 m^{-2} hr^{-1} ($p = 0.002$), and 8.3 μg CH_4 m^{-2} hr^{-1} ($p = 0.045$), respectively. Meanwhile, for the control, 0%, there were no changes between the two phases (p =1.000) with a mean ranging from −13.0 μg CH_4 m^{-2} hr^{-1} to −13.1 μg CH_4 m^{-2} hr^{-1}. Meanwhile, intact samples from OP showed comparable means ranging from −7.3 μg CH_4 m^{-2} hr^{-1} to 0.3 μg CH_4 m^{-2} hr^{-1}.

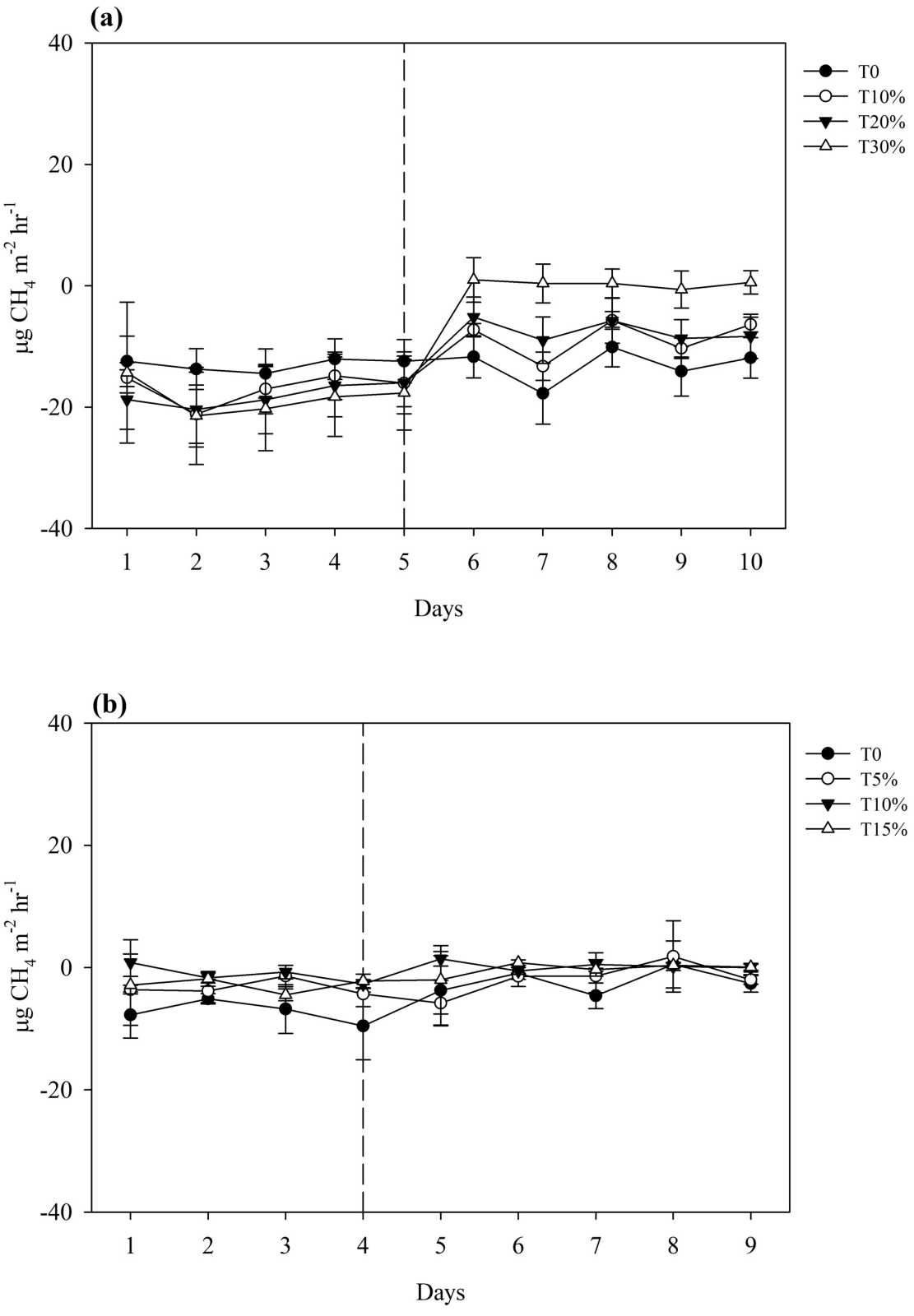


Figure 4.5 CH_4 emissions between compaction treatments and phases within intact samples from: **(a)** secondary peat swamp forest, SF (10 days); and **(b)** oil palm plantation, OP (9 days). The error bars indicate the standard error of means (n = 5). Meanwhile, the medium dash line within ecosystems indicates that artificial compaction was applied.

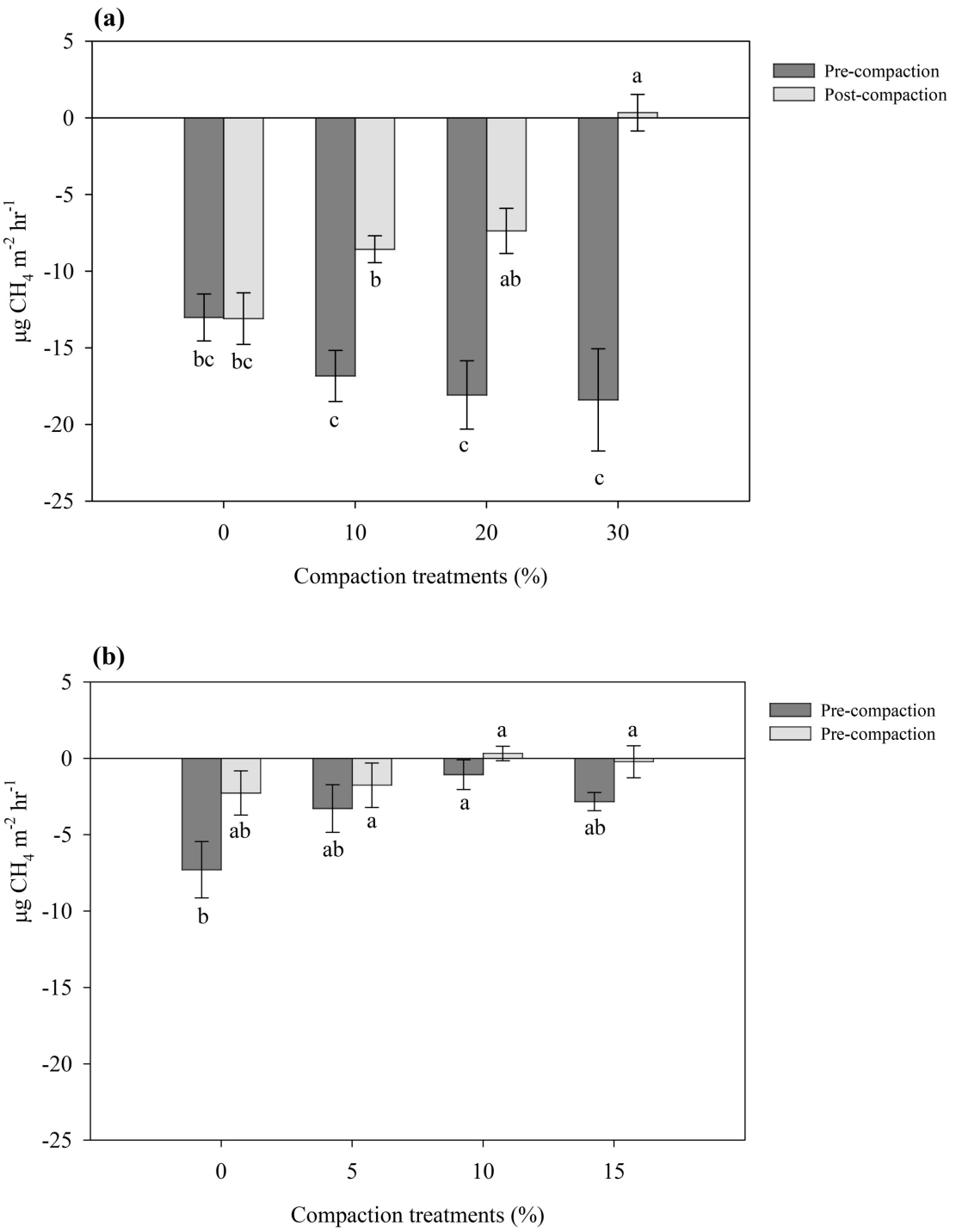


Figure 4.6 CH_4 emissions of intact samples from: **(a)** secondary peat swamp forest, SF; and **(b)** oil palm plantation, OP, in different phases; pre- and post- artificial compaction. The error bars indicate the standard error of means. The different letters indicate significant differences between treatments within different phases. The means were separated using Tukey's HSD post-hoc test ($\alpha = 0.05$).

4.3.5 Correlation between CO_2 and CH_4 emissions with physicochemical properties

An average of the emissions over the 5 and 4 days (for SF and OP respectively) was used in the post-compaction phase to identify the relationship between the peat physicochemical properties and carbon gas emissions. Pearson's correlation coefficient, *r*, between the carbon emissions and peat physicochemical properties for samples from SF and OP was determined and the results summarised in **Table 4.3**. In SF, the results reveal that CO_2 emission was positively correlated with sulphur ($p = 0.003$) and CN ratio ($p < 0.001$) and negatively correlated with water-filled pores space ($p = 0.035$), gravimetric water content ($p = 0.048$), volumetric water content ($p = 0.023$), and total nitrogen ($p = 0.001$). Meanwhile, CH_4 emission was inversely correlated with CO_2 but positively correlated with water-filled pores space ($p = 0.003$), gravimetric water content ($p = 0.002$), volumetric water content ($p = 0.001$), and total nitrogen ($p < 0.001$). It was also negatively correlated with sulphur ($p = 0.042$) and CN ratio ($p = 0.001$). Unlike the SF sample, the CO_2 emission from the OP samples exhibited a positive correlation with total nitrogen ($p = 0.047$) and a negative correlation with the CN ratio ($p = 0.043$). In contrast, no correction was found between CH_4 emission and the physicochemical properties of the OP intact samples.

Table 4.3 Pearson's correlation moment product between CO_2 and CH_4 emissions with some of the physicochemical parameters used in this experiment. The values represent Pearson's correlation coefficient, $\boldsymbol{r}$, between carbon emissions and peat physical properties (n = 20) within the respective ecosystem. The *r* values in bold with *, **, and *** are significant at 0.05, 0.01, and ≤ 0.001, respectively.

	Secondary peat swamp forest (SF)		Oil palm Plantation (OP)	
Variable	CO_2	CH_4	CO_2	CH_4
Bulk density (g cm^{-3})	-0.078	0.028	0.209	0.21
Loss on ignition (%)	0.109	0.228	0.239	-0.158
Total porosity (%)	0.065	-0.182	-0.223	-0.204
Water-filled pore space (%)	**-0.472***	**0.636****	-0.176	0.161
Gravimetric water content (%)	**-0.448***	**0.649****	-0.302	-0.077
Volumetric water content (%)	**-0.505***	**0.671*****	-0.269	0.118
pH (1:2.5) (Peat:water)	-0.005	-0.085	0.013	-0.129
Total carbon (%)	-0.024	0.162	0.301	-0.356
Total nitrogen (%)	**-0.696*****	**0.745*****	**0.449***	-0.303
Hydrogen (%)	0.278	-0.067	0.025	-0.404
Sulphur (%)	**0.627****	**-0.459***	0.352	0.218
CN ratio	**0.791*****	**-0.684*****	**-0.458***	0.073

4.5 Discussion

4.5.1 Limitations and results interpretation

The overall CO_2 emissions for SF and OP with a mean of 238.3 ± 4.6 mg CO_2 m^{-2} hr^{-1} and 214.3 ± 10.1 mg CO_2 m^{-2} hr^{-1}, respectively, were from less than half to the six-order of magnitude of those reported by field measurements in a previous study (**Chapter 3**), (467.5 to 1294.8 mg CO_2 m^{-2} hr^{-1} and 290.18 to 521.6 mg CO_2 m^{-2} hr^{-1}) or elsewhere (Dariah *et al.*, 2014; Husnain *et al.*, 2014; Matysek *et al.*, 2018; Melling *et al.*, 2005a, 2005b; Wakhid *et al.*, 2017)(**Table 3.8**). Moreover, bulk density from reference cylinder samples also exhibited a one-fold increase in this experiment, especially the reference samples from OP, as compared to previous studies conducted *in-situ* **(Table 3.7)** and elsewhere (e.g. Melling *et al.*, 2005a, 2005b; Tonks *et al.*, 2017). It is likely that the process of insertion of the cylinder effected bulk density measurements via peat friction with the cylinder edge. Furthermore, that separation of the sample from its original condition may have causing microbial inactivation via moisture losses, which led to the shrinkage of peat (Hatano *et al.*, 2010; Rezanezhad *et al.*, 2016; Smith *et al.*, 2003; Wösten *et al.*, 1997), nutrient depletion (Chaudhari *et al.*, 2013; Dhandapani *et al.*, 2019b), and temperature inconsistency (Bader *et al.*, 2018; Stres *et al.*, 2008).

Conversely, CH_4 emissions from the intact samples of SF and OP with a mean of −11.9 ± 0.8 µg CH_4 m^{-2} hr^{-1} and −2.2 ± 0.5 µg CH_4 m^{-2} hr^{-1}, respectively, were within the range reported in (**Table 3.9**), with mean values between −48.4 to 59.95 µg CH_4 m^{-2} hr^{-1} and −3.94 to 3.63 µg CH_4 m^{-2} hr^{-1}. These results also agree with the findings of Melling *et al.* (2005b) and Sakabe *et al.* (2018), which obtained a mean between −23.2 µg CH_4 m^{-2} hr^{-1} and 27.86 µg CH_4 m^{-2} hr^{-1} and −43.76 µg CH_4 m^{-2} hr^{-1} to 10.4 µg CH_4 m^{-2} hr^{-1}

for SF and OP/degraded SF, respectively. Hence, the results in this experiment may represent trends in carbon emission patterns rather than actual emission concentration. Therefore, the interpretation of these results should be approached sensibly.

4.5.2 Alteration to physiochemical properties and peat vertical profile as a result of artificial compaction

The hypothesis in this study states that physicochemical properties will change as a result of artificial compaction in the absence of the water table interference. This hypothesis was accepted for both samples from different ecosystems. In turn, the assumption from a previous study (**Chapter 3)** holding that water table fluctuation is capable of repairing compressed peat structures, is also supported. Profound physicochemical changes were observed mostly in the intact samples from the secondary peat swamp forest ecosystems. This is because of the more porous conditions and high compressibility of the peat in SF, which reflects labile carbon content resulting from the prior continuous supply of labile carbon sources from the surrounding trees in the peat forest samples (Jauhiainen *et al.,* 2008) as compared to the matured oil palm plantation (Tonks *et al.,* 2017), which is more exposed to recalcitrant carbon on the peat surface (Cooper *et al.,* 2019; Könönen *et al.,* 2016).

Additionally, high compressibility is also associated with the vertical movement of water table level and pore rearrangement structure due to the uncontrolled water table, as would be the case in a less drained forest system; sequentially forming layers of various decomposition levels (Rezanezhad *et al.,* 2016). Whereas in a drained and controlled system such as an OP plantation the water table level is more controlled by existing water

gate surrounding the plantation. In general, the water is controlled within the range of 40 cm to 60 cm from the peat surface to maintain the survival of oil palm that is intolerance to flooding condition in long period. Thus, the peat advanced decomposition level of oil palm plantation is pronounced at the peat surface (beside lack of labile carbon sources within plantation) compared to deeper peat that within the water table level fluctuation which exhibited slow decomposition rate.

Bulk density value as an index of compactness was relatively unrepresentative of the compression magnitude of artificial compaction on tropical peat. However, given the small BD variance observed in the reference and control BD values, it seems unlikely that the experimental samples, collected at the same location, would have significantly greater BD variability. It is therefore significant that compression effort appears to be an ineffective control of BD, and while that is an important finding for management, which will be discussed later, it is important to consider which other physiochemical variables are likely to have effected emissions according to treatment. Variables such as bulk density, total porosity, gravimetric water content, and pH for both ecosystems were found not significant against the control (**Table 4.3**). However, increasing and decreasing patterns of other parameters such as water-filled pore space, volumetric water content, total carbon, nitrogen, hydrogen, sulphur, and CN ratio from the SF intact samples, and loss on ignition, total carbon, nitrogen, and sulphur from the OP sample were observed to vary according to the treatments and exclusive to the ecosystem origin.

Interestingly, all physicochemical properties of the SF samples changed as a result of artificial compaction. Consideration of the 0 to 10cm soil physiochemistry in relation

to the depth of compaction (within the cylinder) indicates that in those samples compressed to greatest depth (**Figure 4.7**) had decreasing values for CN ratio and total N at the new 0 to 10 cm horizon. These results suggest that the higher N content on the peat surface (Könönen *et al.,* 2015) was translocated down towards the deeper peat horizon as a result of artificial compaction. Higher CN ratio (generally > 20) is normally associated with plant vascular land plant organic matter, whereas lower CN ratios suggests wetter conditions within the range of water table fluctuation (Tanner *et al.,* 2018), which are also reflected by the volumetric water content and water-filled pore space at the deeper peat layer.

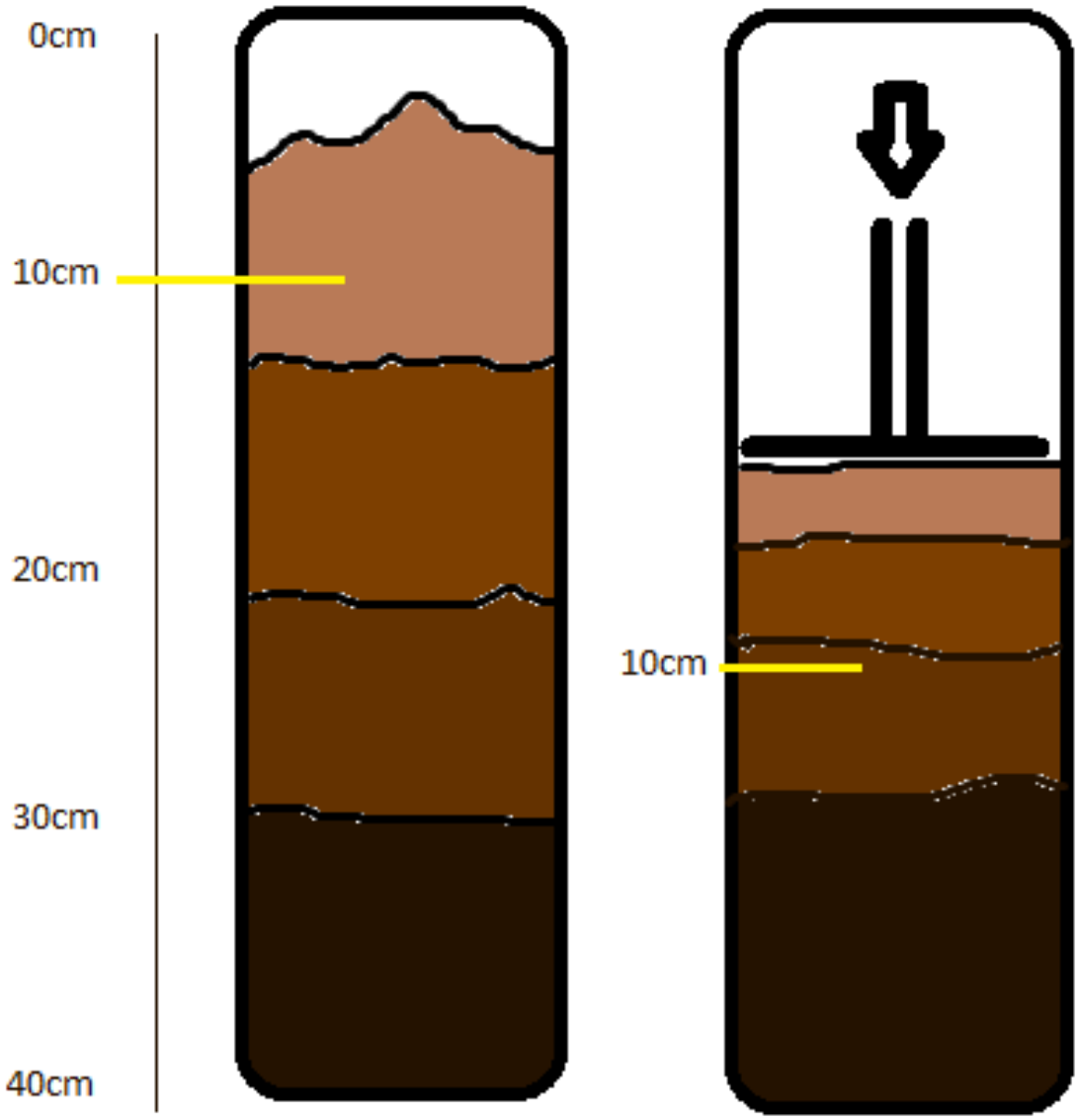


Figure 4.7 The mechanism of consolidation between peat surface and deeper peat as a result from compaction.

Findings are similar to Wakhid *et al.* (2017), who describe a significant decreasing pattern of physicochemical properties such as sulphur and total nitrogen in compacted peat during the establishment of a rubber plantation in Central Kalimantan, Indonesia at a water table level of 1.0 m. Hence, based on the comparison outlined in **Table 4.4**, artificial compaction could be a potential mechanism to support the shifting of surface peat with less advanced decomposition to a deeper horizon with more advanced decomposition (in severely low water table level conditions). Moreover, it is presumed that this shifting could also be accompanied by a new admixture ratio, resulting from the build-up of different stages of decomposition in peat horizons (Moore *et al.,* 2018; Rezanezhad *et al.,* 2016). For example, the CN ratio in this study decreased in accordance with the treatment in SF (**Table 4.4**).

The higher starting bulk densities in the OP samples (as evidenced in the control and reference samples) may solely be due to periodic drainage, which leads to shrinkage. Shrinkage reflects initial constricted pores (Rezanezhad *et al.,* 2016) and may result have resulted in the ineffective artificial compaction owing to low compressibility. The high carbon content observed in the OP intact samples ranging from 40% to 46% supporting this case, and is believed to be associated with the intensive agricultural input since 1978, leading to recalcitrant carbon exposure (Cooper *et al.,* 2019; Könönen *et al.,* 2016). The significant changes in the pattern of physicochemical properties (e.g. loss on ignition, total carbon, nitrogen, and CN ratio) are similar to the characteristics of drained peat in agricultural land.

Table 4.4 Comparison between previous studies on significant physicochemical changes pattern of increasing and decreasing from surface to deeper peat within range (0 to 45.0 cm) peat depth. The increase and decrease pattern of physicochemical changes in different drained land uses are denoted with the symbols (+) and (–).

	References					
	Könönen *et al.* (2015)		Itoh *et al.* (2017)	Wakhid *et al.* (2017)	This study	This study
Ecosystems / Parameters	Drained forest	Drained agriculture	Drained forest	Compacted and drained rubber plantation	Compacted (treatment) drained forest	Compacted (treatment) drained oil palm plantation
Loss on ignition (%)	+	–	nm	nm	ns	–
Water-filled pore space (%)	nm	nm	nm	nm	+	ns
Volumetric water content (%)	nm	nm	nm	+	+	ns
Total carbon (%)	+	–	+	+	ns	–
Total nitrogen (%)	–	–	–	+	+	–
Hydrogen	nm	nm	nm	nm	–	ns
Sulphur	ns	ns	nm	–	–	–
C:N ratio	+	+	+	–	–	ns

Note: ns = not measured; ns = not significant differences between peat depths.

4.5.3 Translocation of peat surface to deeper horizon may potentially control carbon emissions in the absence of a water table

The previous finding showed profound physicochemical changes in the SF samples, so the declining and increasing CO_2 and CH_4 emissions from the intact samples obtained from the secondary peat swamp forest ecosystem could be due to the compression and consolidation between young and old peat, which result in a new admixture, where availability of surface labile C is reduced (e.g. **Figure 4.7**). The inverse emission patterns corroborate with the results of several studies, which measured the same gas species in laboratory conditions with the depth treatment (e.g. Crill, 1991; Moore & Dalva, 1997). In SF, the CO_2 decreasing by 29%, 30% and 42% (average 34%) and CH_4 emissions were increasing by 49%, 59%, and 102% (average 70%) for T10%, T20% and T30%, respectively, or average percentage ratio of *ca.* 1:2 (CO_2 reduction: CH_4 enhancement) from the initial emission. Remarkably, compared to inversely pattern of CO_2 reduction and CH_4 enhancement that reported in **Chapter 3** the percentage ratio is *ca.* 1:3, in which subjected to the water table level control aid. However, although the CH_4 are increasing as a result of compaction by half to 1-fold as compared to pre-compaction, but if calculated together with CO_2 emission in term of global warming potential (GWP), the CH_4 emission is negligible (-4.0 to 0.18 g C m^{-2} yr^{-1}). Results here also similar with reported by Sakabe *et al.,* (2018) in ecosystem-scale of CH_4 (-3.7 to 4.0 g C m^{-2} yr^{-1}) during incubation experiment of heavily disturbed peat swamp forest in Indonesia. Overall, in term GWP, the effect of $CO_{2\text{-eq}}$ reduction can be observed from T20% and T30%, respectively which resulted from 22 to 33% (4.5 to 6.7 t CO_{2eq} ha^{-1} yr^{-1}) of reduction as compared to the control (**Figure 4.8**).

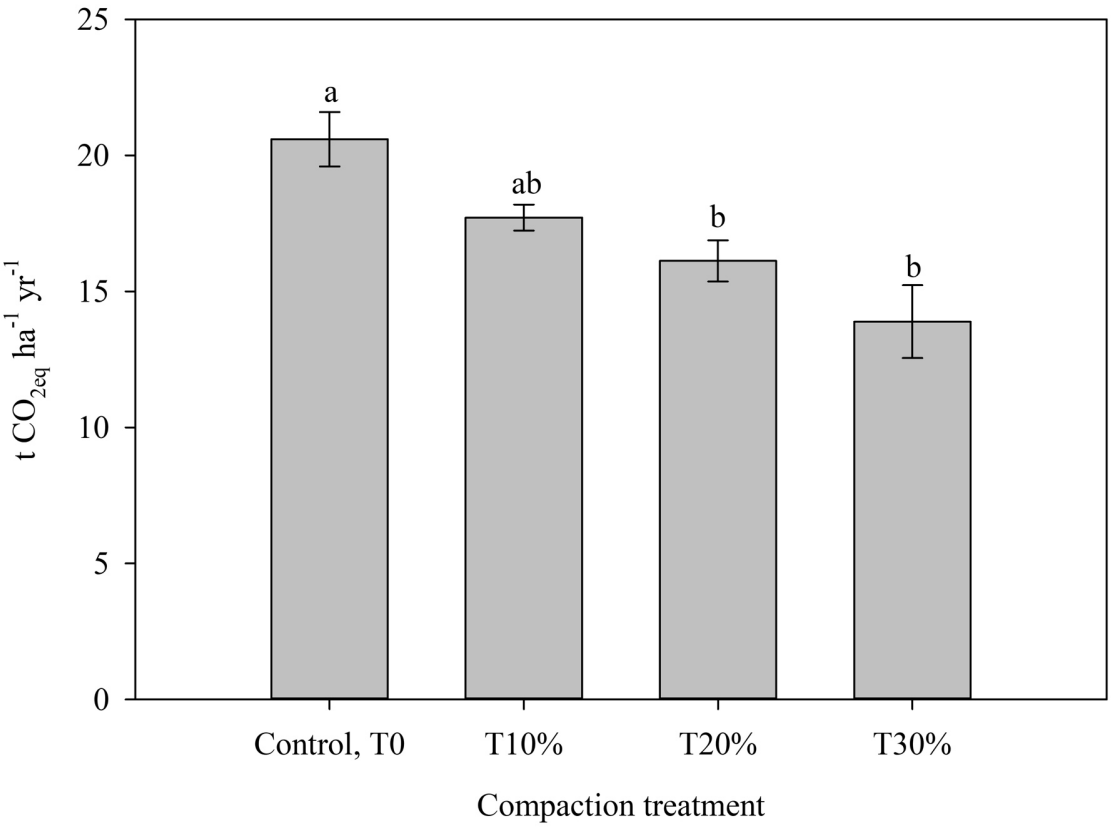


Figure 4.8 The Global Warming Potential (GWP) of studied intact samples from secondary peat swamp forest. The error bars indicate the standard error of means (***n*** =5). The different letters indicate significant differences between treatments within different phases. The means were separated using Tukey's HSD post-hoc test (α = 0.05).

Nevertheless, it is suspected that this carbon emissions reduction will be temporary since peat with fresh labile C will recover immediately after the water table rises and remains at 40.0 cm to 60.0 cm below the peat surface, as suggested by the Roundtable on Sustainable Palm Oil (RSPO). Consequently, the reduction in CO_2 emission due to the consolidation of peat with different decomposition degrees will be ineffective due to this "self-recovery" condition (**Chapter 3**). A similar experiment was conducted on the effect of mineral soil compaction and rainfall by Novara *et al.* (2012). They mentioned that the repaired compressed soil as a result of raindrops triggered an

inefficient CO_2 emission reduction due to aggregate breakdown, causing exposure of encapsulated organic C, which is also in agreement with Wakhid *et al.* (2017), who found that rainfall can induce momentary CO_2 emission on compacted peat in rubber plantations, so confounding water table level was a major predictor for peat decomposition. Indeed, CO_2 production, known as the "birch effect" (Fraser *et al.,* 2016) or the impulsive response to carbon emissions in the form of CO_2 and CH_4 under physicochemical antagonistic recovery, was not observed and should, therefore, be targeted in future research.

As abovementioned, the changes reflect the admixture of different peat layers, which correspond to the stratified water content and decomposition status (Rezanezhad *et al.,* 2016)—also supported by the relationships observed between water content (e.g. water-filled pore space, gravimetric water content and volumetric water content) and decomposition proxies (e.g. total nitrogen, sulphur and CN ratio) against CO_2 (**Figure 4.9**) and CH_4 (**Figure 4.10**). In the deeper soil layers, pores are significantly smaller with less interconnection due to the collapse of vascular plant debris and the development of a horizontal laminar structure (Boelter, 1969), which leads to more restricted flow and greater tortuosity (Rezanezhad *et al.,* 2016). In turn, a new micro niche environment with oxygen limitation, water retention, and substrate enhancement from the peat surface, is established (Arai *et al.,* 2014).

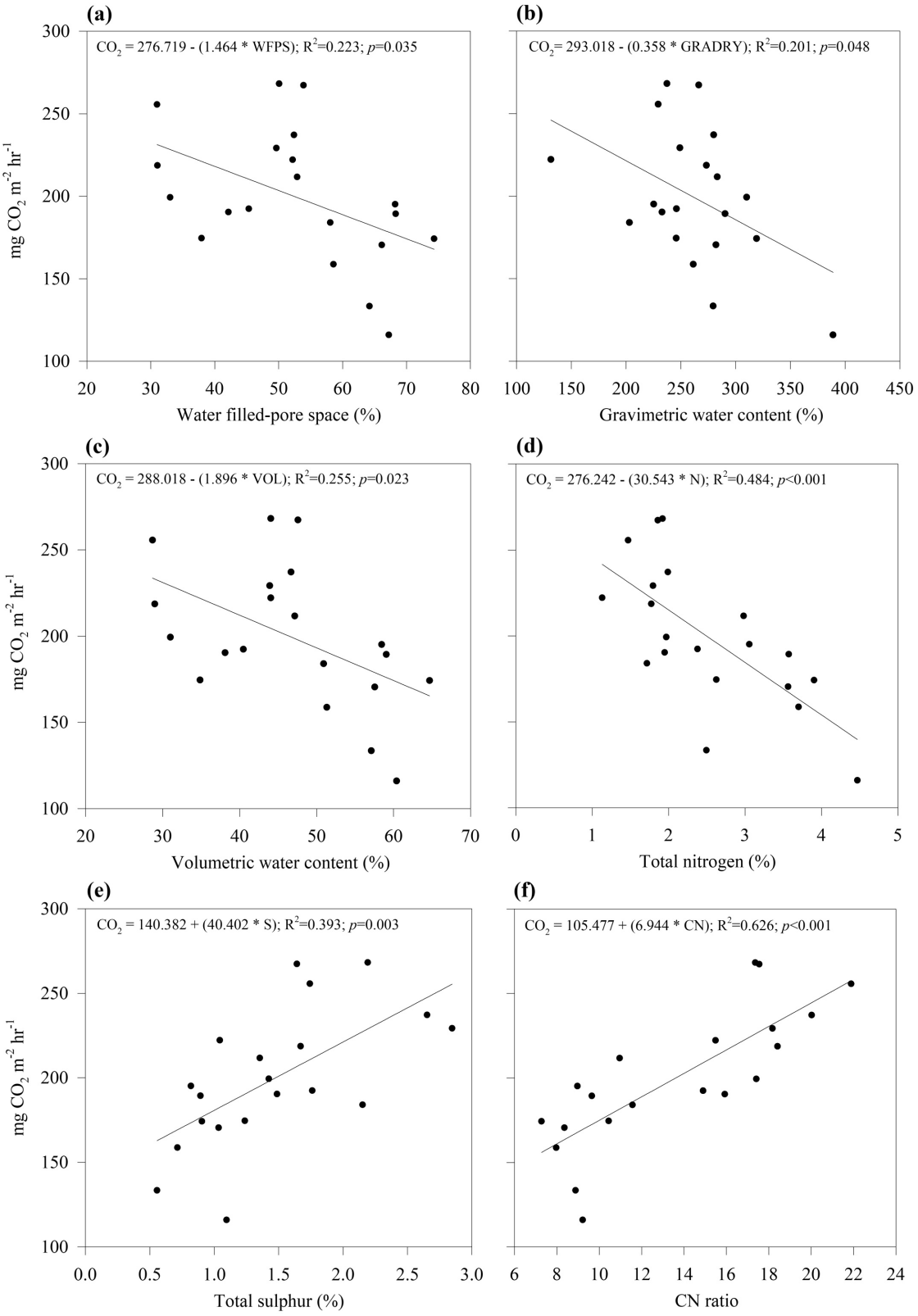


Figure 4.9 The relationship between CO_2 emission with **(a)** water-filled pore space, **(b)** gravimetric water content, **(c)** volumetric water content, **(d)** total nitrogen, **(e)** sulphur, and **(f)** CN ratio from secondary peat swamp forest intact samples that underwent artificial compaction treatment. Total points are (n=20) and solid line indicates regression line.

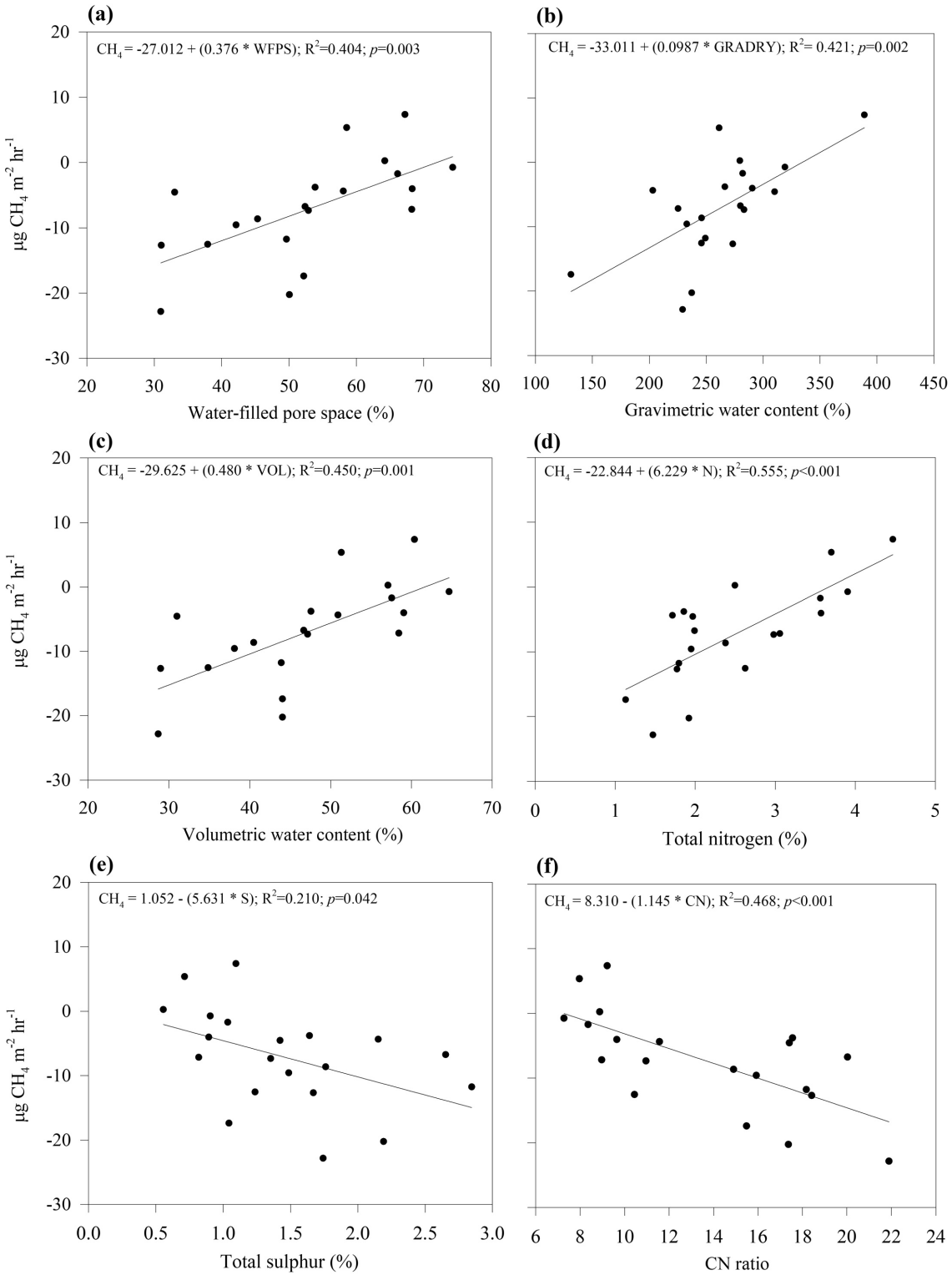


Figure 4.10 The relationship between CH_4 emission with **(a)** water-filled pore space, **(b)** gravimetric water content, **(c)** volumetric water content, **(d)** total nitrogen, **(e)** sulphur, and **(f)** CN ratio from secondary peat swamp forest intact samples that underwent artificial compaction treatment. Total points are (n=20) and solid line indicates regression line.

Despite the OP intact samples showing no difference in carbon emission due to artificial compaction, CO_2 exhibited a positive relationship with total nitrogen and a negative relationship with CN ratio (**Figure 4.11**), which opposes the same variable relationships of the SF intact samples. As discussed previously, the induced artificial compaction at OP was unsuccessful in merging between decomposition stages due to a large composition of inert carbon being exposed to the peat surface (Könönen *et al.,* 2018). Peat in an advanced decomposition state has a more stable structure (Cooper *et al.,* 2019), a more confined and restricted pore volume due to the collapsed anisotropic structure (Rezanezhad *et al.,* 2016), and higher lignin composition (Tonks *et al.,* 2017), making it invulnerable to artificial compaction. Therefore, it is suggested that proposals to undertake artificial compaction of already drained peatlands (e.g. The Borneo Post, 2016) would be both ineffective in altering emissions and would make very little difference to peat structure, including water or air filled pore spaces or bulk density, and as such, would be unlikely to have any impact on the ignitability of drained peatlands and would be ineffective as an 'after-the-fact' management strategy for drained peatland.

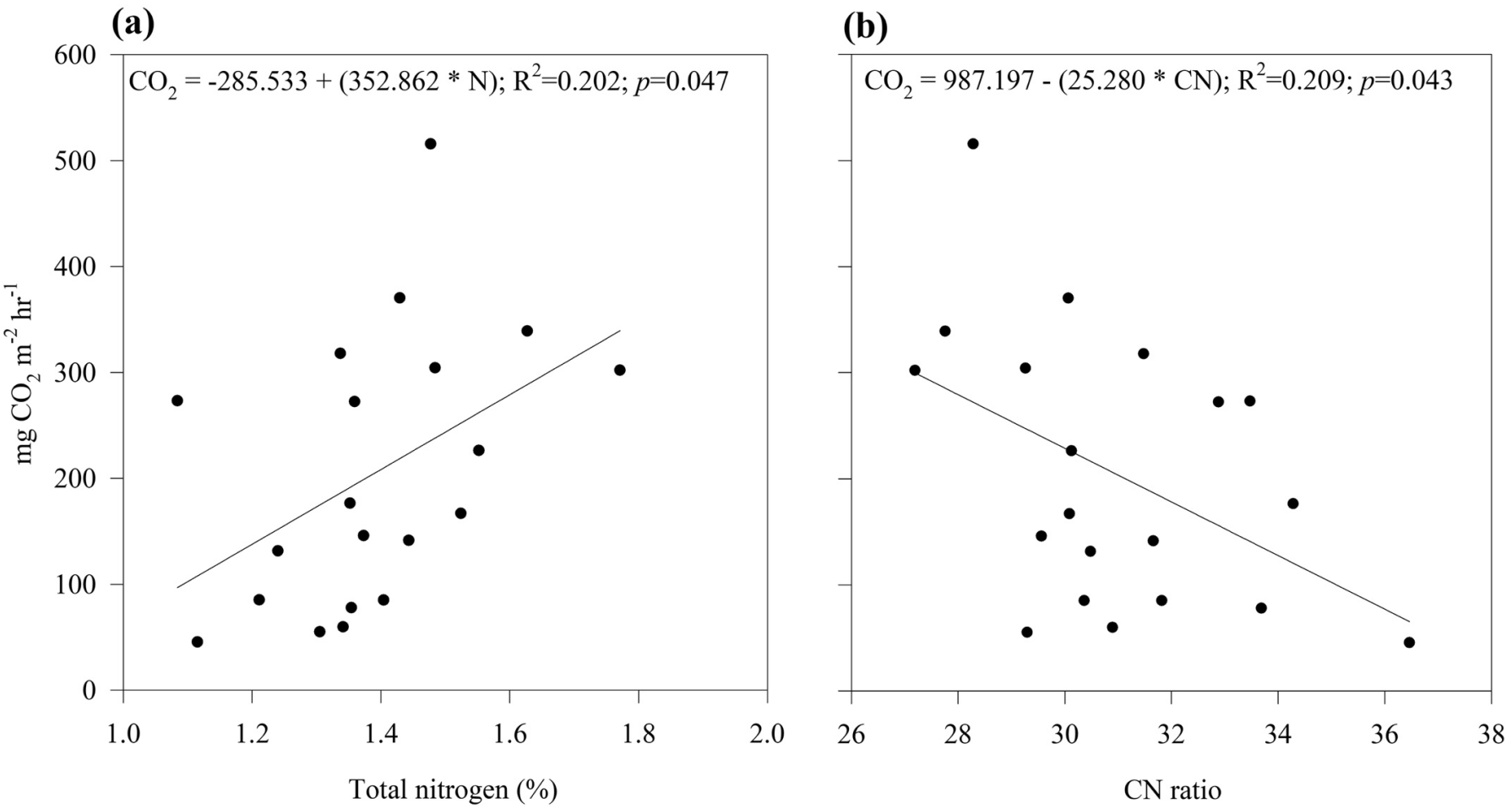


Figure 4.11 The relationship between CO_2 emission with **(a)** total nitrogen and **(b)** CN ratio from oil palm plantation intact samples that underwent artificial compaction treatment. Total points are (n=20) and solid line indicates regression line.

4.5.4 Concluding remarks

Generally, peat compression practices are initiated shortly after the water table lowers with the help of a drainage system within the oil palm plantation area. This study partially agrees that active / artificial compression during the lowering of water table and self-subsidence up to 1.0 meter (Mutert *et al.,* 1999; Wakhid *et al.,* 2017) could change the peat physicochemical properties, provided that the water table level is extremely low. Subsequently, from the peat surface, CO_2 is reduced (34%) but CH_4 is enhanced (70%) or inverse percentage ratio of ca. 1:2, especially in newly opened plantations due to fresh labile carbon. Overall, this study observed increased water content parameters (e.g. water-filled pore space, gravimetric, and volumetric water content) and decomposition proxies (e.g. total nitrogen, sulphur, and CN ratio) of young peat (intact SF samples) due to artificial compaction without the presence of water table interference— Therefore, this study suggests that (1) compaction of SF (presumably for the purposes of, and in the process of converting to oil palm) results in no change to BD but changes in emissions. However, when considered as total global warming potential the net effect is a reduction of 13.0 ± 1.34 (SE) t $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}. However, even if net emissions are reduced by 33%, emissions are still not countered by organic matter inputs so are still net emissions to atmosphere. Furthermore, soils would still be are vulnerable to the "birch effect" when seasonal rewetting does occur.(2) Compaction of pre-drained peat is pointless and will be ineffective in reducing emissions or reducing ignitibility of peat (as air-filled paces unchanged) and (3) as this study considered effect in the absence of water table level variability, any effect derived through compaction of SF will be undone with water table movement in the wet season.

Furthermore, this condition has given rise to the question of what will happen to the quality of fuel source of compacted peat on burning and carbon emission concentration. Peat combustion is one of the alternative routes for carbon emission through smoke (Page *et al.,* 2002). Although peat burning is quite an unpopular exercise for large-scale plantations, the complementary peat-burning occurrence by small plantations is important in the context of net carbon losses from tropical peatland. Therefore, a subsequent study (**Chapter 5**) was designed to assess the effect of artificial compaction in dry conditions on peat fire carbon emissions, in the form of CO, CO_2, and CH_4. From this particular experiment, it is hoped that the inclusion of peat fire in the GHG emission factor would prove useful for estimating the net budget of total carbon losses from an oil palm plantation.

Chapter 5. Pre-combustion peat properties on carbon emission factor through peat fire

5.1 Abstract

Agricultural burning is often practiced by farmers for land clearance and for the perceived benefits of soil conditioning. However, this practice contributes to soil carbon depletion and produces greenhouse gas emissions. Information on the effect of pre-combustion peat physiochemical properties on peat fire emissions is scarce. This study is the first to experimentally explore the relationship between pre-combustion peat physicochemical properties and fire emission factors. Soil cores (40.0 cm long with a diameter of 10.16 cm) were retrieved from oil palm plantation in Selangor, Malaysia in order to gain intact experimental soil columns. Cores then underwent differing treatments of compression in order to provide a range of bulk density levels Malaysia A sub-sample from each core was collected after compression to determine physicochemical properties. Dried intact samples were ignited and allowed to burn in an open-space laboratory burn chamber. The mixing ratios of CO_2, CO, and CH_4 were retrieved from FTIR spectra, from which emission ratios and emission factors were calculated. A correlation analysis was performed to identify the relationship between pre-ignition peat physicochemical properties and fire emission factors. This study found a significant correlation between the pre-combustion peat physicochemical properties and the emission factors of CO_2 and CH_4, but not CO. CO_2 This study confirms a relationship between bulk density and the CH_4 fire emission factor. The model established in this study indicates that increasing bulk density by 0.1 g cm^{-3} could lead to a 97% increase in CH_4 emission. This study suggests that knowledge of pre-combustion soil properties or relevant proxies (e.g. land-

use) may be important in estimating CO_2 and CH_4 emissions in fire effected areas. Furthermore, land management strategies relying on drainage and are vulnerable to, or undergoing intentional burning, will contribute to greater carbon emissions, especially CH_4 and increased Global Warming Potential (GWP).

Keywords: *Emission factor; fire; oxidation; oxygen reduction; pre-ignition physicochemical properties*

5.2 Introduction

Agricultural burning to clear and prepare planting sites has been practised since the agrarian revolution. This practice, however, has resulted in a significant loss of carbon resources and climate manipulation, especially in areas with carbon storage-rich areas such as peatlands. It is estimated that the loss of carbon from tropical peatland through fire, primarily in the form of CO_2, CH_4, and CO, is as much as 4.1 Pg CO_2 yr^{-1} (Huijnen *et al.,* 2016). Among other impacts, burning results in loss of peat soil function and ecosystem resilience, but also haze; which is detrimental to human health, and has even resulted in economic downturn (Page & Hooijer, 2016; Purnomo *et al.,* 2017). Recently, there has been growing interest in understanding how soil processes in peatlands respond to anthropogenic pressure mitigation (Wijedasa *et al.,* 2017). Significant interest has been on the practice of compaction during land clearance activity for fire mitigation purposes. Peat compaction is claimed to increase capillary rise and enhance water retention (Melling, 2016), subsequently counteracting carbon releases by reducing peat oxidation and therefore, CO_2 emission (Ishikura *et al.,* 2018; Sakata *et al., 2015)*. Consequently, more waterlogged soils could prevent fires from occurring. However, the efficacy of these claims is still subject to debate, as experiments that directly investigate the effect of compaction practices on carbon emissions are still limited (Wijedasa *et al.,* 2017).

Studies conducted to understand the changes in soil physicochemical properties as a result of fire events have been widely reported (e.g. Ansley *et al.,* 2006; Ficken & Wright, 2017; Marino *et al.,* 2012; Muranova & Simansky, 2015; Zhao *et al.,* 2010). Conversely, not many studies have investigated the physicochemical properties of peatland pre-combustion because fire occurrence is unpredictable. The only available

study on the subject of peat pre-combustion physicochemical properties is Smith *et al.* (2018). However, they only found a tentative relationship between peat dry bulk density and CH_4 emission factors. In addition, their sampling techniques using unburned peat selection methods was not ideal because the samples may not be absolutely representative of properties of pre-combustion peat fuel quality. The present study aims to addresses this gap by providing the first direct measurement of emission factors, especially CO_2, CH_4, and CO, from vertically intact pre-combustion peat samples of varying bulk densities.

The emission factors from peat fire can be measured from the smoke released, by calculating the emission ratio of the targeted gas species to the abundant gas species, which can be detected via a Fourier-Transform Infrared (FTIR) spectroscopy. However, to date, there has been significant uncertainty regarding the emission factors of peat fires due to the various high variability and ranges in value, as well as the varied conditions used in replicating emission measurements (Smith *et al.,* 2018). For example, the CH_4 emission factor from dried peat measured by Christian *et al.* (2003) was 20.8 g kg^{-1} as compared to 12.8 g kg^{-1} reported by Huijnen *et al.* (2016) in the same laboratory conditions. The 62% variation in these measurements has significantly affected calculations of current Southeast Asian regional GHG estimations. While Smith *et al.* (2018) incorporated a range of studies (e.g. Huijnen *et al.,* 2016; Stockwell *et al.,* 2016) to formulate a recommendation for the range of emission factors of CO_2, CH_4, and CO i.e. within 1557 g kg^{-1} to 1621 g kg^{-1}, 7.84 g kg^{-1} to 11.04 g kg^{-1}, and 230 g kg^{-1} to 288 g kg^{-1}, respectively, the high variability in values is suggestive of variation in the pre-combustion properties of peat. As such, land use in affected regions could strongly affect the emission factors and emission signature of peat fires. With this in mind, information on the physicochemical properties of pre-ignited peat is essential to obtain an accurate

calculation of the carbon emission factor for the now annual peatland fires occurring throughout the region.

Given the research gaps above, this study hypothesises that the emission factors of CO_2, CH_4, and CO are controlled by peat quality, specifically the peat physicochemical characteristics. Therefore, the objectives of this study are: (1) to use Fourier-Transform Infrared (FTIR) spectroscopy to quantify CO_2, CH_4, and CO emission ratios (ER) of peat vertical profile samples that have undergone varied compaction treatments. As such, the calculated emission factor (EF) based on ER value could be used; and (2) to establish the relationship between pre-combustion peat physicochemical properties and the EF of CO_2, CH_4, and CO. (3) To extrapolate any potential relationships between the variables and carbon emissions, especially dry bulk density, by combining the data in this study with the data from Smith *et al.* (2018) and finally (4) to derive a predictor for estimating the CH_4 emission factor under different compaction levels. The implication pre-combustion physicochemical characteristics in the context of artificial compaction practices and fire usage for land preparation is discussed.

5.3 Materials and methods

5.3.1 Sampling of compacted intact peat samples

Peat cores (40.0 cm long with a diameter of 10.16 cm) were sampled from oil palm (OP) plantations from the Sepang area of peninsular Malaysia following the method described in detail in **Section 3.3.1** and **3.3.3**. Soil core profiles were kept intact to ensure that the fire emissions characteristics were not affected by soil mixing. For core removal, metal cylinders were pushed into the soil and an integrated compaction piston was used to compact peat to varying degrees. These apparatuses doubled as an auger and the soil profile was removed as a whole following 21 days of in-situ compaction. In total, 16 intact cores were collected in May 2017 from a single plantation (a 11-year-old, 2nd generation). Cores were removed from areas distal to the base of palm trees (>3.5m) to ensure minimal root contribution. A total of 14 cores were selected at random from the 16 used in **Section 3.3.3** for the burn experiment (see supplementary data in **Appendix 7**), yielding a good range of peat surface bulk densities.

5.3.2 Sub-sampling and analysis of physicochemical properties

Prior to the drying process, intact samples attached using soil collars were immediately sub-sampled for physicochemical analysis. The sampling procedures for bulk density and peat from the soil collar have been explained in **Section 3.3.7**. As intact peat sample in the soil collars was used for the fire experiment, peat sampling could create a cavity on the peat surface. However, this was not an issue in this experiment because only 1.18% or 0.015% of the total peat surface area or peat volume inside the soil collar was used. Besides, the capability of peat to shrink to 34% (Rezanezhad *et al.,* 2016) from its initial state could potentially close any cavity and preserve the peat surface. After peat

sampling, soil collars containing intact peat samples were gently extracted from its original ecosystem by digging around it. Then, the open-ended collars were wrapped with a layer of aluminium foil to avoid any loss of soil. Following that, the cores were transferred to a greenhouse for air-drying purposes. The procedures for determining the physicochemical properties of the peat have been described in **Sections 2.3.3** and **3.3.9**.

5.3.2 Intact peat drying process and smouldering at open-space laboratory burn chamber

During the air-drying process in the greenhouse, moisture variability with the weather resulted in incomplete drying over the 2-week period assigned. Therefore, the 14 peat cores, varying in volume (after compaction) from 3,200 to 9,700 cm^3, were further dried in an oven for 2 days at 105°C according to the standard procedure for drying peat soil and following previous peat burning experiments conducted by Wilson *et al.,* (2015). This approach ensured that comparable replicates were produced, successful ignition could be achieved, and a self-sustaining fire obtained (Rein *et al.,* 2009; Wilson *et al.,* 2015). After drying, the intact samples were left at room temperature (30.0°C) and then used in the combustion experiment the next day. Intact peat samples were taken and placed in a custom-made burn chamber (**Figure 5.1 (a)**). The burn chamber consisted of a fire-resistant container with a capacity of 32 Gallons or 121.33 L. To prepare each sample for burning, the intact peat core was inserted into the chamber and the core was encased in sand (with approximately 1.0 cm width surrounding the peat outer circumference), leaving only the top surface of the peat core exposed to open air (**Figure 5.1 (b)**). In this way, as suggested by Rein *et al.* (2009) and Wilson *et al.* (2015), heat

loss and oxygen exchange from the other surfaces were reduced. Prior to combustion, the chamber was placed in a fume cupboard in an open–air space to allow good airflow.

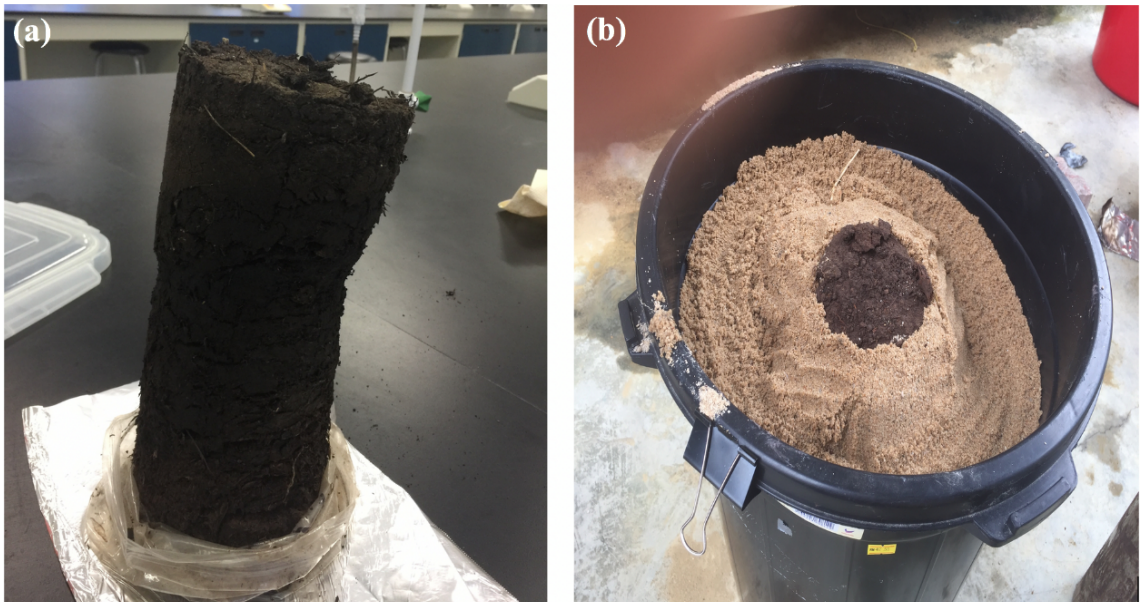


Figure 5.1 (a) shown the dried sample of intact peat. **(b)** shown a dried peat sample that inserted into the pit and exposed its surface for the ignition purpose.

The peat was ignited uniformly using a coiled galvanised wire on a ceramic plate heated to ~600°C, placed in contact with the surface of the peat for 30 minutes (**Figure 5.2**). This represents natural ignition conditions in accordance with the methodology of Rein *et al.* (2009) and Wilson *et al.* (2015). Following the ignition protocol, and once it was confirmed that the samples had achieved self-sustaining combustion (Wilson *et al.,* 2015), the burn chamber was placed under a fume hood for smoke sampling.

Over the following 60 to 90 min, the resulting smoke was continuously sampled using a pump and a 90 cm sample line with a funnel was held 12.0 cm above the smouldering peat. The smoke was sampled and placed in a 5-litre infrared White (multi-

pass) cell (Specac Ltd. UK) and the infrared spectra collected using a Fourier Transform Infrared (FTIR) spectrometer. An example of this setup is presented in Wilson *et al.* (2015). The FTIR spectral analysis was performed using Multi-Atmospheric Layer Transmission (MALT) software (Griffith, 1996; Smith *et al.,* 2011), yielding trace gas mole fractions inside the White cell, from which emission factors were calculated. The reader is referred to Paton-Walsh *et al.* (2014) and Smith *et al.* (2014) for a full description of the spectral retrieval process.



Figure 5.2 The induction of fire on dried intact peat sample using heating coil that wrapped on ceramic plate.

5.3.3 Calculation of emission ratio and emission factor of smoke

The emission ratio can be calculated using **Eq. (5.1),** in accordance with Paton-Walsh *et al.* (2014), by determining the slope of linear regression between the abundance of species, i against the abundance of reference species, y. Where Δ[i] is the excess mole fraction of species i.

$$\boldsymbol{ER}_{\frac{i}{y}} = \frac{\Delta[\boldsymbol{i}]}{\Delta[\boldsymbol{y}]} = \frac{[\boldsymbol{i}]-[\boldsymbol{i}]_{\boldsymbol{background}}}{[\boldsymbol{y}]-[\boldsymbol{y}]_{\boldsymbol{background}}} \qquad \textbf{Eq. (5.1)}$$

Emission factor (EF) is expressed in unit g of compound emitted per kg of dry mass burned. Here, the EF was derived using two equations: **Eq. (5.2)** for all species except CO_2 and CO and **Eq. (5.3)** for CO_2 and CO, as previously used by Smith *et al.* (2018) for field measurements of smouldering peat fires. Although most of the literature before Smith *et al.* (2018) (i.e. Akagi *et al.,* 2011; Huijnen *et al.,* 2016; Nara *et al.,* 2017; Stockwell *et al.,* 2014; Wilson *et al.,* 2015; Wooster *et al.,* 2011; Zhang *et al.,* 2014) discounted particulate matter (PMC) from the total calculation of carbon fraction for CO_2 owing to its small concentration, this study adopted the calculation revised by Smith *et al.* (2018) and Jayarathne *et al.* (2018), in which the value of 0.0127 g kg^{-1} (consisting of 76% carbon) was used as a factor for the carbon fraction of CO_2, as shown by **Eq. (5.3)** below:

$$\boldsymbol{EF_i} = \boldsymbol{ER_{i/c0}} \times \frac{\boldsymbol{MM_i}}{\boldsymbol{MM_{co}}} \times \boldsymbol{EF_{CO}} \qquad \textbf{Eq. (5.2)}$$

$$EF = (Fc - PMC) \times 1000 \times \frac{MM}{12} \times \frac{\Delta_{CO_2\ or\ CO}}{\sum_{i=1}^{n}(\Delta NCi \times \Delta i)} \quad \textbf{Eq. (5.3)}$$

*Where Fc is the mass fraction of peat carbon content (measured according to the methodology outlined in **Section 5.3.3**); PMC is a factor representing the particulate matter of carbon (0.0127 g kg^{-1}); $MM_{CO_2\ or\ CO}$ is the molar mass of compound CO_2 or CO (g mol); 12 is the molar mass of carbon (g mol^{-1}); and ΔCi is the excess mass mixing ratio of the compound for each species (mol m^{-3}) i.e. the concentration measured in the smoke minus the background concentration.*

Meanwhile, modified combustion efficiency (MCE) was calculated based on an approach that measures combustion efficiency, i.e. equation **Eq. (5.4)**:

$$MCE = \frac{\Delta CCO2}{\Delta CCO2 + \Delta CCO} \quad \textbf{Eq. (5.4)}$$

5.3.4 Statistical analyses

The relationship between both of each gas carbon species with physicochemical properties were performed using Pearson's correlation moment. Significant correlation, r was further analysed using regression, R^2 model at $p \leq 0.05$, unless stated otherwise. All statistical analyses were calculated and formulated with the help of Minitab version 18.1 software (Penn, USA, 2017). The graphs were plotted using Sigmaplot 12.5 graphing software (Systat Software Incorporation, UK, 2014).

5.4 Results

5.4.1 Fuel properties of intact peat from the artificial compaction study

Core samples (*n* =14) collected and compressed provided a wide range of physicochemical gradients to reflect the heterogeneity of peat soil characteristics. The maximum and minimum value of dry bulk density was between 0.110 g cm^{-3} and 0.389 g cm^{-3} with a loss on ignition of 78.89% to 89.74%, which corresponded to a total soil porosity of 76.05% to 93.17%. Meanwhile, gravimetric water content was 112.6% to 255.4%, and volumetric water content ranged between 23.03% and 54.93% whereas the water-filled pore space ranged between 24.71% and 64.63%. similarly, the chemical properties were also wide-ranging. For example, pH values, ranged between pH 2.73 to pH 3.60; total carbon ranged between 36.28% and 46.74%, total nitrogen was between 1.08% and 1.63%; hydrogen ranged from 9.98% to 19.62%; sulphur ranged between 0.24% and 0.98%; and CN ratio was 27.76 to 36.46.

5.4.2 Emission ratio (ER), emission factor (EF) and modified combustion efficiency (MCE) of intact peat samples

The emission ratio (ER) and emission factor (EF) of CO_2, CH_4, and CO, and the MCE of each sample were calculated, and the results presented in **Table 5.1**. The results show that the minimum and maximum values of ER for CO_2 and CH_4 had a wide range of values i.e. between 2.900 to 4.088 and 0.030 to 0.068, respectively. In this study, the minimum and maximum EF of CO_2, CH_4, and CO were between 1404 to 1527 g kg^{-1}, 1.61 to 13.2 g kg^{-1} and 180.8 to 238.4 g kg^{-1}, respectively. Meanwhile, the MCE for this study was between 0.76 and 0.84.

Table 5.1 Emission ratio (ER), emission factor (EF) and modified combustion efficiency (MCE) from fire peat intact samples. Values are mean ± SD of n=14.

Parameter	Mean ± SD
CO_2:CO	3.74 ± 0.54
CH_4:CO	0.05 ± 0.03
CO_2EF	1473.2 ± 34.7
CH_4EF	6.49 ± 3.38
COEF	208.7 ± 18.4
MCE	0.870 ± 0.216

5.4.3 Correlation between pre-combustion physicochemical properties and emission factor

To identify the correlation between physicochemical properties and gas emission by-product of ignited peat, the emission factor, EF, of CO_2, CH_4, and CO was calculated further. Pearson's correlation coefficient analysis was performed, and the results presented in **Table 5.2**. The results of the correlation analysis show that loss on ignition was negatively correlated with the EF of CO_2 (p = 0.038). Meanwhile, dry bulk density (p = 0.023) and pH value (p = 0.045) were positively correlated with the EF of CH_4 and negatively correlated with total porosity (p = 0.017) and gravimetric soil water content (p = 0.024). However, the EF of CO did not show any correlation with any of the pre-combustion physicochemical properties.

Table 5.2 Values represent Pearson's correlation coefficient $\boldsymbol{r}$, between carbon emission factors and peat physicochemical properties (n = 14). The bolded r values with *, ** and *** are significant at p = 0.05, 0.01 and $\leq$ 0.001, respectively.

Emission factor	Physical property					
	Bulk density (g cm^{-3})	Loss on ignition (%)	Total porosity (%)	Gravimetric water content (%)	Volumetric water content (%)	Water-filled pore space (%)
CO_2	0.013	**-0.559***	0.019	-0.199	-0.074	-0.07
CH_4	**0.603***	0.315	**-0.623***	**-0.598***	0.191	0.300
CO	0.117	0.212	-0.131	-0.178	-0.047	-0.003
	Chemical property					
	pH value (1:2.5) (Peat:water)	Total carbon (%)	Total nitrogen (%)	Hydrogen (%)	Sulphur (%)	C:N ratio
CH_4	0.398	-0.267	-0.267	0.365	-0.207	0.185
CO	**0.542***	0.353	0.467	0.092	0.189	-0.309
CO_2	-0.310	0.300	0.239	-0.444	0.417	-0.098

5.5 Discussion

5.5.1 Physicochemical properties from the intact peat samples

The bulk density, loss on ignition, total porosity, total carbon, nitrogen, sulphur, and CN ratio obtained in this study were comparable to previous studies on converted tropical peatlands (e.g. Firdaus & Gandaseca, 2010; Firdaus *et al.,* 2011, 2012; Ishikura *et al.,* 2017; Melling *et al.,* 2005a, 2005b) (**Table 3.7**). This result confirms that the intact peat samples used in this study are representative of typical tropical peat characteristics for peat obtained from land converted to a plantation. In contrast, the water-related variables measured in this study such as gravimetric water content, volumetric water content, and water-filled pore space, were slightly lower than the reported range for plantation peatlands. The reason behind this is likely to be that the soil cores were covered loosely to protect them from rainfall and flooding during the compaction period. Furthermore, the pH values obtained were also lower than that of previous studies, reflecting higher hydrogen content in the peat sample of this study compared to the reported range. It is presumed that the reason for this occurrence is the formation of acid sulphate soil because peat has a shallow depth (≤ 1.0 m) (**Section 2.3.2**).

5.5.2 Comparison between previous studies on smouldering carbon emissions in laboratory and field conditions

In this study, the EF for CO_2, CH_4, and CO, as well as MCE, were determined. It was found that the EF for CO_2, CH_4, and CO, and the MCE were 1473.2 ± 35 g kg^{-1}; 4.49 ± 3.38 g kg^{-1}; and 209 ± 18 g kg^{-1}; and 0.81 ± 0.22 g kg^{-1}, respectively. The calculated EF of MCE was within the mean value reported by Smith *et al.* (2018), Stockwell *et al.* (2016), Huijnen *et al.* (2016), and Stockwell *et al.* (2014), which was measured *in-situ* (field measurement) and in laboratory conditions (**Table 5.3**). Hence, this experiment, which was conducted in a controlled open space, could be an alternative approach to the field measurements of emission factors of CO_2, CH_4, and CO, as long as the peat samples remain intact.

Table 5.3 The comparison of emission factor (EF) of carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO), and modified combustion efficiency (MCE) between this study with previous studies. All values are presenting in mean ± SD (g kg^{-1}), except for Christian *et al.* (2013) which are in means.

$EFCO_2$	$EFCH_4$	EFCO	MCE	References
1473.2 ± 35	4.49 ± 3.38	209 ± 18	0.81 ± 0.22	This study**
1579 ± 58	11.00 ± 6.11	251 ± 39	0.80 ± 0.03	Smith *et al.* (2018)*
1564 ± 77	9.51 ± 4.74	291 ± 49	0.77 ± 0.05	Stockwell *et al.* (2016)*
1625 ± 170	7.80 ± 2.50	234 ± 47	n.m.	Huijnen *et al.* (2016)*
1637 ± 204	12.8 ± 6.6	233 ± 72	0.816 ± 0.07	Stockwell *et al.* (2014)**
1703	20.8	210	0.838	Christian *et al.* (2003)**

Note: *In-situ* or field measurement and laboratory-based measurement are marked by superscript asterisk * and **. N.m. is not measured.

5.5.3 The relationship between pre-combustion physicochemical properties and the EF of CO_2 and CH_4

The decomposition status of peat could be determined from the severity of the peat smouldering by-products i.e. CO_2 and CH_4. For example, the CO_2 EF decreased with the peat loss on ignition, indicating decreased organic matter content (R^2 = 0.312; p = 0.038) (**Figure 5.3 (a)**). This decrease in organic matter shows that the oxidation of peat had produced ash as a by-product (Firdaus *et al.,* 2012); thus it can be interpreted that the increased CO_2 emissions were due to ash content (**Figure 5.3(b)**). In an unrelated event, Yildiz *et al.* (2015) reported that the presence of ash could act as a catalyst to accelerate pyrolysis, further boosting the total yield of CO plus CO_2 by more than 10% and favouring CO_2 as a by-product of the decarboxylation reaction. Hence, there is evidence that compaction by peat oxidation may lead to increased ash content; consequently, increasing the CO_2 EF.

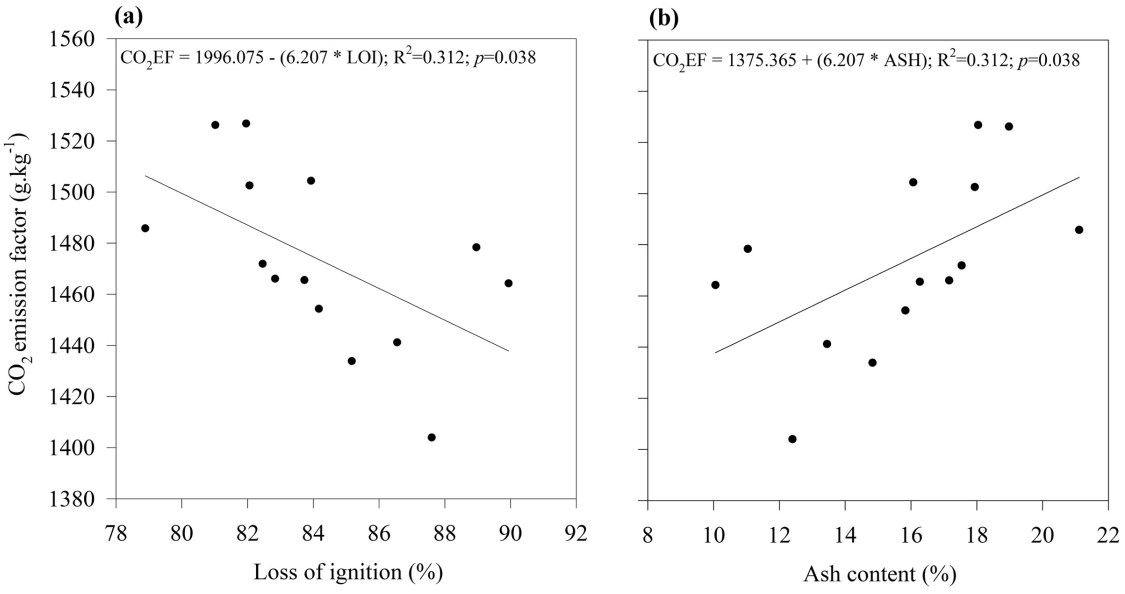


Figure 5.3 The relationship between CO_2 emission factor with **(a)** loss on ignition and **(b)** ash content (n=14).

Meanwhile, the decomposition proxies were also found to affect the EF of CH_4. In particular, CH_4 emission were found to increase with the dry bulk density ($R^2 = 0.363$; $p = 0.023$) (**Figure 5.4(a)**) and reduced pore space ($R^2 = 0.388$; $p = 0.017$) (**Figure 5.4(b)**). Thus, the decomposition proxies can be explained by the peat comprises of decomposed woody material that contains different amounts of cellulose, hemicellulose, and lignin (Tonks *et al.,* 2017). When decomposition occurs, the dual-porosity structure collapses, resulting in the reduction of total porosity. Following this, the lignin composition is expected to be higher (Kool *et al.,* 2006; Rezanezhad *et al.,* 2016; Tonks *et al.,* 2017). One study measuring the gas evolution profile in thermochemical conversion characteristics of switchgrass, wheat straw, eastern redcedar and dried distilled grains were found that higher lignin content was associated with increased CH_4 emission (Pasangulapati *et al.,* 2012). Subsequently, a distinct thermal decomposition of the by-products during gasification and pyrolysis was observed (Dorez *et al.,* 2014).

Moreover, the collapsed woody material could turn into a horizontal laminar structure within the peat soil profile, resulting in constricted pores and ending up with restricted oxygen supply (Boelter, 1965; Estop-Aragonés *et al.,* 2012; Rezanezhad *et al.,* 2016). The same phenomenon was observed by Mulholland *et al.* (1991), who found that a decrease in O_2 from 21% to 14% could increase the decomposition emission ratio of CH_4 to CO two-fold. In fact, gravimetric soil water content ($R^2 = 0.357$; $p = 0.024$; **Figure 5.4(c)**) was also found to be negatively related to bulk density. Water content is one of the main factors that help retard smouldering (DeBano, 1991), so this study assumes that a decreased gravimetric water content probably indicates water evaporation by shrinkage or compaction (Hooijer *et al.,* 2012). Huat *et al.* (2011) also mentioned that the water removal from the upper peat by drainage and subsequently by oxidation, could lead to

compaction. Interestingly, pH value ($R^2 = 0.235$; $p = 0.045$; **Figure 5.4(d)**) also increased with increased CH_4 EF. It is possible that availability of Boric acid in peat as retardant (Di Blasi *et al.,* 2007) during smouldering phase. Because Boron is absorbed by hydroxide Fe and organic substances (i.e. carbohydrate) (inland peat) (Keren & Bingham, 1985; Yonebayashi *et al.,* 2004) in the form of Boric acid molecule that dominant in low pH (Goli *et al.,* 2019). Thus, become abundant compared to high tropical peat pH. However, we did not measured Boron element in our samples but similar case was also reported by Yonebayashi *et al.* (2004) at inland tropical peat in South Sumatera, who found that Boron accumulation could be derived from sea water (i.e. Total Boron is highly positive correlation with water soluble Natrium content and Mg/Ca ratio) intrusion during ebb and flow of the tides. In fact, this is also supported by our sampling location that was at shallow peat and 12km away from the Strait of Malacca).

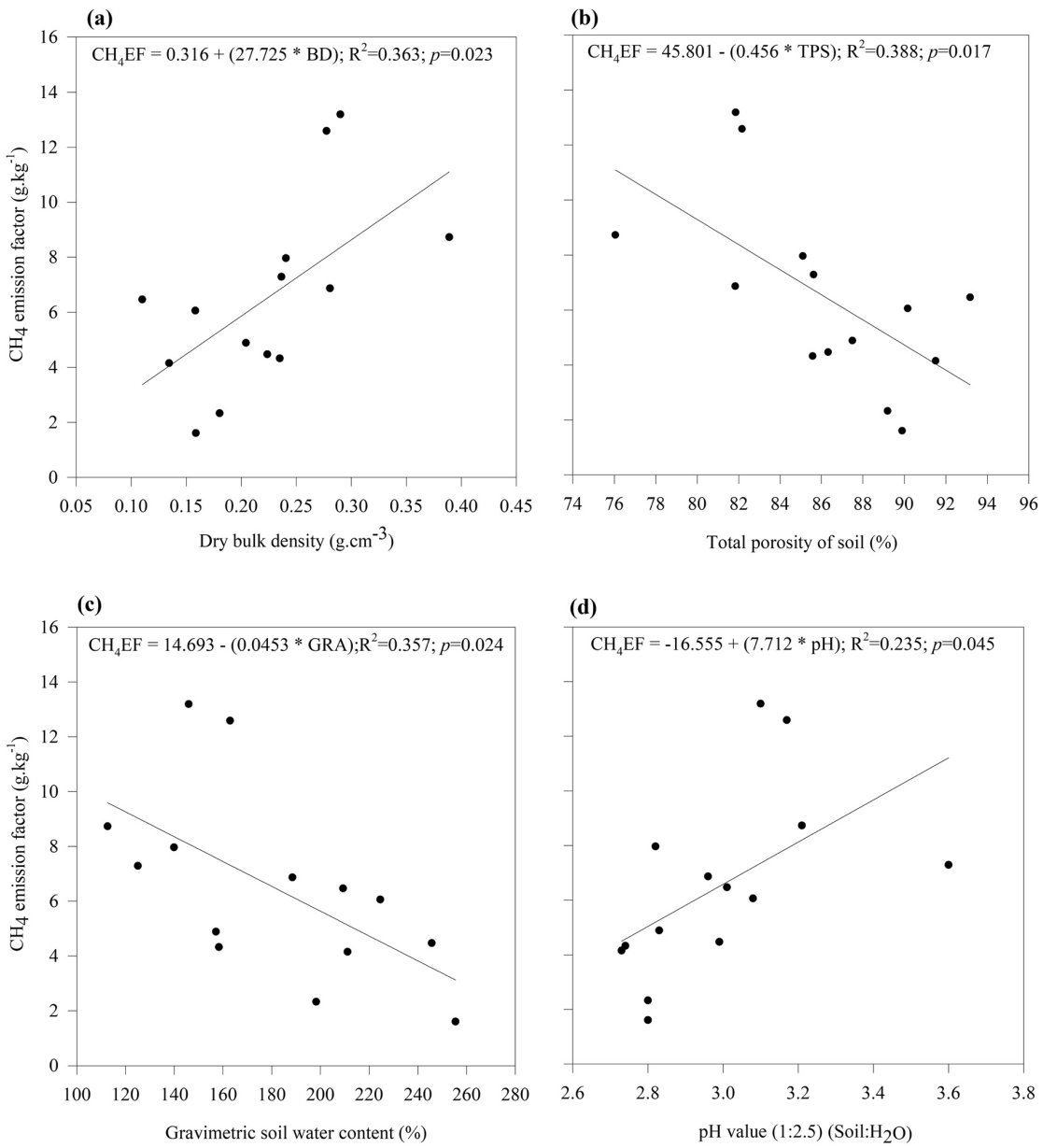


Figure 5.4 Relationship between CH_4 emission factor with **(a)** dry bulk density, **(b)** total porosity of soil, **(c)** gravimetric soil water content and **(d)** pH value with (n = 14).

5.5.3 Implication of artificial compaction practice on carbon emission via fire path for land use shifting

The relationship between the CH_4 emission factor and dry bulk density observed in this study is in good agreement with a previous field study on ten tropical peatland fires in Peninsular Malaysia conducted by Smith *et al.* (2018). The results in this study showed a moderate relationship between CH_4 emission factor and dry bulk density ($R^2 = 0.363$; $p = 0.023$; $n = 14$; **Figure 5.5(a)**), though not as strong as Smith *et al.* (2018) between the same variables ($R^2 = 0.608$; $p = 0.008$; $n = 10$; **Figure 5.5(b)**). However, in this study, the standard error of estimate in this study was observed to be smaller (S = 2.804) than that of Smith *et al.* (2018) (S = 4.048). A smaller standard error estimate indicates a more accurate regression analysis. In addition, by combining all data samples (this study and Smith *et al.* (2018)) so that $n = 24$, a strong significant relationship between dry bulk density and CH_4 EF ($R^2 = 0.601$, $p < 0.001$) was observed with a small standard error of estimate, S = 3.3031 (**Figure 5.5(c)**). Hence, we can be confident that bulk density is a reasonable predictor of CH_4 EF.

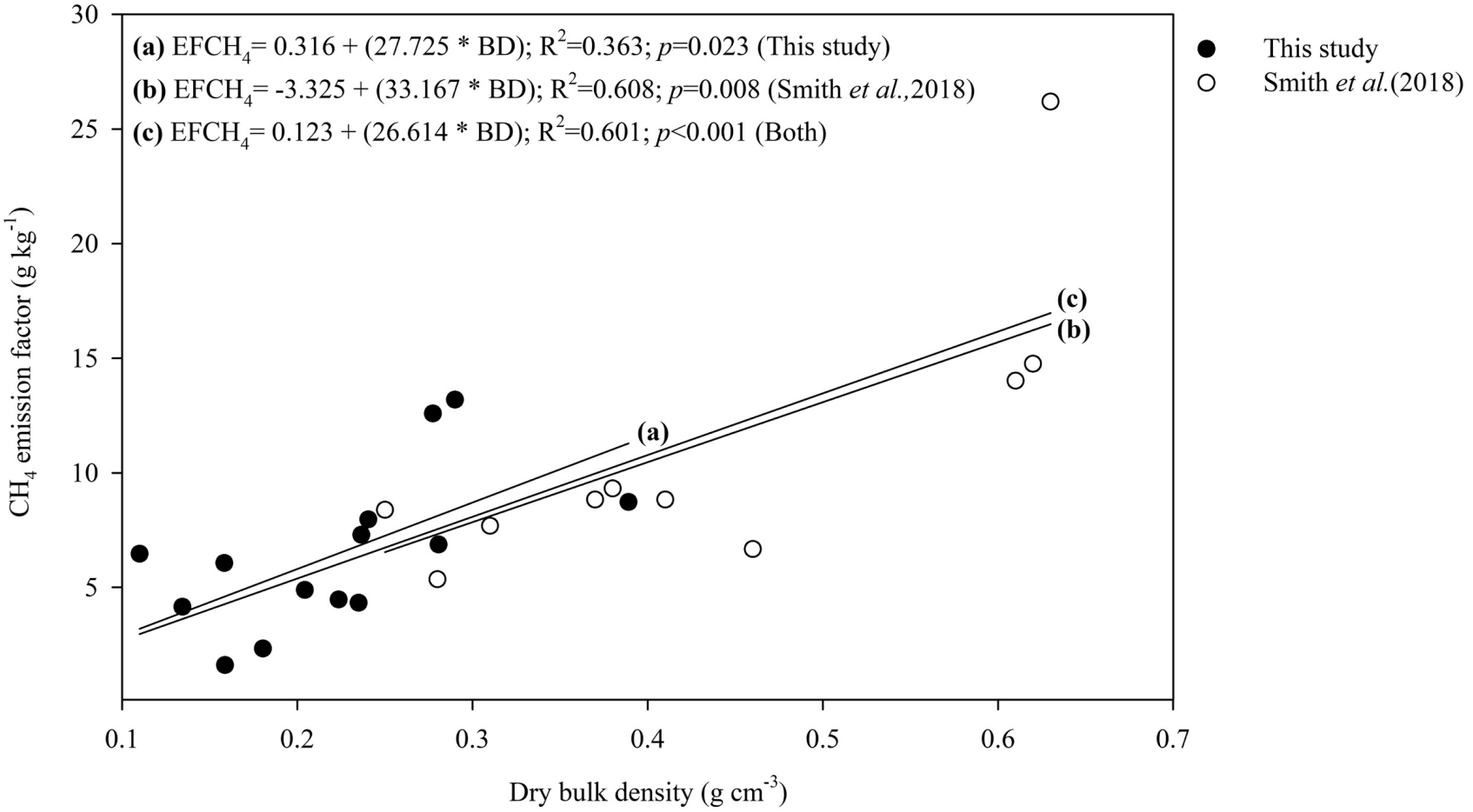


Figure 5.5 The relationship between CH_4 emission factor (g kg^{-1}) to dry bulk density (g cm^{-3}) from **(a)** this study (*n* = 14), **(b)** Smith *et al.,* 2018 (*n* = 10) and **(c)** combination of studies (*n* = 24). The regression lines are marked by stated letters.

This relationship could inform agricultural regions practising compaction methods (Mutert *et al.,* 1999) and burning to increase crop productivity. In general, compaction by oxidation, shrinkage, and consolidation due to drainage can increase the bulk density of peat in a secondary peat swamp forest by up to 0.10 g cm^{-3} (Könönen *et al.,* 2016; Melling *et al.,* 2008; Tonks *et al.,* 2017). Based on this example, CH_4 emission factor could increase by 97%, from 2.78 g kg^{-1} to 5.45 g kg^{-1}. In comparison, the default value proposed by IPCC (2014) (Hirashi *et al.,* 2014) showed an increase from 7.84 g kg^{-1} to 11.04 g kg^{-1}, which shows that the value obtained in this study is relatively small. This is consistent with a number of other recent studies, which have also found smaller CH_4 EFs than those used by IPCC (e.g. Huijnen *et al.,* 2016; Stockwell *et al.,* 2016).

Given that both bulk density (BD) and loss and ignition (LOI) are both influenced by conversion of peat swamp forest to oil palm (e.g. Cooper *et al.,* 2018) as well as water table fluctuations in established plantations (**Chapter 3**), here we propose to develop a model which uses these variables to construct a relationship between land use scenario (i.e. the implementation of drainage and the increased BD and reduced LOI associated with long-term conversion from peat swamp forest to OP plantation) to project potential emissions factors associated with fire events on those land uses. This is important as 505,887 ha of 2015 peat fires were on existing OP plantation in SE Asia, compared to 176,179 ha on peat swamp forest (Glauber & Gunawan, 2016) and emissions estimates to date have not accounted for land use in providing area-based EFs.

To construct the model, the relationships between (1) loss on ignition and CO_2 (**Figure 5.3(a)**), and (2) bulk density and CH_4 (using the combined data for CH_4 with that of this and Smith *et al.* (2018) (**Figure 5.5(c)**) as well as the mean CO value from this study was used (see **Table 5.4**). The value of loss on ignition is the 1st quartile value, while the 3rd quartile value is the bulk density and represents an extremely low water table in the respective ecosystem. The reason that values in the 1st and 3rd quartiles were used was that these values represent the data population in this study, when compared to the minimum (Min) and maximum (Max) value which representing only one sample.

Table 5.4 Derived model and global warming potential (GWP) as in $CO_{2\text{-eq}}$. The carbon monoxide (CO) value is the mean from this study. All values are presented in g kg^{-1}.

Gas species	Pre-combustion peat parameter as a predictor	Equation	$CO_{2\text{-eq}}$.
CO_2	Loss on ignition (LOI)	1996 – (6.207 × LOI)	* 1
CH_4	Bulk density (BD)	0.123+(26.614 × BD)	*28
CO	n/a	n/a	208.7*3

Note: n/a is not available and asterisk * is multiply by GWP.

Table 5.5 Mean (n =16) of respective variables (e.g. bulk density and loss on ignition) from secondary peat swamp forest and oil palm plantation that calculated to 1st (Q1) and 3rd (Q3) quartile values.

Variable	Land use	Mean	Q1	Q3
Bulk density ($g.cm^{-3}$)	Secondary peat swamp forest (SF)	0.171	0.124	0.223
	Oil palm plantation (OP)	0.232	0.164	0.280
Loss on ignition (%)	Secondary peat swamp forest (SF)	80.65	75.71	89.58
	Oil palm plantation (OP)	84.27	81.98	87.21

Baseline values for loss on ignition and bulk density were based on the mean from un-compacted control peat swamp forest sites (From North Selangor peat Swamp Forest) and the plantation peats from the same sample area and timeframe used to collect and compact the burn samples (see **Chapter 3** for further details). Although this study found no relationship between any pre-combustion physicochemical property variables and carbon monoxide (CO), the mean from CO was still used to represent all land uses i.e. 208.7 CO g kg^{-1}. The carbon emission from peat fire values was converted to Global Warming Potential (GWP) in terms of $CO_{2\text{-eq}}$, where CH_4 and CO were multiplied by a factor of 28, and 3, respectively, to yield the fire by-product (Hatano *et al.,* 2016). Since bulk density and the depth of the burnt peat sample (*ca.* 10cm) are already known based on the peat fire combustion experiment, the value of g kg^{-1} for the emission factor can be converted to t $CO_{2\text{-eq}}$ ha^{-1}. It is important to mention that although the peat fire sampling time was between 60 and 90 minutes, the time variable could not be applied directly because peat fire occurrence is unpredictable (Rein *et al.,* 2009). Thus, the values of carbon emission from the peat fire are presented as t $CO_{2\text{-eq}}$ ha^{-1} (**Table 5.6**). The calculation to convert g kg^{-1} to t ha^{-1} was adapted from Schlesinger (1990) that of soil carbon content.

Table 5.6 Carbon loss via peat fire from different water table fluctuation scenarios. Mean (n =32) of water table level from secondary peat swamp forest and oil palm plantation that calculated to 1st (Q1) and 3rd (Q3) quartile values that represent low and high-water table.

Land use scenario	t CO_{2eq} ha^{-1}	Differences (%)
Secondary peat swamp forest (High; -28.50cm)	243.4	nil
Secondary peat swamp forest (Low; -42.23cm)	365.3	+50
Oil palm plantation (High; -37.50cm)	284.7	-22
Oil palm plantation (Low; -62.80cm)	459.7	+61

Note: The plus (+) and (-) symbols indicate enhancement and reduction of carbon emission from peat fire during land use transition. Land uses transition are listed down from top to below column.

In general, increased bulk density and decreased loss on ignition are expected when the water table is lowered due to differences in the soil moisture regime (Grzywna, 2017); thus causing periodic shrinkage and oxidation within the aerobic horizon of the peat soil (Grzywna, 2017; Kennedy & Price, 2005; Wösten *et al.,* 1997). As such, we suggest that this can be extended to suggest that carbon emissions in their respective land use will increase by 50% and 61% (when combustion occurs in low water table scenarios). Although there is no reference for directly comparing $CO_{2\text{-}eq}$ value, the single species CO_2 value was compared with that of Drösler *et al.,* (2014), as per EPA (2014), where CO_2 emission from prescribed fires was set to 264 t CO_2 ha^{-1} for peat fires generally (as opposed to differentiating between land use type). Based on single species carbon emission i.e. the CO_2 emission in low water table scenarios, the estimated value of the prescribed fire from the secondary peat swamp forest and the matured oil palm plantation was 241 t CO_2 ha^{-1} and 295 t CO_2 ha^{-1}, respectively, falling well within the proposed

value. This result clearly shows that the model adopted in this study can be used as a benchmark to assess peat fire from prescribed fire, especially in the tropical peatland landscapes of Peninsular Malaysia. Thus, the model in this study is the first to include 3 species of carbon emission using pre-combustion peat properties in the form of CO_2, CH_4, and CO in $CO_{2\text{-eq}}$, to complement the estimation of emission factor from the prescribed fire for land use shifting between 365.3 t CO_{2eq} ha^{-1} and 459.7 t CO_{2eq} ha^{-1}.

In addition, the proposed model was also capable of estimating carbon emissions in one cycle of land use transition. For example, when a secondary peat swamp forest is opened up for oil palm plantation, water table levels are lowered up to 0.8 m (Mutert *et al.,* 1999) to facilitate heavy machinery use for clearance and planting and OP seeding growth and survival. In turn, the bulk density and ash content (**Fig 5.2(b)**; **Eq. (2.3)**) of peat will increase due to shrinkage and oxidation. If burned, carbon emissions from the peat alone are estimated to increase by 50% from the initial state compared to the undrained forest, from 243.4 t $CO_{2\text{-eq}}$ ha^{-1} to 365.3 t $CO_{2\text{-eq}}$ ha^{-1}. For a plantation where the water table depth is maintained within recommended limits of -40.0 cm to -60.0 cm (RSPO, 2018) a plantation fire at that point will produce emissions of 284.7 t $CO_{2\text{-eq}}$ ha^{-1} (**Table 5.6**) as the higher prescribed water table control decreases bulk density and ash content. Where plantations are less well managed and water tables remain below the recommended -40 to -60cm, or where WTD has been reduced intentionally for the control of disease, for example, *Ganoderma boninense* Pat. Fungus via combustion and (ASEAN Secretariat, 2003; *Integrated Management Plan NSPSF 2014-2023 vol.2*, 2014), the resulting increased bulk density and ash content will mean that during this event, an increase (compared to less drained plantation) of 61% from 284.7 t $CO_{2\text{-eq}}$ ha^{-1} to 459.7 t CO_{2eq} ha^{-1} is estimated for fire events.

This study recommends employing a simple step to reduce carbon emissions from peat fire, namely by targeting the reduction of bulk density and ash content. To decrease bulk density and ash content, water table level needs to be raised and the plant biomass input gradually increased (e.g. such as intercropping with other crops) (Dhandapani *et al.,* 2019a) or paludiculture (Giesen, 2015), so that the intensity of peat decomposition also increases (Hooijer *et al.,* 2012). Although some increases in CO_2 from the peat surface are expected (Harpenslager *et al.,* 2015), at least the emissions will be temporarily subdued with time. The finding presented in **Chapter 2** also supports the effectiveness of this method, where the incorporation of oil palm frond biomass with the oil palm plantation management may reduce the carbon emission factor of a matured oil palm plantation. Therefore, based on the rule of thumb, in preventing the reoccurrence of peat fire in both ecosystems, the water table level must be kept as high as possible. As suggested by Putra *et al.* (2018), who used a model approach of integrated metadata from Tropical Rainfall Measuring Mission by GES-DISC NOAA, ground water level, and historical satellite of fire reoccurrence by NASA-EODIS; the fire reoccurrence can be prevented as long as ground water level be maintained at -10 cm or higher.

5.6 Concluding remarks

The relationship between peat physicochemical properties and smouldering carbon EF was investigated using selected intact samples from a matured oil palm plantation. The intact peat samples showed typical characteristics of tropical peat derived from land converted to a plantation. The smouldering carbon emissions were comparable to that of previous studies, indicating that the measurement performed under a controlled open area could be an alternative to field measurements, if prevailing conditions do not permit field sampling. However, it is important to ensure that the peat sample remains intact. The results in this study revealed that the EF of CO_2 and CH_4 was associated with the variation in pre-combustion peat physicochemical properties, but not so the EF of CO. The EF of CO_2 decreased with a decreased loss on ignition. Hence, ash content resulting from peat oxidation could also increase the EF of CO_2. Meanwhile, the CH_4 EF increased with bulk density and pH; and decreased with total porosity and gravimetric water content. A comparison between the sample data in this study with that of Smith *et al.* (2018) showed a strong regression relationship between bulk density and the EF of CH_4 ($R^2 = 0.601$; $p < 0.001$). Using the established model in this study, it is suggested that compaction as a result of oxidation, shrinkage and consolidation by draining tropical peatland could lead to higher carbon emissions.

Overall, the peat samples showed typical characteristics of tropical peat derived from land converted to a plantation. The smouldering carbon emissions were comparable to that of previous studies, indicating that the experimental ex-situ measurement approach performed under a controlled open area, assuming the peat samples remain structurally intact, could be an alternative to field measurements, if prevailing conditions do not

permit field sampling or manipulation of peat samples is required. This study recommends employing a simple step to reduce carbon emissions from peat fire, namely by targeting the reduction of bulk density and ash content. To decrease bulk density and ash content, water table level needs to be raised and the plant biomass input gradually increased. The most obvious approach to this is replanting PSF species and raising water tables. Paludiculture options are also likely to have a positive impact.

Chapter 6. General discussion

Compaction is undertaken because of claims that confined and restricted peat pores may enhance soil moisture due to the effect of capillary rise (Rezanezhad *et al.*, 2016; The Borneo Post, 2016). The increase in soil moisture is said to lead to additional benefits of reduced C emissions and reduced risk and extent of peat fires (Busman *et al.,* 2018; Melling & Tang, 2018; The Borneo Post, 2016). This thesis outlined why there is clear ambiguity with this claim. This thesis also explored a number of issues surrounding compaction with the aim of clarifying what impacts it has on peat structure, physio-chemistry and the resulting emissions, and if claims of environmental benefits hold true. For example, while peat is known for its high organic matter content and therefore high potential compressibility, it has a complex anisotropic structure and plasticity which this study as suggested may result in inconsistent results of compaction. Further where water table level is low (e.g. in an oil palm plantation) and is far away from the peat surface (-40cm onwards), the thesis has explored the impact to emissions when compaction causes disconnection of peat pores from each other and from water table fluctuation. This thesis also explored the notion of a misconception in definition of peat compaction in tropical peatland landscape due to confounding factors between (passive) natural compaction by oxidation, shrinkage and compression and (active) artificial compaction- by heavy machinery. This study suggest that this could be a reason for wide interpretation on peat compaction processes. Therefore, the aim of this research project was to assess the impact of artificial compaction on the tropical peat physicochemical properties and carbon emissions from peat surface as well through peat fire. For the first time ever, artificial compaction was experimentally applied in the field and laboratory conditions to gain some mechanistic understanding into the geo-physicochemical changes which occur and how they control of carbon emissions. Through undertaking this study our findings either

directly or indirectly allow for the recommendation of a range of effective measures to reduce carbon emission from peat surfaces and peat fires.

This thesis explored compaction from a range of different perspectives, firstly to determine any existing heterogeneity in compaction via assessments of bulk density (BD) as degree of compactness within a plantation in order to identify if heterogeneity in emissions occurred and if these were linked to bulk density microsites. While there was significant variability within microsites, BD was not a controlling variable in emissions within a plantation of the same age (rather it was controlled by rooting zones, soil moisture proxies and pH). However, between ages, the significance of long-term drainage and changes to BD from decomposition did have an impact. Therefore, within plantations, we propose that inaccuracies in carbon accounting have been widespread due to not accounting for microsite emissions variability (**Chapter 2**). It is suggested that use of microsite area calculation approach or 'surface area correction' (SAC) will aid in both accounting and management. Specifically, in relation to the latter, it can be suggested that carbon emission might be reduced by increasing the areas of frond piles (FP) in non-rooting areas far from palm (FF), which could result in a 11% reduction in carbon emissions.

Artificial or active compaction was also explored through in-situ compaction of soils at secondary forest (SF) and oil palm (OP) plantation sites. The resulting impact of the compaction was inadvertently to move the surface soils into closer proximity to the water table level. In doing so, **Chapter 3** in fact explored in detail the role of altered water table level manipulation and the effects it had on carbon emissions (**Section 3.5.1)**. A

model illustrating the carbon emission exchange and water table level (**Figure 3.9**), established in **Chapter 3**, was derived that is exclusive for SF. The water table relationship was also supported by the fact that finding suggested that no other physicochemical properties were found to be related to carbon emissions as a result from compaction treatments (see **Section 3.5.3**). From this, we used water table scenarios that represent seasonal variation and resulted in 59.1% variation in emissions. Results were consistence to the value between undrained and drained tropical peat swamp forest that of 50% variation as reported by Dhandapani *et al.,* (2019b). While differences in term of physiochemical properties between SF and OP were described as linked to passive compaction and the long-term effects of drainage and enhanced decomposition, we ascribed that the effect of compaction at SF were in fact subdued by the wide range water table fluctuation observed during the study period. From this study suggests that water table fluctuation mitigates compaction. With RSPO, 2018 making recommendations that plantation and drainage-based subsistence trends mean that plantations should be removed with a minimum of 40 years of subsidence allowance before flooding issues ensue, 'afterlife' management plans should ensure that the effects from both active (heavy machinery) and passive compaction (drainage) should not be just left abandoned to nature. This may result in huge amount of carbon emission from peat oxidation and also prone to peat fire. Therefore, this study strongly advocates that increasing water table level (blocking drainage) to the optimum limit, for instance in this study, up to +6.0 cm during dry season, the effect of compaction would be supressed especially by resetting the stratification of decomposition proxies (e.g. layering of peat with varied values of CN ratio and N) (**Chapter 4**) of which are pivotal to the control of carbon emissions (**Chapter 4 & 5**).

While **Chapter 3** results pointed to the role of water table level in mitigating emissions, and also in the role of mitigating the effects of compaction, it meant that role of compaction and increased BD was impossible to untangle from that of the alteration of water table relative height. As such **Chapter 4** provided an ex-situ study to consider compaction alone. **Chapter 4** compressed structurally intact peat cores under controlled soil moisture conditions in order to determine how SF and OP peats would respond. Results from SF in **Chapter 3 & 4** showed that emissions trends responded in an inverse ratio (CO_2 reduction %: CH_4 enhancement %). Whereby, the compaction alone resulted in a 34:70 (*ca.* 1:2) ratio (**Chapter 4**) as compared to 50:153 (*ca* 1:3) for in situ samples subjected to water table interaction (**Chapter 3**). Despite of successful attempt in finding the offset caused by the confounded factors of water table and decomposition proxies, the remaining inverse relationship between CO_2 and CH_4 still occurs due to consolidation between surface peat and below peat horizon. However, in the presence of water table, this effect of consolidation on carbon emissions can be reset by the level fluctuation (**Section 3.5.3**). This implies that under natural peatland condition, the effect of reduced CO_2 emission is solely dependent on the absence of any interaction with water table, which we feel would be unlikely under *in-situ* conditions. In addition, a further important conclusion was the lack of impact of compaction in pre-drained soils (i.e. oil palm sites) pointing towards this being an ineffective approach in pre-drained sites. This is significant given the recommendations that drained Indonesian peats should be compressed in retrospect to reduce emissions and fire risk (The Borneo Post, 2016). While results show directly that artificial compaction results in no changes to emissions, indirectly, this study can also suggest that fire ignition risk reduction indicators, e.g. increased soil water-filled pore spaces, increased soil moisture or decreased air-filled pore spaces were in fact unaffected by compaction treatment. As a result, we suggest there would be no reduction

in fire risk, and as emissions via decomposition were also unaffected, results suggest no benefit as a post-drainage mitigation approach.

This study was also interested in if the mechanism of compaction, via increasing BD resulted in a change of fire emissions factors in any subsequent fires (**Chapter 5**). Via experimental burning of treatment samples covering a range of bulk densities, this study found a clear positive relationship between BD and CH_4 emissions. In addition, there was also a negative relationship between Loss on ignition (LOI) (and a positive relationship between ash content) with CO_2 fire EFs. Using the assumption that land use change results in significant alteration to both LOI and BD (i.e. LOI ranged 75 to 89% and BD ranged 0.12 to 0.28 $g.cm^{-3}$) by water table depth (i.e. -28.5 to -62.80cm) (**Chapter 3**) and peat burnt cavity (*ca.* 10cm) (**Chapter 3 & 5**), this study combines these relationships, and modeled predicated carbon emission factors for specific land use changing scenarios from secondary forest to oil palm plantation. From this, we derived the following emissions factors in the form of global warming potential (GWP) that have been calculated using the following three gas carbon species: CO, CO_2 and CH_4, for land use shifting between SF and OP of 365.3 to 459.7 t $CO_{2\text{-eq}}$ ha^{-1}, respectively. Compared to our single species CO_2 emission of prescribed fire from the secondary peat swamp forest and the matured oil palm plantation (i.e., from 241 to 295 t CO_2 ha^{-1}); these values are consistent with Drösler *et al.,* (2014), as per EPA (2014) and Leng *et al.,* (2019) that of from 264 to 323 t CO_2 ha^{-1}. However, compared to estimations from Indonesian (Sumatra, Papua and Kalimantan) peatland fire carbon emissions in year 2015 (Setyawati and Suwarsono, 2018) through hot spot and remote sensing approaches with burnt depth of 4.0 cm over a total area of 623,304 ha, indicates those current estimates may be significantly lower (16.8 t $CO_{2\text{-eq}}$ ha^{-1}). By using GWP and accounting for BD and LOI

variability occurring through land use change, this study provides more accurate and land-use specific emission factors required for accounting for regional haze events and global GHG emissions estimates linked to the type of land use being burnt. It also indicates the importance of good management of drained and subsiding peatlands given the significantly greater emissions linked to fires in these areas of higher BD. Likewise, using a single emissions factor for tropical fires in general on peat is not appropriate and should be modified to account for pre-combustion fuel heterogeneity. Thus, more focus should be put on understanding the drivers behind emission variability; however, this study shows clearly that the level of exiting drainage and the resulting changes to BD and LOI are clearly important. To minimize fires moving forward as well the emissions from future fires, raising water tables will both reduce fire occurrence but will also contribute to decreasing BD value (**Chapter 3**) where fires do occur. This result also highlights that any efforts to compact peat as a mitigation measure against fire is in fact more likely to increase EFs overall.

Overall therefore, as we found no effect of additional compaction to carbon emissions at OP plantation sites due to their resiliency to active compaction (**Chapter 3 & 4**). We suggest that restoration to areas where inert carbon exposed on the peat surface by oxidation, consolidation and shrinkage (e.g. the matured oil palm plantation), can be undertaken by adding in carbon stock (labile plant biomass) under high water table depth condition. This recommendation is made, as in contrast to current industry recommendations, when comparing responses of SF and OP in terms of emissions, soil physicochemical and fire EFs, decreasing BD and ash content under high water table level, as abovementioned, is capable of reducing, by almost *ca.* 50%, soil respiration and preventing peat fire at the drained tropical peatlands (**Chapter 3, 4, & 5)**. Therefore,

while reforestation is ideal, to address issues of economic sustainability associated with the need for alternative income strategies of local communities, paludiculture (or wetland-based agriculture), where crops are produced drainage free can be an option to combat this problem. As estimated, more than 400 of peat swamp forest (PSF) species have been identified to have productive use (Giesen, 2015) for starch, vegetable oil, medicinal potential, furniture, and clothing (Giesen, 2018). This so called back-to-basics technique has been established for centuries especially by the indigenous people that live surrounding peatlands. Crops that are suitable for paludiculture practice include sago (*Metroxylon sagu*), rattan (*Calamus deerratus*), gelam (*Melaleuca cajuputi*), jelutong (*Dyera costulata*), tengkawang (*Shorea stenoptera*) and purun grass (*Lepironia conifera*) (Parish *et al.,* 2019). Interestingly, this also in agreement with the latest RSPO (2018) guideline, where they listed down a new section under principles and criteria 7.7 of 'No new planting on peat, regardless of depth after 15 November 2018 and all peatlands are managed responsibly' [sic] , specifically 7.7.5 (c) (P&C 2018) to restore and rehabilitate peatlands by "phasing out" or not replanting expired oil palm plantation (e.g. *ca.* 40 years or two cycles) and follow RSPO Manual on Best Management Practices (BMPs) for existing oil palm cultivation on peat', version 2 (2018) (Parish *et al.,* 2019). We should also however emphasize the need for these new crops to be produced in such a way that promotes C inputs to the soils to counter emissions in order to provide a net sink of terrestrial carbon and therefore mimicking conditions within pristine PSFs.

Lastly, this study seeks to consider why peat compaction is considered as a popular course to plantation management and establishment (e.g. Busman *et al.,* 2018; Melling & Tang, 2018; Mutert *et al.*, 1999; Othman *et al.,* 2009; The Borneo Post, 2016) despite its apparent fruitlessness based on this study? We suggest that instead of its

environmental credentials, the intention to introduce heavy machinery into plantations is to ease the workload in land clearing. As mentioned in the general introduction chapter of this thesis, peat swamp forest after extreme drainage may be prone to the exposure of semi-decomposed woody biomass at the surface in which is not suitable for growing oil palm. Thus, with the help from heavy machinery, the semi-decomposed woody biomass can easily be removed, stacked, or buried at designated location. Furthermore, peat surface level heterogeneity (associated with the hummock and hollow configuration of natural PSFs) and cavities or slopes resulting from the biomass removal can be levelled by vehicle passes. Furthermore, a strong driver is in terms of strengthening the bearing capacity to battle "palm love syndrome". However, our findings suggest little impact to BD from artificial compaction, and that in fact mechanical artificial compaction is outweighed by oxidation, consolidation, and shrinkage (passive compaction) brought on the extreme drainage during early stage of land clearing. Therefore, the used of heavy machinery after peatland drainage, appears primarily as a tool for aesthetic purposes and ease of clearance.

As such, this study does not recommend applying compaction to either land use type. Primarily this is because: (1) there is no effect from the practice on already drained peatlands (as found in **Chapter 3 & 4**), (2) undertaking this in degraded sites as a mechanism to reduce emissions as part of rehabilitation in sites marked for reforestation and rewetting would likely fail due to the fact that compressed peat will return to its original structure due to the increased water table fluctuation (**Section 3.5.1**), or even via rainfall, or any interaction with water sources such that the efforts to induce artificial compaction on tropical peatland are rendered useless (**Chapter 3**); (3) when considered in relation to global warming potential (by combining the loss of CH_4 sink with the

reduced CO_2 emissions observed; **Table 6.1**), the results from compacting treatments within the forest soils indicated negligible CH_4 emission in relation to $CO_{2\text{-eq}}$ though the enhancement is 2-fold greater than the reduction of CO_2. As such the net effect is 41.1 t $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}.

Table 6.1 CO_2 (mg CO_2 m^{-2} $hr^{-}1$) and (CH_4 μg CH_4 m^{-2} $hr^{-}1$) emissions (mean ± SE) (n=32) from secondary peat swamp forest with compaction treatments according to peat depth (i.e. from 0 cm to -30cm). The GWP presented in t $CO_{2\text{-eq}}$ ha^{-1} yr^{-1}.

Treatment	CO_2	CH_4	-CO_2: +CH_4 percentage ratio	GWP
T0	1295 ± 157	-49.67 ± 5.61	nil	113
T10	983 ± 105	-27.02 ± 4.36	24% : 46%	86
T20	829.6 ± 85.9	-7.5 ± 1.87	*36% : 85%	73
T30	467.5 ± 71.0	59.9 ± 25.1	*64% : 221%	41
		Average:	*50% : 153% (*Ca*. 1:3)	

Note: Plus '+' and minus '-' symbols indicated enhancement and reduction as compared to the same gas species of control, T0. Asterisk * denotes significant different between control.

(4) The results towards CO_2 emissions reduction found in **Chapter 4,** SF soils indicated that compacting treatment did not impact bulk density and that where CO_2 emissions were reduced, it was due to the consolidation of surface soils with those at deeper layers with lower labile carbon and higher values for other decomposition proxies. Thus, methanotrophic microbes in anoxic layers were likely delivered greater labile C and overall, emissions remain unhalted. It can be therefore concluded that this practice purely appeared to hasten the physical subsidence expected within the first 5 years of an

oil palm conversion and therefore make peats more prone to the negative impacts of subsidence such as flooding and seawater intrusion (Hooijer *et al.,* 2012). Overall, considering the confounding effect between water table level and decomposition proxies, the cost of this approach compared to the ambiguous effects, means that from an economic point of view and severe environmental disturbances to other biodiverse communities in the forest and soil biomes, we feel there is no real net benefit. (5) It is recommended that to reduce carbon emissions via peat surface respiration and prevent peat fire as well as restoring degraded peat soil (recalcitrant carbon), reforestation or paludiculture is the best option and perhaps, combine with governance policy (**Chapter 2, 3, 4 ,5, & 6**).

6.1 Overall conclusion

Based on the results obtained from this extensive study, artificial compaction will not cause changes in the bulk density of the peat surface. However, the degree of decomposition could still potentially be affected because of the translocation of the peat surface to a deeper horizon, accompanied by a consolidation of different degrees of decomposition in peat, especially in locations with higher labile carbon composition (e.g. secondary peat swamp forest) under a low water-table level. In turn, the pattern of CO_2 and CH_4 emissions will become inversely related according to a percentage ratio of *ca.* 1:2. However, in the presence of wide range of water table fluctuation, the effect of artificial compaction is negligible due to the self-recovery mechanism of the tropical peat. As a result, the water table interference will trigger other possible immediate and temporary effects. For example, CO_2 emission will be higher in this peatland compared to undisturbed peat due to aggregate breakdown, and microorganisms will become encapsulated. Besides, CH_4 would also be emitted higher by 1-fold due to the environment having ample substrate availability promoted by the translocation of labile materials to deeper peat, in close proximity to the water table level and anoxic conditions. Lastly, it is suggested that the terminology of compaction should be differentiated according to the nature of compaction: (1) oxidative or shrinkage compaction or passive compaction —oxidation of peat due to lowered water table, causing peat to collapse and become compressed under its own weight; and (2) artificial or active compaction— induced by horizontal load compression that causes admixture (consolidation) between distinct degrees of decomposition in peat.

6.2 Recommendation for future study

It is recommended that future research conduct the same study but integrated with paludiculture environment. In particular, an abandoned peatland that exiting phrase out period could be assessed to further understand the impact of heavily compacted peat on the restoration of physicochemical properties (especially bulk density). Besides, the chronosequence of carbon input and losses from soil surface through the ecosystem succession could also be potentially examined.

This study also revealed evidence of the self-recovery effect arising from artificial compaction due to the water table management, especially in drained peatland. Therefore, future work could perform studies to understand the adverse effects of physiochemical properties and carbon emissions on artificial compaction in a large-scale of industrial plantation with longer period of time (monitoring approach). This is because in this study, we only experienced some momentary carbon emissions due to extreme increase of water table fluctuation on compacted peat. It would be even more interesting if these effects were combined with microbial response.

Peat structure is very unique, as it comprises an anisotropic structure or a dual-pore configuration (Rezanezhad *et al.,* 2016). Typically, artificial compaction using heavy machinery is solely done axially (one-way vertical compression). Hence, future work could investigate water retention using hydraulic conductivity equation, $Ksat = {Kh}/{Kv}$ that proposed by Beckwith *et al.* (2003) that exclusive for peat anisotropic structure. Based on this equation, when the horizontal path, Kh, exceeds the vertical path, Kv, the hydraulic conductivity will be higher. Therefore, by manipulating certain degree

of hydraulic conductivity (with mineral infilling) especially at horizontal path, the exact value of water retention in peat can be controlled. This application is useful to mitigate flooding occurrence or to control carbon emission related to water table fluctuation, especially in forest reserves or for plantation management. Possibly, this study also can be combined with a micro-morphological assessment. At present, there is a dearth of information on the micro-morphology research of tropical peatland. The micro-morphology method not only preserves the sensitive or fragile tropical peat structure, but also enables structural changes to be evaluated explicitly.

Chapter 7. References

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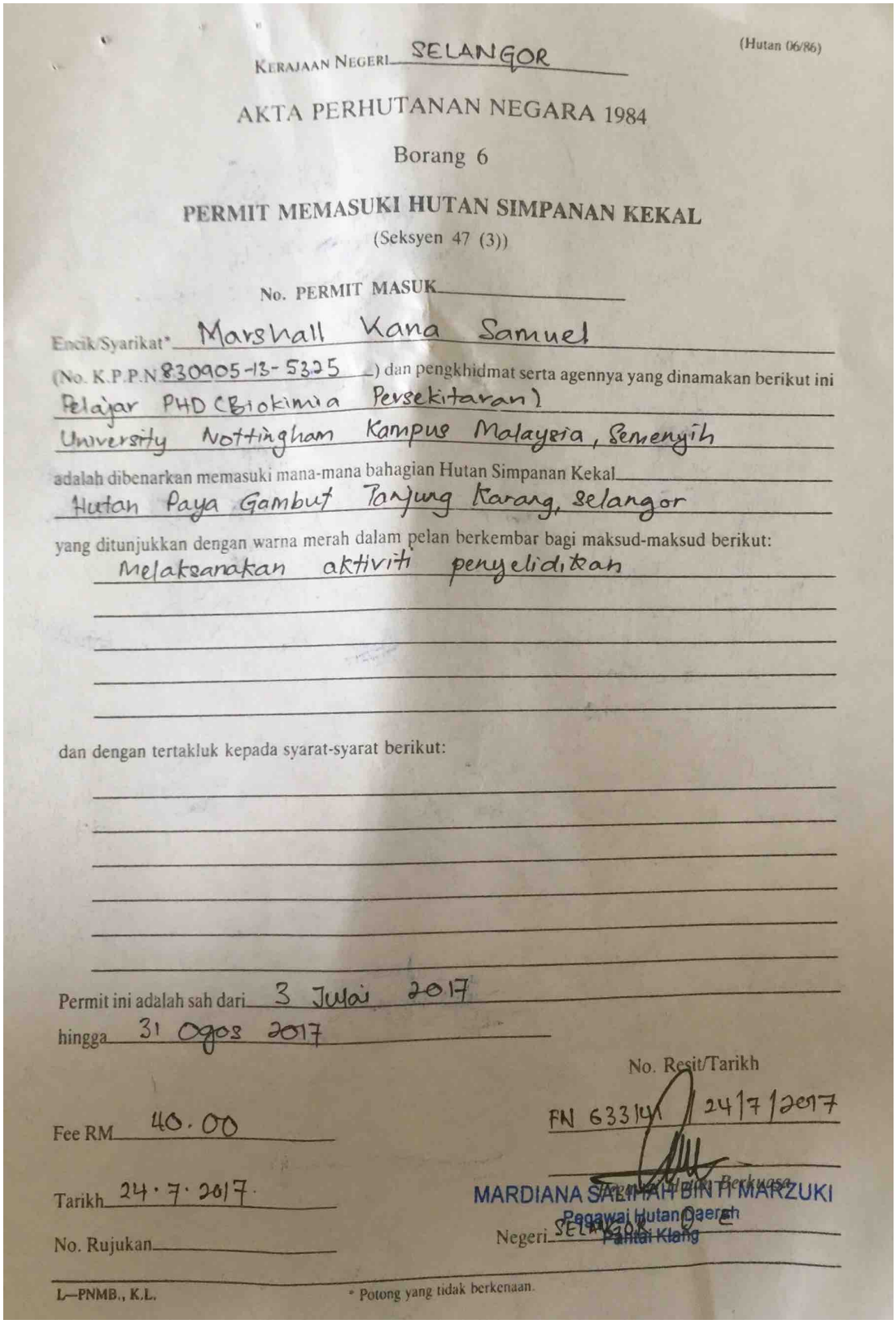
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Chapter 8. Appendices



KERAJAAN NEGERI SELANGOR (Hutan 06/86)

AKTA PERHUTANAN NEGARA 1984

Borang 6

PERMIT MEMASUKI HUTAN SIMPANAN KEKAL

(Seksyen 47 (3))

No. PERMIT MASUK

Encik/Syarikat* Marshall Kana Samuel

(No. K.P.P.N 830905-13-5325) dan pengkhidmat serta agennya yang dinamakan berikut ini

Pelajar PHD (Biokimia Persekitaran)

University Nottingham Kampus Malaysia, Semenyih

adalah dibenarkan memasuki mana-mana bahagian Hutan Simpanan Kekal

Hutan Paya Gambut Tanjung Karang, Selangor

yang ditunjukkan dengan warna merah dalam pelan berkembar bagi maksud-maksud berikut:

Melaksanakan aktiviti penyelidikan

dan dengan tertakluk kepada syarat-syarat berikut:

Permit ini adalah sah dari 3 Julai 2017

hingga 31 Ogos 2017

No. Resit/Tarikh

Fee RM 40.00 FN 633141 24/7/2017

Tarikh 24.7.2017

No. Rujukan

MARDIANA SALMAH BINTI MARZUKI

Pegawai Hutan Daerah

Pantai Klang

Negeri SELANGOR

L—PNMB., K.L. * Potong yang tidak berkenaan.

Appendix 1. Permission permit to enter the study area in the forest reserve of Tanjung Karang, North Selangor, Malaysia

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

Rujukan Kami : **MN/017173/2017/03**
Tarikh : **31 Mac 2017**
Kepada : **Encik Nizam Bin Buniran (Pengurus MAB Agriculture-Horticulture Sdn Bhd)**
Perkara : **Permohonan untuk Memasuki Kawasan Ladang Kelapa Sawit KLIA Plantation**

Salam Sejahtera,

Tuan,

Saya dengan hormatnya merujuk perkara di atas.

2. Seperti yang diusulkan pada tahun 2016 dalam kajian ijazah kedoktoran saya, lokasi penyelidikan teknik permampatan tanah gambut akan diteruskan dikawasan kelapa sawit KLIA. Tujuan utama saya pada kali ini adalah untuk mengukur keberkesanan teknik permampatan tanah bagi mengurangkan kadar perlepasan gas rumah hijau di kawasan ladang kelapa sawit diatas tanah gambut. Untuk pengetahuan tuan, keputusan awal penyelidikan kami dikawasan hutan Sg. Karang, menyatakan bahawa teknik ini mampu mengurangkan sehingga 72.28% karbon dioksida ($F_{(2,159)}$=65.15, $p<0.0001$). Walaubagaimanapun, faktor permampatan tanah (peratus pori tanah) hanya menyumbang 3.67% berbanding faktor paras air iaitu 16.72%. Oleh itu, kesuaian lokasi ini bagi menjalankan penyelidikan dapat memberi sedikit sebanyak informasi bagi permurnian sektor perladangan kelapa sawit di negara kita, khususnya.

3. Dengan ini, penyelidikan ini memerlukan pengunaan kawasan yang berkeluasan 25m^2 di plot tahun 2000. Tempoh ujian keberkasan teknik ini adalah selama 4 bulan bermula **3 April 2017 - 3 Ogos 2017 (4 bulan)** dan aktiviti persampelan tanah akan dilakukan dalam selang 2 minggu. Disini saya juga nyatakan bahawa kumpulan penyelidikan saya terdiri daripada seorang pembantu makmal iaitu Encik Dzularsyil Aizat Bin Shahrin.

4. Oleh itu, besarlah harapan saya agar permohonan kami untuk memasuki kawasan kelapa sawit KLIA diluluskan agar perlaksanaan aktiviti ini berjalan dengan lancar. Diharap juga bahawa kerjasama ini dapat memberi manfaat kepada kedua belah pihak.

Sekian, terima kasih.

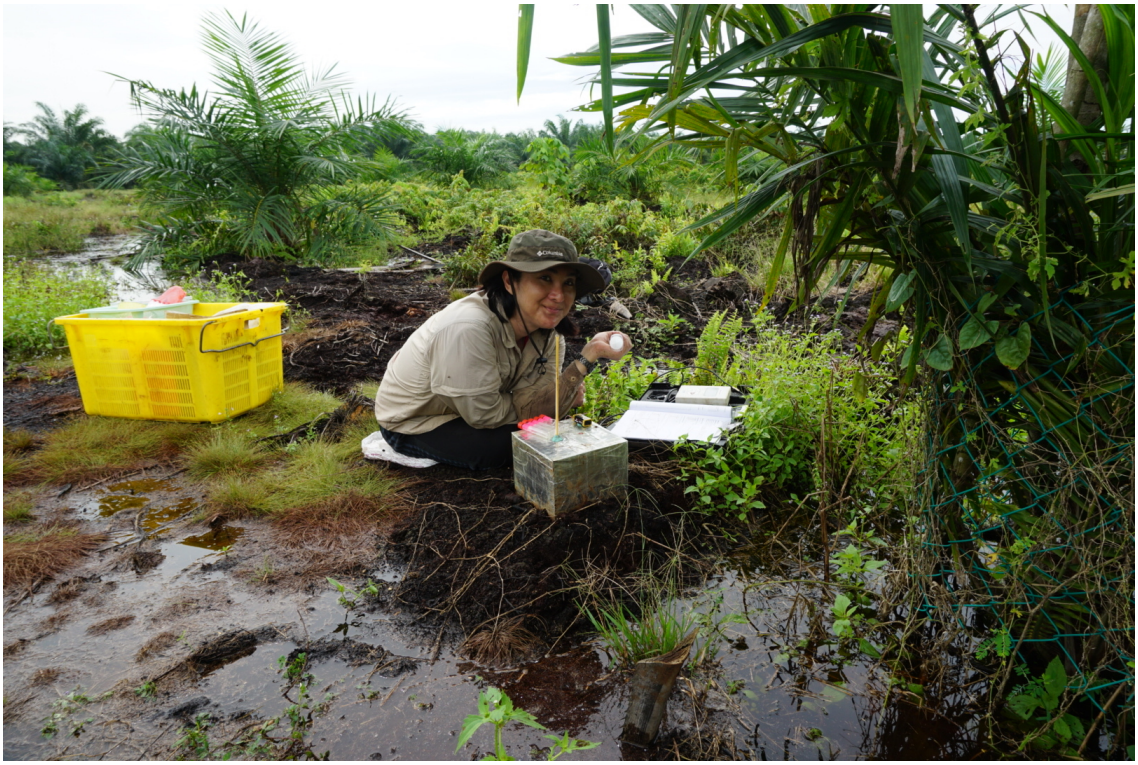
Yang benar,

(Marshall Kana Samuel)
b/p: Prof. Madya Dr. Stephanie Evers,
Pelajar Ph.D. (Biogeokimia Persekitaran)
Fakulti Sains, Sekolah Biosains,
Universiti Nottingham Kampus Malaysia
Jalan Broga, 43500 Semenyih,
Selangor.

Appendix 2. Letter of permission to enter the oil palm plantation area at Sepang, South Selangor.



Appendix 3. Animal tracks that observed at harvesting path in oil palm plantation, Sepang, South Selangor.



Appendix 4. Gas sampling during flooding occurrence at microsite under canopy (UC) within site A3 on November 2015. A steeper peat surface was selected to prevent water disturbance.

Appendix 5. Table of Density of water (g/mL) vs temperature (^{0}C) from Handbook of Chemistry and Physics, 53rd Edition, p.F4. Retrieved from https://bit.ly/1fSWm6K . *Whole degrees* are listed down the left hand side of the table, while *tenths of a degree* are listed across the top.

	0.0	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**
15	0.999099	0.999084	0.999069	0.999054	0.999038	0.999023	0.999007	0.998991	0.998975	0.998959
16	0.998943	0.998926	0.998910	0.998893	0.998877	0.998860	0.998843	0.998826	0.998809	0.998792
17	0.998774	0.998757	0.998739	0.998722	0.998704	0.998686	0.998668	0.998650	0.998632	0.998613
18	0.998595	0.998576	0.998558	0.998539	0.998520	0.998501	0.998482	0.998463	0.998444	0.998424
19	0.998405	0.998385	0.998365	0.998345	0.998325	0.998305	0.998285	0.998265	0.998244	0.998224
20	0.998203	0.998183	0.998162	0.998141	0.998120	0.998099	0.998078	0.998056	0.998035	0.998013
21	0.997992	0.997970	0.997948	0.997926	0.997904	0.997882	0.997860	0.997837	0.997815	0.997792
22	0.997770	0.997747	0.997724	0.997701	0.997678	0.997655	0.997632	0.997608	0.997585	0.997561
23	0.997538	0.997514	0.997490	0.997466	0.997442	0.997418	0.997394	0.997369	0.997345	0.997320
24	0.997296	0.997271	0.997246	0.997221	0.997196	0.997171	0.997146	0.997120	0.997095	0.997069
25	0.997044	0.997018	0.996992	0.996967	0.996941	0.996914	0.996888	0.996862	0.996836	0.996809
26	0.996783	0.996756	0.996729	0.996703	0.996676	0.996649	0.996621	0.996594	0.996567	0.996540
27	0.996512	0.996485	0.996457	0.996429	0.996401	0.996373	0.996345	0.996317	0.996289	0.996261
28	0.996232	0.996204	0.996175	0.996147	0.996118	0.996089	0.996060	0.996031	0.996002	0.996973
29	0.995944	0.995914	0.995885	0.995855	0.995826	0.995796	0.995766	0.995736	0.995706	0.995676
30	0.995646	0.995616	0.995586	0.995555	0.995425	0.995494	0.995464	0.995433	0.995402	0.99371



Appendix 6. The aboveground plant biomass in FF microsite area form a thick root mats like structure.

Appendix 7 Physicochemical properties of each intact sample according to sample number for fire experiment.

NO.	Bulk density (g cm^{-3})	Loss of ignition (%)	Total porosity (%)	Gravimetric water content (%)	Volumetric water content (%)	Water-filled pore space (%)	pH value (1:2.5) (Peat:water)	Total carbon (%)	Total nitrogen (%)	Hydrogen (%)	Sulphur (%)	C:N ratio
1	0.281	89.94	81.83	188.5	52.89	64.63	2.96	44.67	1.36	9.98	0.98	32.88
2	0.134	86.55	91.51	211.1	28.37	31.00	2.73	46.34	1.35	12.58	0.67	34.28
3	0.290	85.17	81.85	145.9	42.32	51.70	3.10	45.86	1.52	14.67	0.46	30.09
4	0.389	82.84	76.05	112.6	43.81	57.61	3.21	45.17	1.63	12.35	0.60	27.76
5	0.237	81.02	85.62	125.1	29.59	34.56	3.60	46.74	1.55	19.62	0.46	30.13
6	0.235	82.46	85.57	158.4	37.21	43.49	2.74	42.63	1.40	14.56	0.24	30.37
7	0.158	84.17	90.16	224.6	35.56	39.44	3.08	40.58	1.37	11.72	0.46	29.56
8	0.110	83.93	93.17	209.3	23.03	24.71	3.01	40.66	1.12	13.35	0.43	36.46
9	0.277	88.96	82.16	162.9	45.19	55.00	3.17	41.78	1.48	13.07	0.41	28.28
10	0.204	82.06	87.49	157.1	32.10	36.69	2.83	42.08	1.34	13.49	0.37	31.48
11	0.159	87.60	89.89	255.5	40.55	45.11	2.80	41.44	1.34	13.35	0.34	30.90
12	0.241	83.73	85.10	139.9	33.63	39.52	2.82	38.52	1.21	12.97	0.28	31.82
13	0.180	78.89	89.19	198.3	35.76	40.09	2.80	38.24	1.31	13.41	0.32	29.30
14	0.224	81.96	86.32	245.7	54.93	63.64	2.99	36.28	1.08	12.82	0.27	33.47

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