



Faculty of Resource Science and Technology

**Characterization of the Humification Degree of Peat Soils under
Cultivation of Sago and Oil Palm Plantations**

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Characterizations of the Humification Degree of Peat Soils under Cultivation of Sago and Oil Palm Plantations

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DECLARATION

I declare the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. It is original and is the result of my work, unless otherwise indicated or acknowledged as reference work. The thesis has not been accepted for any degree and is not concurrently submitted in candidature for any other degree.

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ABSTRACT

Sago palm (*Metroxylon sagu*) and oil palm (*Elaeis guineensis*) is a tropical crop that can adapt the acidic condition of peat soil, which is cultivated at large scale in Sarawak (Malaysia). The question is whether this large-scale development on peat soil are sustainable because of the challenges in their production yield. The production of sago palm and oil palm on deep peat are inconsistent, and not all the tree is able to grow to maturity and produce a yield. Besides, the production yield of the oil palm and sago palm at the mineral soil is greater than the one been cultivated on deep peat soil. For this reason, it is hypothesis that the extent of humification may have been the root cause to the slower and poorer performance of oil palm and sago palm on deep peat. This study is set out to investigate humification degree of peat soil under oil palm and sago palm plantations to provide a deeper insight. The soil samples were collected from the sago palm and oil palm estate. The physical and chemical soil characterisation were conducted between the sample's origin and depth. Meanwhile, the carbon dioxide measurement was only conducted on the surface soil in oil palm estate and forest. The result indicated the peat soil in sago palm and oil palm had the most nutrient at the surface soil while, the degree of humification decreased with increasing depth. The trunk performance at trunking plot might be due to higher conductivity ($460.00 \mu\text{Scm}^{-1}$) ($p < 0.05$) and lower C/N ratio (47.27%) ($p > 0.05$) compared to the non-trunking plot at the surface soil, while the FTIR shown the uncultivated peat was humified than cultivated peat because the latter was continuously replenished with new plant matter. On the basis of FTIR spectroscopy, no significant difference was found between cultivated peat sampled adjacent to trunking and non-trunking palms. On the other hand, the UV-Vis and FTIR data suggested lower humification degree in the underlying peat which may have led to inconsistent growth. Meanwhile, the oil palm result shown the forest was more humified

than the oil palm estate with significantly higher in conductivity ($451.87 \mu\text{Scm}^{-1}$) ($p < 0.05$). The leaching of K ($0.21\text{-}0.50 \text{ cmolc.kg}^{-1}$) and Ca ($0.55\text{-}1.119 \text{ cmolc.kg}^{-1}$) ($p < 0.05$) at the oil palm estate indicated the estate has lower nutrient, the lower C/N (21.43%) ($p > 0.05$) in forest revealed a higher degree of humification, the higher N-enrich litter falls led to higher nitrogen fixation in the forest. Besides, the FTIR spectra suggested the forest is more humified than the oil palm estate and the forest is significantly has lower carbon dioxide flux ($1.04 \text{ kg CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$) than oil palm estate ($1.16 \text{ kg CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$). However, the Pearson correlation shown a weak liner regression between the degree of humification and carbon dioxide flux, $R^2 = 0.1516$ in oil palm and $R^2 = 0.0005$ for forest. The correlation coefficient (r) for oil palm and forest is 0.389 and 0.023 ($p > 0.05$). The carbon dioxide was not influence by the degree of humification nevertheless the higher air ($27.2\text{-}33.3 \text{ }^\circ\text{C}$) and soil temperature ($27.0\text{-}28.4 \text{ }^\circ\text{C}$) ($p < 0.05$) at oil palm estate might be the factor for the higher carbon dioxide flux.

Keywords: Decomposition, carbon dioxide flux, soil degradation, histosol, soil fertility, productivity yield, Sarawak.

Klasifikasi Darjah Humifikasi Tanah Gambut di bawah Penanaman Sagu dan Ladang Kelapa Sawit

ABSTRAK

Pokok sagu atau rumbia (Metroxylon sagu) dan pokok kelapa sawit (Elaeis guineensis) adalah tanaman tropika yang boleh beradaptasi pada keadaan tanah gambut yang berasid, di mana ia ditanam secara berskala besar di Sarawak (Malaysia). Persoalannya, adakah penanaman secara berskala besar di tanah gambut ini mampan kerana cabarannya dalam pengeluaran hasil tanaman. Pengeluaran hasil pokok sagu dan kelapa sawit ditanah gambut dalam adalah tidak konsisten, dan tidak semua anak pokok tumbuh hingga matang dan mengeluarkan hasil. Sementara itu, hasil pengeluaran kelapa sawit dan pokok sagu di tanah mineral jauh lebih tinggi berbanding pada tanaman yang ditanam di tanah gambut dalam. Oleh kerana itu, ia dihipotesiskan bahawa darjah humifikasi tanah gambut dalam mungkin merupakan punca utama kepada prestasi kelapa sawit dan pokok sagu yang perlahan dan sedikit di tanah gambut dalam. Kajian ini bertujuan untuk mengkaji tahap humifikasi pada tanah gambut dalam di ladang kelapa sawit dan pokok sagu. Sampel diambil daripada ladang pokok sagu dan kelapa sawit. Sifat fizikal dan kimia tanah dikaji diantara tempat asal sample diambil dan kedalaman sampel. Manakala, pengiraan pelepasan karbon dioksida hanya dikaji di atas permukaan tanah di ladang kelapa sawit dan hutan simpanan. Hasil kajian menunjukan bahawa permukaan tanah di tanah gambut pada pokok sagu dan kelapa sawit mengandungi nutrien yang lebih banyak dan tahap humifikasinya menurun dengan peningkatan kedalaman tanah. Prestasi pembesaran batang pokok sagu yang lebih baik pada plot trunking mungkin disebabkan oleh kekonduksian elektrik ($460.00 \mu\text{Scm}^{-1}$) ($p < 0.05$) yang lebih tinggi dan nisbah C/N yang lebih rendah (47.27%) ($p > 0.05$) pada permukaan tanah berbanding plot bukan trunking, manakala FTIR menunjukkan tanah gambut yang tidak ditanam mempunyai humifikasi yang lebih tinggi berbanding tanah

gambut yang ditanam kerana tanahnya yang sentiasa dijatuhi dengan daun palma yang baru. Namun, data spektroskopi FTIR menunjukkan tidak terdapat perbezaan yang signifikan diantara bukan trunking dan trunking. Sebaliknya, data UV-Vis dan FTIR menunjukkan darjah humifikasi yang lebih rendah di bawah permukaan tanah gambut menyebabkan pertumbuhan pokok yang tidak konsisten. Hasil kajian pada ladang kelapa sawit menunjukkan tahap humifikasi di hutan adalah lebih tinggi berbanding ladang kelapa sawit dengan kekonduksian elektrik yang lebih tinggi ($451.87 \mu\text{Scm}^{-1}$) ($p < 0.05$). Sementara itu, pelepasan K ($0.21\text{-}0.50 \text{ cmolc.kg}^{-1}$) dan Ca ($0.55\text{-}1.119 \text{ cmolc.kg}^{-1}$) ($p < 0.05$) di estet kelapa sawit menunjukkan ladang mempunyai nutrien yang lebih rendah dan C/N yang lebih rendah (21.43%) ($p > 0.05$) pada hutan menunjukkan tahap humifikasi yang tinggi. Kandungan serap N di dedaun pokok menyebabkan penebalan nitrogen di dalam hutan. Selain itu, spektrum FTIR juga menunjukkan hutan mempunyai darjah humifikasi yang tinggi berbanding ladang kelapa sawit dan hutan secara signifikannya mempunyai fluks karbon dioksida yang lebih rendah ($1.04 \text{ kg CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$) berbanding ladang kelapa sawit ($1.16 \text{ kg CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$). Korelasi Pearson menunjukkan regresi liner yang lemah di antara darjah humifikasi dan fluks karbon dioksida, $R^2 = 0.1516$ untuk kelapa sawit dan $R^2 = 0.0005$ pada hutan. Koefisien korelasi (r) untuk ladang kelapa sawit dan hutan adalah 0.389 dan 0.023 ($p > 0.05$). Ini kerana, karbon dioksida tidak dipengaruhi oleh darjah humifikasi tetapi suhu udara ($27.2\text{-}33.3 \text{ }^\circ\text{C}$) dan tanah ($27.0\text{-}28.4 \text{ }^\circ\text{C}$) ($p < 0.05$) merupakan faktor fluks karbon dioksida yang lebih tinggi pada ladang kelapa sawit.

Kata kunci: Penguraian, karbon dioksida fluks, degradasi tanah, histosol, kesuburan tanah, hasil pengeluaran, Sarawak.

TABLE OF CONTENT

	Page
DECLARATION	i
ACKNOWLEDGEMENT	ii
ABSTRACT	iii
<i>ABSTRAK</i>	v
TABLE OF CONTENT	vii
LIST OF TABLES	xii
LIST OF FIGURES	xiii
LIST OF ABBREVIATIONS	xiv
CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW	1
1.1 Introduction	1
1.2 Objectives	4
1.3 Distribution of peat soil in Malaysia	4
1.4 Formation of tropical peat	6
1.5 Classification of peat in Malaysia	7
1.6 Exploitation of peat for agriculture	9

1.7 Physical characteristics of peat	10
1.8 Chemical characteristics of peat	11
1.9 Humic substances	12
1.10 Extraction and fractionation of humic substances	14
1.11 Characterization of humic substances	16
1.11.1 Elemental composition	16
1.11.2 Ultraviolet-visible (UV-Vis) properties	17
1.11.3 Fourier Transform Infrared	17
CHAPTER 2: MATERIALS AND METHODS	19
2.1 Study sites	19
2.2 Sampling (sago plantation)	19
2.3 Sampling (oil palm plantation and forest)	21
2.4 Sample preparation	22
2.5 Soil pH and electric conductivity	22
2.6 Exchangeable bases and cation exchange capacity (CEC)	23
2.7 Ash content	25

2.8 Bulk Density and Moisture content	25
2.9 Humification index	26
2.10 Functional group characterization	27
2.11 Elemental analysis	27
2.12 Carbon dioxide emission	28
2.13 Statistical analysis	29
CHAPTER 3: HUMIFICATION DEGREE UNDER SAGO PALM PLANTATION	30
3.1 Introduction	30
3.2 Results and discussion	30
3.2.1 pH	30
3.2.2 Moisture content	31
3.2.3 Ash content	31
3.2.4 Elemental analysis	32
3.2.5 Electrical conductivity (EC)	36
3.2.6 Cation Exchange Capacity (CEC), base saturation, sum of exchangeable cations	36

3.2.7 Fourier Transform Infrared (FTIR)	38
3.2.8 E ₄ /E ₆	43
3.3 Conclusion	44
CHAPTER 4: HUMIFICATION DEGREE UNDER OIL PALM PLANTATION	46
4.1 Introduction	46
4.2 Results and Discussion	46
4.2.1 Ash content, moisture, and bulk density.	46
4.2.2 Soil pH	49
4.2.3 Electric conductivity (EC)	49
4.2.4 Cation exchange capacity and exchangeable bases	50
4.2.5 Carbon-to-Nitrogen ratio (C/N)	51
4.2.6 FTIR	54
4.2.7 E ₄ /E ₆	58
4.2.8 Soil carbon dioxide flux	59
4.3 Conclusion	64
CHAPTER 5: CONCLUSION AND RECOMMENDATIONS	66

5.1 Conclusion	66
5.2 Recommendations	68
REFERENCES	69
APPENDICES	85

LIST OF TABLES

	Page
Table 1.1 The area of peatland in Malaysia according to states.	5
Table 1.2 Soil classification based on the wood content.	8
Table 1.3 Soil classification based on depth.	9
Table 1.4 Suitability of the various crops on peat soil of various thicknesses.	10
Table 1.5 Fraction of humic substances and their characteristics.	13
Table 1.6 Humic acid contents and their elemental compositions extracted under air and N ₂ gas atmosphere.	15
Table 3.1 Physicochemical characteristics of peat soil at the sago palm plantation.	34
Table 3.2 Cation exchange capacity and base saturation of cultivate and uncultivated.	35
Table 3.3 The E4/E6 values of humic acid extracted from uncultivated and cultivated peat, according to depth.	40
Table 4.1 The ash content, moisture and bulk density of peat from oil palm estate and forest.	47
Table 4.2 Chemical characteristics of peat soil from the oil palm estate and forest.	53
Table 4.3 The organic compound in the peat soil.	54
Table 4.4 The E4/E6 of oil palm and forest peat samples.	59
Table 4.5 Soil CO ₂ flux and cumulative flux for forest and oil palm estate.	61
Table 4.6 Correlation table of carbon dioxide and degree of humification in oil palm and forest plot.	63

LIST OF FIGURES

		Page
Figure 1.1	Distribution of lowland peatlands in Malaysia.	5
Figure 1.2	The formation of peatland.	7
Figure 1.3	Chemical structure of humic substances.	13
Figure 2.1	The sampling plots in Sungai Talau Research Center.	19
Figure 2.2	Photographs of non-trunking and trunking sago palm.	20
Figure 2.3	The sampling plot in Sebungan estate and Sebau forest.	21
Figure 3.1	The C/N ratio according to peat depth in the Trunking, Non-trunking and Control.	32
Figure 3.2	The FTIR profiles of uncultivated peat and cultivated peat sampled adjacent to trunking and non-trunking sago palms.	38
Figure 3.3	The spectral regions of selected bands for cultivated and uncultivated peat.	44
Figure 4.1	The soil profile of oil palm estate and forest at 15 cm to 300 cm.	55
Figure 4.2	The selected spectra region of selected band of oil palm and forest from 15 cm to 300 cm depth.	56
Figure 4.3	Air temperature (a), Soil temperature (b) at surface soil of oil palm estate and forest.	61
Figure 4.4	The carbon dioxide flux from the 25 subplots in oil palm estate and forest.	62
Figure 4.5	The correlation graph of E4/E6 with carbon dioxide emission from (a) oil palm estate and (b) forest.	63

LIST OF ABBREVIATIONS

ATR	Attenuated Total Reflectance
ANOVA	Analysis of Variance
C	Carbon
Ca	Calcium
CEC	Cation exchange capacity
C-H	Carbon hydrogen bond
cm	Centimeter
Cmolc Kg ⁻¹	Centimoles per kg
CO ₂	Carbon dioxide gas
C-O	Carbon oxygen bond
C=O	Carbonyl group
COOH	Carboxylic acid
C/N	Carbon over Nitrogen ratio
DOA	Department of Agriculture
Df	Degree of freedom
EGM	Environmental gas monitor
FA	Fulvic acid
FAO	Food and Agriculture Organization of United Nations
FTIR	Fourier-transform infra-red
g/cc	Gram per cubic
g	Gram
Gt	Gigatonnes
HA	Humic acid

Ha	Hectare
HCl	Hydrochloric acid
h	Hour
H ⁺	Hydrogen ion
HS	Humic substances
K	Potassium
Kg	Kilogram
M	Meter
Mg	Magnesium
Mm	Millimeter
Mha	Milionhectra
μm	Micrometer
μs	Microsiemens
Mmhos	Millimhos
N	Nitrogen
Na	Sodium
NaCl	Sodium chloride
NH ₄ ⁺	ammonium
NaOH	Sodium hydroxide
Na ₄ P ₂ O ₇	Tetrasodium pyrophosphate
C ₂ H ₇ NO ₂	Ammonium acetate
O	Oxygen
OH	Hydroxyl group
PVC	Polyvinyl chloride
SD	Standard deviation

T-C	Total carbon
T-N	Total nitrogen
UV-Vis	Ultra-violet visible spectrophotometry

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

2.1 Introduction

Peat is soil consists of partially decomposed biomass that develops in wet coastal areas where the rate of biomass production is greater than the rate of decomposition. This is due to the presence of a consistently high-water table that prevents aerobic decomposition of plant debris (Laiho, 2006). Typically, peat soil contains 65% of organic matter within at least 50 cm depth (Melling et al., 2007). Tropical lowland peat is acidic with pH 3-4 and ash content less than 2%. Tropical peat soil is commonly classified into hydric tropohemists, dysic, isohyperthermic although troposaprists and tropofibrists can also be found (Paramanathan, 2014). It is generally heterogeneous as it contains admixtures of fine and fibrous materials as well as woody fragments which develop through time from the residues of trees and shrubs that occupy the forest floor of the swamp (Melling et al., 2007).

The peat in Sarawak occurs in large basin and in small interior valleys that is developed in comparatively recent time (Zulkifley et al., 2014). The large basin swamps are generally dome-shaped. The organic soil deposits occupying the central portion of the dome is generally known as 'ombrogenous peat'. It comprises mainly of disaggregated tree trunks, branches, leaves, roots and fruits (Murtezda et al., 2002). The peatland represents an important long-term sink of atmospheric C (450 Gigatonne (Gt) of Carbon (C)) that constitutes of brown to black organic materials, forming under waterlogged condition from the partial decomposition of plant litter (Yu, 2011).

Peat swamp forest plays a crucial role in maintaining the regional ecosystem balance and to support social and economic system. Hydrological functions are especially important

at the local scale. Peat acts as a sponge that absorbs water during wet periods and releases it slowly during dry periods. Thus, peatland plays a role in preventing loss of life, controlling flood and maintaining minimal flows in rivers over dry season to support irrigation works and to prevent saline intrusion (United Nations Development Programme, 2006). However, due to increasing population and the need to eliminate rural deficiency, vast area of peatland, particularly in Indonesia and Malaysia, have been logged and cleared for pulp, sago and oil palm plantation over the last twenty years (Paramananthan, 2014).

Sarawak has the largest reserve of peatland in Malaysia, there are about 1.6 million hectare (ha) of peatland in Sarawak (Naim et al., 2016). This accounts for 66% of the peatland in Malaysia. Most of the peatland in Sarawak has been cleared for agriculture development of which 27.5% is used for oil palm (*Elaeis guineensis*) (Wong, 2016) and 7.6% for sago palm (*Metroxylon Sagu*) (Yamamoto et al., 2003). Sago and oil palm are two crops that can thrive in the harsh swampy environment; they have been exploited as valuable sources for economies in Sarawak to support the demands in market (Jamaludin, 2002).

The next question to consider is whether this large-scale development on peat soil is sustainable. As reported in the literature, one of the challenges of oil palm and sago palm plantation is their production yield on deep peat soil. Generally, these palms grow slower compare to those planted on mineral soil and shallow peat soil (Veloo et al., 2015b). In the experience of sago plantation where the trunk is harvested as the end product, the palms cannot produce a trunk even after 10 years of cultivation (Sim et al., 2005). According to Yamamoto et al. (2014), the time taken for harvesting was longer in the sago palms cultivated on deep peat soils compare to those cultivated on mineral soil. Jong et al., (2006) compare the growth performance of sago palm cultivated on deep and shallow peat. It was reported

that only 20% of sago palm produce trunk in deep peat while on the shallow peat they grew better with more than 80% trunking in 5-6 years and reaching maturity in ten years.

As reported by Kakuda et al. (2000), the poor growth of sago palms cultivated on deep peat is associated with the lower mineralization of nitrogen per unit volume. The insufficient nutrient in the deep peat is the cause to the slower and poorer growth (Sim et al., 2005). Likewise, the yield potential of oil palm planted on peatland has also been a divisive subject. The low yield of fresh fruit bunch in deep peat soil is found to associate with the presence of undecomposed wood in the peat profile which contributes to poor rooting and nutrient uptake, causing pre-mature dehydration of the fronds (Veelo et al., 2015b).

Commonly, the poor growth performance of sago palm and oil palm on deep peat were associated with the soil characteristics. According to Melling (2000), the degree of humification is a very important factor to consider when developing peat for agriculture as it has profound effects on the bulk density, moisture holding capacity and nutrient availability. During the decomposition process, a stabilized organic material consisting of hydrophobic and hydrophilic functional groups, referred to as humic materials, is formed (Semenov et al., 2013). The humified materials serve to agglutinate soil (Totsche et al., 2018), improving aeration and water retention capacity which ultimately lead to increased crop production (Piccolo, 2002). A more humified soil is often characterized by higher nitrogen (N) content which is indicated with a lower C/N ratio (Xu & Saiers, 2010). Venegas-González et al. (2013) further states that the growth of blackberry in compost with increased degree of humification has resulted in enhanced nutrient uptake. For these reasons, it is hypothesized that the extent of humification may have been the root cause to the slower and poorer performance of oil palm and sago palm on deep peat.

Although Veloo et al. (2015b) has identified humification degree as the cause to the poor growth performance of oil palm, the study thorough profile of humification degree at both sago and oil palm plantation is still limited. The inconsistent growth of sago palm on deep peat is yet to be explained and the humification profile across oil palm plantation has not been studied. Hence, this study is set out to investigate humification degree of peat soil under oil palm and sago palm plantations to provide a deeper insight.

2.2 Objectives

The specific objectives of the study are to characterise the humification degree of peat soil under:

- i. sago plantation against the uncultivated peat;
- ii. oil palm plantation against the forest peat.

2.3 Distribution of peat soil in Malaysia

Malaysia has approximately 2.6 million hectare (Mha) of peatland, of which 1.6 Mha are found in Sarawak (Wong, 2016). They represent 66% of the total peatland in Malaysia. Figure 1.1 illustrates the distribution of peatland in Malaysia and Table 1.1 summaries the area of peatland according to states. In Sarawak, peat occurs mainly between the lower stretches of the main river courses (basin peat) and in poorly drained interior valleys (valley peats). They are mainly found in Kuching, Samarahan, Sri Aman, Sibul, Sarikei, Bintulu, Miri and Limbang (Zainorabidin & Wijeyesekera, 2007).

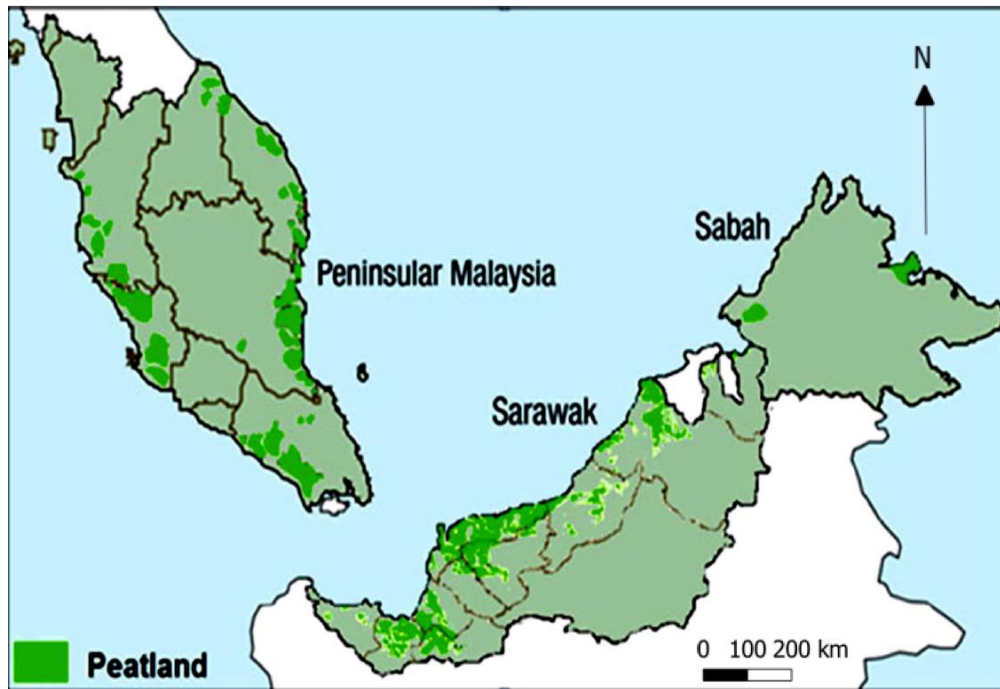


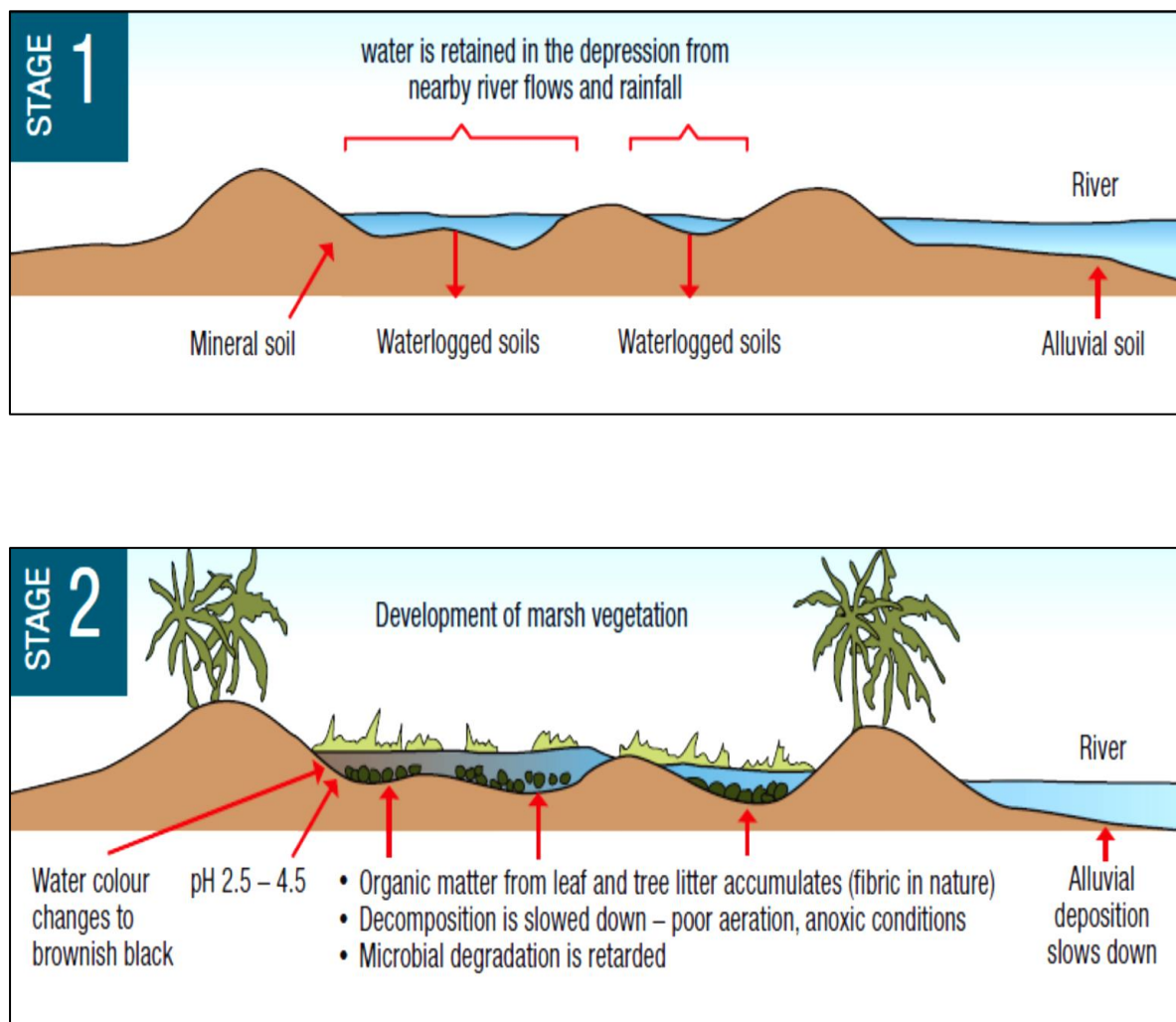
Figure 1.1: Distribution of lowland peatlands in Malaysia (DOA Malaysia, 2002).

Table 1.1: The area of peatland in Malaysia according to states (Zainorabidin & Wijeyesekera, 2007).

State	Area (ha)
Sarawak	1,657,600
Johor	228,960
Pahang	219,561
Selangor	194,300
Perak	107,500
Terengganu	81,245
Sabah	86,000
Kelantan	7,400
Negeri Sembilan	6,300
Total	2,588,866

2.4 Formation of tropical peat

Peat is formed under the conditions of constant water logging with abundant organic matter fed from the vegetation of mangroves, grasses, and swampy forest. The saturated and anaerobic conditions greatly reduce the rate of decomposition (Gao et al., 2016). Figure 1.2 shows the formation processes of peat. The large basin swamps in dome shape with organic soil deposited in the central portion is generally known as ‘ombrogenous peat’. It is typically found near the river or coastal area. The surrounding fringes of the peat dome is predominated by ‘topogenous peat’ which comprises mainly of slight to moderately decomposed plant matter and fine clastic sediments (Murtedza et al., 2002).



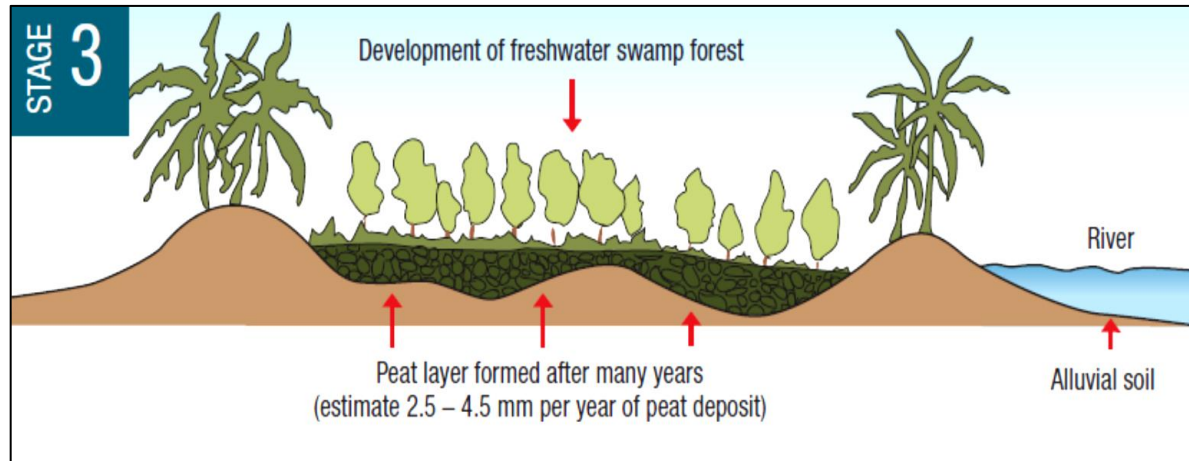


Figure 1.2: The formation of peat (United Nations Development Programme, 2006).

Tropical peat is generally heterogeneous consisting of partially decomposed woody materials of the pre-existing forest. Well preserved tree trunks, branches and coarse roots are mostly found within a matrix of dark brown amorphous organic material (Page et al., 2006). Tropical peats are different from temperate peats; temperate peatlands are mainly covered by sedges and moss, whereas tropical peatland in low-elevation areas are covered by forests. The tropical climate which is typically high in rainfall and temperature further differentiates the lowland peats from the temperate-boreal (Zinck, 2011).

2.5 Classification of peat in Malaysia

Peat soil is classified with different systems in Peninsular Malaysia, Sarawak and Sabah. In Peninsular Malaysia and Sarawak, peat soils are classified based on the USDA soil taxonomy with some criteria adapted according to local conditions while in Sabah, FAO/UNESCO Legend (1990) of soil classification is applied (Paramanathan, 2010).

Standardization of the soil classification systems in these three regions have been quite challenging due to the deviations in definitions and classifications.

The Department of Agriculture (DOA) Malaysia in collaboration with Sarawak Tropical Peat Research Laboratory Unit has developed a Malaysian Unified Classification System (2014) - a modified version of soil taxonomy to standardize the soil classification in the three regions. This classification system categorizes the different types of peat based on the wood content and peat depth (Tables 1.2 and Table 1.3) (Melling, 2016).

According to Paramanathan, (2014) before the Malaysia Unified Classification System is established, the tropical peat depth was classified by three depths which is shallow peat, medium deep and deep peats. Meanwhile in Sarawak, there are only two classes: the shallow peat (50-100 cm) and deep peat (> 150 cm) (Paramanathan, 2008).

Table 1.2: Soil classification based on the wood content (Melling, 2016).

Wood content			
Degree of woodiness		Size of wood	
Terminology	Wood volume (%)	Terminology	Wood diameter (cm)
Few	0-5	Fiber	<2
Common	>5-15	Small	2-5
Many	>15-35	Medium	5-10
Abundant	>35	Large	10-15
		Very large	>15

Table 1.3: Soil classification based on depth (Melling, 2016).

Peat depth	
Organic soil material depth (cm)	Terminology
< 50	Peaty phase
50-100	Very shallow
>100-200	Shallow
>200-300	Moderately deep
>300	Deep

2.6 Exploitation of peat for agriculture

Most of the peatland in Malaysia has been exploited for agriculture; the major crops cultivated on peat soil is sago palm and oil palm because of their ability to survive under low pH and water-logged environment. The oil palm and sago palm are the largest agriculture profits in Sarawak (Jamaludin, 2002). The peat swamp is drained to encourage decomposition enhancing broken-down of organic materials. This process will lead to the formation of sapric and hemic layers. Drainage of peatland is necessary for agricultural purpose to attain the sapric-hemic-fibric morphology (Veloo, 2015a). This is because sapric and hemic layers could serve as a rooting medium for anchorage where this is normally absent in fibric materials.

Despite the presence of sapric and hemic layers, many of the drained peat areas continue to encounter serious issues relating to the use of agricultural machinery. The peat soil is

naturally low in bulk density where compaction cannot be carried out (Batey & Mckenzie, 2006). The acidic peat can be neutralized by liming or empty fruit bunch ash. Peat soils are not comparable to mineral soils; the latter is highly suitable for a wide range of crops especially those with shallow rooting and fibrous roots system (Radjagukguk, 2004). Table 1.4 summarizes the suitability of peat soils for various crops according to depth.

Table 1.4: Suitability of the various crops on peat soil of various thicknesses (Radjagukguk, 2004).

Crops	0 -100 cm	100 – 200 cm	> 200 cm
Wetland rice	Moderate	Low	-
Upland food crops (rice, soybean, corn, peanut)	High	Moderate	Low
Horticulture (Chinese cabbage, papaya, pineapple, rambutan, garlic)	High	High	High
Estate (sago palm, oil palm, cacao, coffee, rubber)	High	Moderate	Moderate
Industrial (rami, medicinal, etc.)	High	Moderate	Moderate

The humification degree of peat can be measured based on physical, chemical as well as the characteristics of organic compounds present, often known as humic substances.

2.7 Physical characteristics of peat

Peat is identifiable by its colour, humification, loss-on-ignition, bulk density, porosity, water holding capacity and hydrology characteristics (Murtedza et al., 2002). It is generally reddish brown to very dark brown in colour depending on the stage of

decomposition (Melling, 2000). More decomposed hemic peat is generally darker than the underlying less decomposed (fibric) peat which is characterized with very raw and woody materials i.e., tree trunks, branches and roots. Generally, peat has moisture content and water holding capacity of 15-30 times greater than their dry weight; this leads to high buoyancy and pore volume with low bulk density and bearing. A higher organic content in peat soil can causes the ash content to be less than 10% (Larney et al., 2004).

According to Katimon and Melling (2007), sapric materials at the surface normally have a bulk density of slightly more than 0.1 g/cc even the soil has very low ash content. On the contrary, the bulk density of hemic and fibric materials is generally less than 0.1 g/cc. Organic soil materials with high ash content can have bulk density up to 0.2 g/cc or more. Thus, the ash content and degree of decomposition are very important factors determining the bulk density of peat.

2.8 Chemical characteristics of peat

The lowland peat in Malaysia is characterized by low pH of 3.0-4.0. Shallow peat tends to have a slightly lower pH than the deeper peat. This is due to the thickness of the organic horizon, the nature of the subsoil and the frequency of flooding (Saint-Laurent et al., 2016). The thicker is the organic horizon, the more improvise are the surface layer and if the soil is regularly flooded, it will have higher amount of mineral contents and it enhances the fertility of the peat.

The surface charges of soils are pH dependent; increasing in humification is generally associated with increase in cation exchange capacity (CEC) and decreasing in base saturation (Steven, 2000). Peat soils are strongly buffered however the high CEC is not due to the

presence of Na, K, Mg or Ca but the presence of exchangeable H^+ . The peat has very low number of exchangeable bases causing them to have low percentage of base saturation (Goulding, 2016).

The nitrogen (N) content of peat is rather high but its availability for plant uptake is low (Melling, 2000). According to Flowers (2003), the electrical conductivity values are generally less than 1 mmhos cm^{-1} and the micronutrients, particularly Cu and Zn, are very deficient. The surface layers of organic soils in Malaysia usually have more than 1% of total N but the C/N ratio is generally higher than 20 and a high C/N ratio coupled with low pH would result in low mineralization in peat (Chapin et al., 2003).

2.9 Humic substances

Humic substances (HS) are found in significant quantities in the aquatic and soil environment of peat swamp. Fageria (2012) reported that humic substances are naturally part of the peat soils and it is generally categorized by the colour of the organic soil from brown to black. Figure 1.3 shows a structure of HS proposed by Stevenson (1994) (Joshi et al., 2014). HS are categorized into humin, humic acids (HA) and fulvic acids (FA) according to solubility in acid (Table 1.5) (Tan, 2003). HA are complex organic molecules with high molecular weight ranging from approximately 5,000-100,000 Daltons (Asing et al., 2009). The formation of humic acid and humins predominates under aerobic conditions; conversely under the anaerobic conditions, fulvic acid with lower molecular weight is more pronounced.

Table 1.5: Fraction of humic substances and their characteristics (Tan, 2003).

Fraction	Solubility	Colour
Humin	Not soluble in water at any pH and cannot be extracted with a strong base, such as sodium hydroxide (NaOH).	Black
Humic acid	Soluble in water when the conditions more acid than pH 2.	Dark brown to Black
Fulvic acid	Soluble in water under all pH conditions.	Light yellow to Yellow-brown

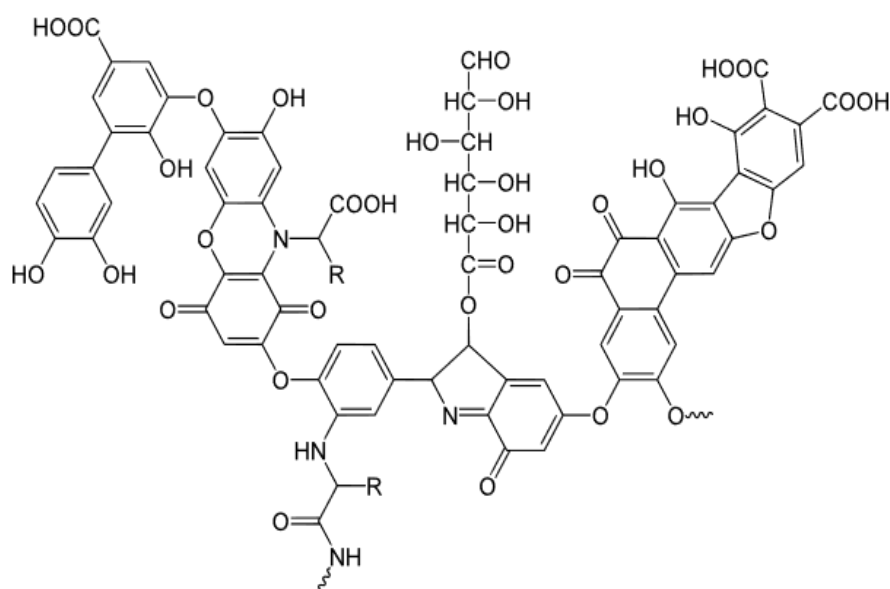


Figure 1.3: Chemical structure of humic substances proposed by Stevenson (1994) (Joshi et al., 2014).

The organic component of soil, peat and natural waters are mostly HS and they influence the formation of fossil fuels contributing to the global carbon (C) geochemical cycle. Peat soils can store up to ca. 450 Gigatonne (Gt) of C, where more than half of the C is in the atmosphere (750 Gt). However, the importance of peatland in global C cycles and climate regulation such as their capacity to maintain a record of environmental change is often overlooked, (Page, 2016).

HS correspondingly improves the soil fertility through the humification process. Humification can be defined as the transformation of numerous substances and individual molecules present in living organic matter into groups of substances with similar properties (humus) (Francioso et al., 2003). The soil mechanism and properties are improved in the presence of humus as it supplies macro and micronutrients, reduces soil toxicity through heavy metal complexation, enhances physical and chemical characteristics of soils and prevents nutrient loss (Lakzayi et al., 2015). Besides, they interact with the cellular metabolism of plants, facilitating the absorption of nutrients and solubilization of complexes (Canellas & Olivares, 2014). Thus, the role of HS in improving agricultural soil is well established, especially in soil with low organic matter content (Pettiet, 2002). Numerous studies have evidenced the beneficial effects of HS on crops such as barley, corn and blackberry (Venegas González et al., 2013). Therefore, HS in peat soil is crucial substances to enhance the nutrient availability.

2.10 Extraction and fractionation of humic substances

HS is the important indicator to determine the soil fertility. HA and FA are classically extracted using the alkaline extraction method. The acidification of the alkaline extract would lead to precipitation of HA leaving FA fraction in the solution (Benites et al., 2003). Although the method is effective, the alkaline extractants may partially hydrolyzed or self-oxidize the organic matter (Kurniati et al., 2017).

The alkaline extractants method has been criticized by Bremner (1950) as it may have modified the nature of HA (Saito & Seckler, 2014). Nonetheless, Young et al. (2004) indicated that there is no chemical shift in the chemical structures and characteristics of soil organic matter after extraction with diluted alkali under N₂ at room temperature. Extraction

with 0.1 N NaOH yielded higher organic matter than that obtained at higher concentrations. At 0.05 N NaOH, organic matter with low ash content is extracted. When $\text{Na}_4\text{P}_2\text{O}_7$ is used as the extractant, it is practically impossible to remove the phosphate from the extracted organic matter, and this would cause problem to the subsequent characterizations (Mikkuta et al., 2005).

The usage of N_2 gas in the extraction procedure is modified by Tan et al. (2005); the N_2 gas was substituted with air. It is apparent that if the use N_2 can be omitted, this not only will speed up the extraction process but also considerably simplified the procedure. Using the topsoil of subtropical Ultisols and Alfisols, Tan et al. (2005) found no evidence of differences in amount and elemental compositions of HA extracted under ambient air and N_2 (Table 1.6). On the other hand, the total acidity showed higher values for HA extracted under N_2 atmosphere than that under ambient air. The latter was accompanied by correspondingly higher phenolic OH and COOH concentrations.

Table 1.6: Humic acid contents and their elemental compositions extracted under air and N_2 gas atmosphere (Tan et al., 2005).

Origin	HA	C	H	O	N	S	Total acidity	COOH	Phenolic- OH
	(mg/g)			(g/100g)				(meq/g)	
Cecil- Air	5.7	52	5.2	39	4.1	0.4	4.5	3.9	0.7
Cecil- N_2	7.1	51	5.5	39	3.9	0.5	5.3	4.3	1.0
Onaway- Air	1.8	51	5.1	39	4.5	0.4	4.3	4.1	2.5
Onaway- N_2	1.3	51	5.1	39	4.9	0.5	4.9	6.3	2.2

The amount of extractable HA from HS and its chemical characteristics depend on several factors. These include the types of organic matter from which HA is extracted, temperature, grain size, frequency of extraction, the extracting agent and its strength and drying procedure (Asing et al. 2009). Several extraction methods of HA were reported (Tahir et al., 2007). It is difficult to compare the data obtained by researchers due to the differences in preparation methods. The inconsistency in preparation method has been an obstacle to the studies on HA.

2.11 Characterization of humic substances

1.11.1 Elemental composition

Carbon and oxygen are the main elements in HA with 50-60% and 30-35%, respectively. HA also contains 4-6% H, 2-6% N, and 0-2% S. The C/N ratio can be used as an index of humification (Borgmark, 2005). It is used as a measure of peat degradation by Silamikele et al. (2010). According to Martin et al. (2011), a decreasing C/N ratio indicates increasing peat decomposition and vice versa.

The H/C ratio is an index of molecular complexity. The molecular complexity is a molecular entity formed by loose association involving two or more component molecular entities (ionic or uncharged), or the corresponding chemical species (Piccolo et al., 2018). The O/C ratio is an indicator of carbohydrate and carboxylic contents; it is directly related to aromatization of the organic matter. The O/C ratio decreases with depth however, in layers with higher decomposition degree, the values of this indicator may be high. Kalvins et al. (2008) reported that the atomic ratio O/C, H/C, and N/C indices are useful in the identification of structural changes and the degree of maturity of peat in different

depositional environments. Typically, the range elemental compositions for peat soil are 40-59% C, 3-5% H, 1-5% N, 30-48% O and 0.4-1% S (Zaccone et al., 2007).

1.11.2 Ultraviolet-visible (UV-Vis) properties

In acid, neutral and alkaline aqueous solutions, HA yields an uncharacteristic spectrum in UV and visible region (Khan et al., 2014). The absorbance reduces as the wavelength increases. Despite the featureless spectrum pattern, the ratio of absorbance at 465 nm and 665 nm (E_4/E_6) has been widely used for characterization of HA. It describes the extent of condensation of the aromatic C-containing structures: a low ratio reflects high degrees of condensation of aromatic while a high ratio indicates the presence of large quantities of aliphatic structures (Weishaar et al., 2003). The range of E_4/E_6 reported for HA and FA were 2.4-9.5 and 1.9-22.0, respectively for water and soil (Sim & Murtedza, 2007). The magnitude of the E_4/E_6 is inversely related to the molecular size and it has been used as an indicator of humification. A high E_4/E_6 value reflects prominent aliphatic structures suggesting a lower degree of humification while a low E_4/E_6 values indicates the dominance of aromatic constituent demonstrating a higher humification degree (Zhang et al., 2015).

1.11.3 Fourier Transform Infrared

Fourier Transform Infrared (FTIR) has been commonly used to get an insight in the structure of HS to relate to the humification degree. During the humification process the chemical compositions (protein, carbohydrate, lipids, etc. and individual molecules) present in living organic matter are transformed into group of substances with similar properties (humic substances). The degradation of chemical compositions in soil organic matter was distinguished by the disappearance and formation of the new band in the soil organic matter

spectra. The presence of an O-containing functional groups, such as -COOH, -OH, -OCH₃ and -C=O (Canellas et al., 2002) as well as the occurrence of aliphatic C-H in the infrared spectra offer evidenced of more humified characteristics of HS (Margenot et al., 2015). The analysis of humic substances by FTIR spectroscopy reveals that fulvic acids (FA) consist mainly of polysaccharides, while the humins are generally composed of modified lignin. This distribution varies little as a function of soil management and environmental conditions. Since the C distribution in the functional groups in humic acids is altered significantly, this variation can be used for the evaluation of the process of soil organic matter humification (Canellas et al., 2002).

According to Utami & Suswati (2016), the most typical band reported for peat soils is the C-H vibration band of aliphatic methyl and methylene groups (2920 and 2850 cm⁻¹). The bands in the region of 1600-1650 cm⁻¹ and 1707-1710 cm⁻¹ are assigned to C=O vibrations of aromatic and carboxylates, respectively. The band at 1370 cm⁻¹ represents C-H and N-H (amide II) bending motions whilst the peak at 1510 cm⁻¹ is assigned to both amide II and aromatic C=C vibrations. The bands between 1080 and 1030 cm⁻¹ are characteristics of C-O stretching and O-H deformation, indicative of polysaccharides. The functional group characteristics can be used to distinguish HS of diverse origins and to evaluate the effects of different extractants, chemical modification, and formation of derivatives.

CHAPTER 2

MATERIALS AND METHODS

2.1 Study sites

The sago palm plantation studied was located in Sungai Talau Sago Research Station, Mukah, Sarawak whilst the oil palm plantation was in Bintulu at the estate of Sarawak Oil Palms Berhad (SOP).

2.2 Sampling (Sago Plantation)

At sago plantation, the peat soil samples were collected from two plots: the cultivated (N 02°49'08.8" E111°54'51.0") and the uncultivated plots (N 02°49'23.6" E111°55'15.1") as shown in Figure 2.1. The station is characterized with varying thickness of peat ranging from less than 1 m to more than 6 m.



Figure 2.1: The sampling plots in Sungai Talau Research Centre.

The soil samples were collected from the area with 5–6 m of peat at the cultivated plot, planted with nine-year-old sago palms. The palm growth was observably inconsistent; some palms were found to grow to expected trunk size whilst some were not. The palms that grow well are referred to as the trunking palms whilst those poor growing palms are called the non-trunking palms (Figure 2.2). The trunking palms sampled were characterised with diameters at breast height ranged from 45 to 57 cm, whilst no trunk formation was observed in the non-trunking palms. For comparison, the peat soil samples were also collected from an uncultivated plot as a control. The control plot was left undisturbed for five years from cultivation activities. Note that the water table was maintained at 20–40 cm below the ground surface in both plots.



Figure 2.2: Photographs of non-trunking (left) and trunking (right) sago palms.

The peat soil was collected under the canopies of seven trunking and seven non-trunking palms. The soil was cored to a depth of 1 m using an Eijkelkamp gouge auger and cut into five depth at an interval of 20 cm. The sample was stored in ziplock bags and transported to the laboratory.

2.3 Sampling (oil palm plantation and forest)

The soil samples were collected from a 1 ha plot in Sebungan Oil Palm Estate (N 03°09'58.32" E 113°21'15.43") and Sabaju 4 Forest (N 03°09'58.32" E 113°24'21.32"), as shown in Figure 2.3. The peat soil at the estate has a depth from 1 m to more than 3 m, whereas the forest was a secondary forest (the peat depth is uncharacterized).

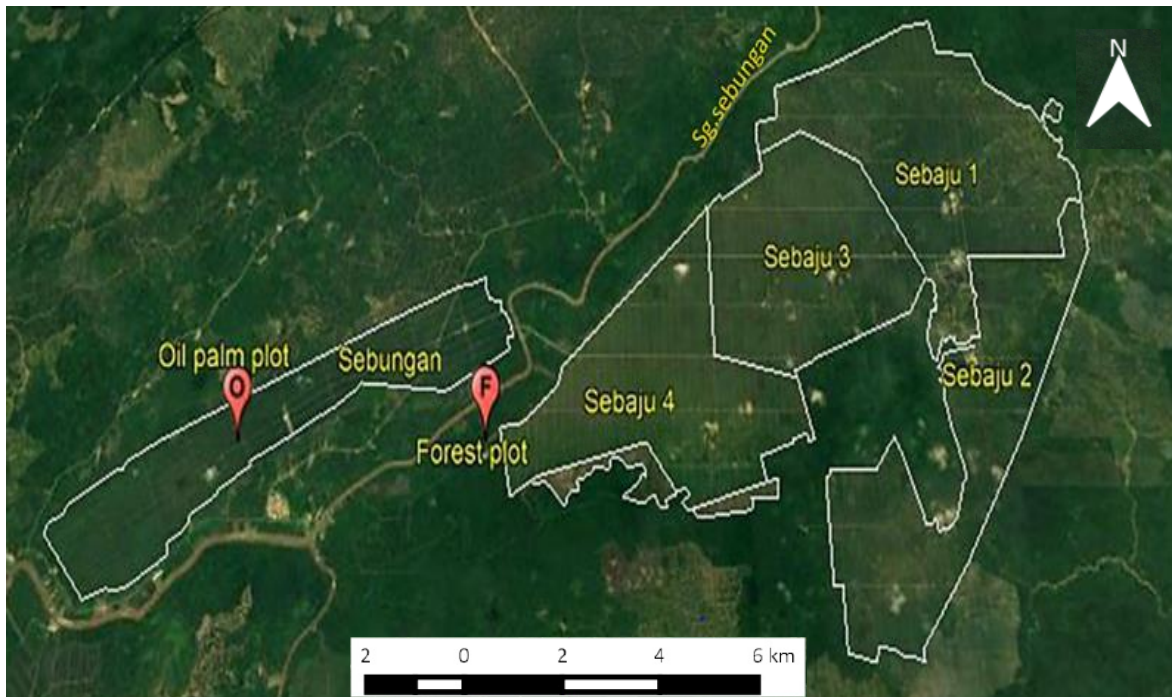


Figure 2.3: The sampling plot in Sebungan Estate and Sabaju Forest.

The soil samples were randomly collected at the area under the palm canopies. The samples were taken from the surface 0-15 cm and core to 1 m and 3 m using an Eijkelkamp gouge auger with extension rod (core diameter 52 mm, length 0.5 m). The samples were removed from the auger and placed in ziplock bags with gloved hands. The samples were labelled as '0-15 cm', '1 m', '2 m' and '3 m'. For comparisons, the samples were collected in the same way from Sabaju 4 Forest which is a reserved forest. In Sebungan Estate and Sabaju Forest, the plot size was 100 m × 100 m consisting 25 subplots, each with a dimension

of 20 m × 20 m. The water table was maintained at 30-40 cm below the surface in Sebungun Estate whilst the water table in Sebaju Forest was unregulated.

2.4 Sample preparation

The soil samples from sago plantation were oven dried at 30 °C overnight. The samples from oil palm plantation however were air-dried at the site due to logistic constraints as the sampling took one and a half month to cover the area intended. The soil was ground into fine particles with mortar and pestle and sieved through 2 mm sieve. The samples from sago and oil palm plantations were subjected to the analyses including pH, electrical conductivity, exchangeable bases, cation exchange capacity, organic matter content, humification index and functional groups characterization. For the oil palm estate and forest, carbon dioxide emission was measured in addition.

2.5 Soil pH and electric conductivity

The pH and conductivity were measured using the pH and conductivity meter (EXTECH D0610: ExStik II, Massachusetts, USA) in a soil to water suspension of 1:5 (McLean, 1982). Eight gram of soil samples were weighed into a polyethylene bottle and added with 40 mL of deionised water, stoppered and left overnight before the measurement was recorded. The probe was rinsed after each determination and the meter was calibrated with buffer solution pH 4,7,and 10 before use. The measurements were taken in triplicates. The detection limit for the pH is 0 to 14 while the salinity or conductivity is 156.25 to 1560.93 μS .

2.6 Exchangeable bases and cation exchange capacity (CEC)

Two grams of soil ($\leq 2\text{mm}$) were weighed in a 100 mL Erlenmeyer flask and added with 40 mL of 1 M NH_4OAc . The sample was left overnight and filtered through a $0.45\ \mu\text{m}$ membrane filter. This process was repeated four times with 25 mL of 1 M NH_4OAc ($\text{C}_2\text{H}_7\text{NO}_2$). The leachate was transferred into a 250 mL volumetric flask and made up to mark with deionized water. The filtrate was analysed for exchangeable bases (Ca, Mg, Na and K) using the Inductively Coupled Plasma Optical Emission Spectrophotometer (ICP-OES) (Perkin Elmer, Optima 800, Massachusetts, USA).

The ICP-OES were calibrated with the blank and standard from 0.1, 0.5, 1.0 and 2.0 ppm. The detection limit for the Ca (0.05 mg/L), Mg (0.04 mg/L), Na (0.5 mg/L) and K (0.005 mg/L). All optima ICP-OES detection limit was obtained under simultaneous multi-element conditions with the axial view of a dual-view plasma using a cyclonic spray chamber and a concentric nebulizer.

For determination of CEC, excess NH_4OAc in soil was leached with 150 mL ethanol to wash away all the electrolytes and the leachate was discarded. The soil sample was then leached with 250 mL of 10% acidified NaCl. The leachate was transferred to 800 mL Kjeldahl flask and added with 25 mL of 1 M NaOH. A 60 mL of the solution was distilled into 50 mL of 2% boric acid. The solution was titrated with 0.1 M HCl to determine the adsorbed NH_4^+ in the presence of bromocresol green – methyl red as the indicator.

At the end point, the color changed from bluish green to pink. Blank samples were analysed on each run. The titration figure was corrected with the blanks and CEC were calculated in the unit of cmol_c/kg or $\text{meq}/100$ ($1\ \text{meq}/100\ \text{g} = 1\ \text{cmol}_c/\text{kg}$). The exchangeable bases and CEC were calculated according to Malaysian Standard, (1980).

1. CEC (NH_4^+) equation for titration method in cmol.kg^{-1} soil is:

$$\text{CEC} = \frac{(\text{Sample} - \text{Blank titre}) \times \text{molarity of HCl} \times 100}{\text{Weight of soil taken (g)}} \quad \text{Equation 2.1}$$

2. Exchangeable base equation:

$$\text{Cmol. kg}^{-1} = \frac{s \times V}{m \times j \times 10^3} \times 100 \quad \text{Equation 2.2}$$

3. Calculate percent base saturation as follows:

$$\% \text{ Base saturation} = \frac{(\text{Ca} + \text{Mg} + \text{K} + \text{Na})}{\text{CEC}} \times 100 \quad \text{Equation 2.3}$$

Where:

s = Concentration of cation (mg/L)

V = Volume of leachate samples (mL)

m = Weight of soil sample (g)

j = Molar mass of the element (g.mol^{-1})

2.7 Ash content

The ash matter content was determined according to the loss-on-ignition (LOI) method by Agus et al. (2011). The peat soil sample were dried in an oven at 100 °C overnight to eliminate moisture in the sample. One gram of peat soil was weighed into a crucible and combusted in a furnace (Biobase, MC4-10, China) at 550 °C temperature for 6 hours. The sample was then left to cool in a desiccator and the sample was weighed. The loss of weight indicates the amount of total organic matters in the samples. The ash content is calculated according to the following equation.

$$\text{Ash content} = \frac{(A - B)}{A} \times 100\% \quad \text{Equation 2.4}$$

where:

A = Initial weight of crucible + soil

B = Final weight of crucible + soil

2.8 Bulk Density and Moisture content

The weigh balance been used have three decimal places. The bulk density and moisture content of the soil was calculated by using the formula below:

$$\text{Bulk density} = \frac{\text{Mass of dry soil (g)}}{\text{Volume of soil (100 cm}^3\text{)}} \quad \text{Equation 2.5}$$

$$\text{Moisture content} = \frac{W_1 - W_2}{W_1} \times 100 \quad \text{Equation 2.6}$$

Where:

W_1 = Weight of wet soil samples (g)

W_2 = Weight of dry soil samples (g)

2.9 Humification index

The humification index was determined using the UV-Vis spectrophotometer, with modified method from Khan et al., (2006). A 0.5 gram of peat soil was added with 60 mL of 0.5% NaOH and centrifuged at 3600 rpm for 15 minutes. The supernatant was transferred into a 50 mL beaker and acidified with 0.6 M of concentrated HCl until pH 1. The solution was left to stand for one hour for the humic acid fraction to precipitate. The solution was then centrifuged at 4000 rpm for 15 minutes. The supernatant was discarded; the precipitate was washed with distilled water and centrifuged for 5 minutes. The humic fraction was dissolved in 5 mL of 0.1 M NaOH and the solution was brought to mark in a 100 mL volumetric flask. The absorbance at E_{465} and E_{665} nm was recorded using a UV-Vis spectrophotometer (Shimadzu, UV-1800, Tokyo, Japan). The humification index was measured based on E_{465}/E_{665} ratio, often referred to as E_4/E_6 . The Uv-Vis spectrophotometer range are from 190 nm to 1100 nm, concentrated solution or sample will produce high noise in the wavelength. Hence, the sample must be diluted with particular concentration in order the light to pass through the sample. To ensure the stability of the instrument blank was run every 10-12 samples.

2.10 Functional group characterization

The soil samples were analysed using an Attenuated Total Reflectance-FTIR (ATR-FTIR) equipped with diamond crystal, controlled by OMNIC software (Thermo Nicolet Analytical Instruments, Madison, Wisconsin). A flat tip powder press was used to achieve even distribution and contact. All spectra were collected at 32 scans with a resolution of 4 cm^{-1} in the range 4000–670 cm^{-1} . The spectrum of each sample was ratioed against a fresh background spectrum recorded from the bare ATR crystal. The ATR crystal was cleaned with ethanol and the samples were scanned in triplicates. The wavelength range of ATR-FTIR detection is 525–4000 cm^{-1} and the noise level are maintained between the range 0.0–0.12 cm. ASTM E-1421 was performed for the standard calibration of ATR-FTIR.

2.11 Elemental analysis

The carbon and nitrogen content were measured using an CN elemental analyzer (LECO, Michigan, USA), controlled by the software of TruMac. The samples were heated at 60 °C for 24 hours prior to analysis with the elemental analyzer. A TruMac can be calibrated using several replicates of a single mass range (nominal 0.50 g) of Ethylenediaminetetraacetic acid (EDTA) utilizing a single standard calibration. The calibration can be verified by analyzing different compounds such as phenylalanine (0.25 g), nicotinic acid (0.15 g) or other reference materials with a similar matrix to the samples being analyzed. The blank was determined by entering 1.0000 g mass into sample login using Blank as the sample name. Then the boat crucible is placed to the appropriate position of the autoloader. Repeat the step minimum of three times. Initiate the analysis sequence and set the blank following the procedure outline in the operator's instruction manual.

2.12 Carbon dioxide emission

The carbon dioxide (CO₂) emission was measured using EGM-4 Infra-Red Gas Analyzer (IRGA) (PP system, Massachusetts, USA), provided by Malaysia Palm Oil Board (MPOB). The detection limit for the carbon dioxide measurement is 0-100,000 ppm. However, EGM4 IRGA cannot read the carbon dioxide gas when it less than 250 ppm. The machine will automatically do the calibration for carbon dioxide measurement.

Two PVC collar of approximately 10 cm in length were installed at each subplot in Sebungun Estate and Sebau Forest (25 subplots in total for both plots, respectively) yielding a total of 100 collars. Before the collar's insertion, any vegetation and litter were removed to improve the chamber insertion into the ground and minimize the influence of litter decomposition and root respiration on the measure gas (Hergoualc'h & Verchot, 2013). Five centimeters of PVC collar was gently hammered into the ground at each subplot. The collar was labelled and left for a week before been measured, to reduce the carbon dioxide gas disturbance in the soil. The CO₂ emission was only been measured for one-month. At each measurement, the height of the collar as well as the soil moisture, soil temperature and air temperature were recorded. The carbon dioxide emission was calculated according to the following equation.

1. Raw carbon dioxide measurement equation:

$$R_{uc} = \frac{C_f - C_i}{t_f - t_i} \times \frac{p}{(T_a + 273.15)} \times \frac{V_d}{A} \times \frac{44.01 \times 0.36}{R_u} \text{ g CO}_2 \text{ m}^{-2} \text{ h}^{-1} \quad \text{Equation 2.7}$$

2. Corrected carbon dioxide measurement equation:

$$R_C = R_{uc} \times \frac{V_d + V_{added}}{V_d} \text{ g CO}_2 \text{ m}^{-2} \text{ h}^{-1} \quad \text{Equation 2.8}$$

3. Volume of collar:

$$V_{\text{added}} (\text{Cm}^3) = 3.1416 \times \left(\frac{d_{\text{Collar}}}{2} \right)^2 \times h \quad \text{Equation 2.9}$$

Where the following defined terms apply:

R_{uc} is uncorrected CO₂ efflux (g CO₂ m⁻² h⁻¹)

R_{c} is corrected CO₂ efflux (g CO₂ m⁻² h⁻¹)

t_{f} and t_{i} are the final and initial times (sec)

C_{f} and C_{i} are the final and initial CO₂ Concentrations (ppmv)

P is ambient pressure at time t_{i}

T_{a} is air temperature at t_{f} (°C)

V_{d} is the SRC-1 chamber volume which is 0.0012287m³.

A is the area exposed soil which the SRC+ collar have been placed.

R_{u} is the universal Gas constant which is 8.31432 J mol⁻¹K⁻¹

2.13 Statistical analysis

One-way analysis of variance (ANOVA) was used to test the significant difference among means of different sample groups at a confidence level of 95%. Tukey's test was applied for multiple comparisons. Pearson's correlation and linear regression were applied to determine the relationships between the degree of humification and carbon dioxide emission.

CHAPTER 3

HUMIFICATION DEGREE UNDER SAGO PALM PLANTATION

3.1 Introduction

The rapidly changing status of one of the world's most prominent terrestrial carbon-stored ecosystem, which is tropical peatlands has attracted greater attention. The peatland has been reported to have a lower soil fertility and by converting the peatland to the large scale of agriculture activities causes a changing of climates (Page et al., 2004 : Paramananthan, 2014). An intensive research has been done in previous studies to discovery whether this agriculture is sustainable. This can be seen when the production and performance of sago palm at the peat soil is lower compared to the mineral soil (Sim et al., 2005). The aim of this study is to determine the humification degree in the soil profile of sago palm plantation located in Sungai Talau Sago Research Station, Mukah, Sarawak. Refer to the chapter 2 for the methodologies.

3.2 Results and Discussion

3.2.1 pH

The physicochemical properties of soil are summarized in Table 3.1 and Table 3.2. The mean pH of soil at sago palm plantation was found in the range of 2.8 to 4.8. The results indicate acidic environment which is typical to the lowland organic soils in Malaysia. The pH tends to be lower as the depth increases (Könönen et al., 2015). The pH was noticeably reduced with increasing depth nevertheless, no significant different was deduced between

control, trunking and non-trunking plots ($p > 0.05$). According to Putra et al. (2016), the increasing soil pH was affected by the high content of humic acids; the humic acids possess negative charges that act as a buffer to prevent the soil from becoming more acidic. The higher pH of surface peat at cultivated and uncultivated plots suggest that the soil is more humified. The water table is regulated at 20-40 cm exposing the surface peat. For this reason, the decomposition process is expected to accelerate at the surface forming more humified materials. The declining pH at 40-100 cm samples indirectly indicate that the underlying peat may be less humified. The slower decomposition under anaerobic condition for deeper peat would produce carbonic acid lowering the pH.

3.2.2 Moisture content

From Table 3.1, the moisture content of peat soil from cultivated and uncultivated plots are comparable. The range of moisture was found between 76.94% and 88.42% with no significant different between both plots ($p > 0.05$). Nevertheless, the moisture content of the peat soil at trunking plot was higher than that attained at the control and non-trunking sites. According to Larionova et al. (2015), a negative correlation was established between moisture content and degree of humification. Putra et al. (2016) further suggests that a lower moisture content could encourage the formation of clay fraction fostering humification.

3.2.3 Ash content

The range of ash content was between 0.65% and 3.60%. The ash content in tropical peat is typically less than 10%. Statistically, no significant different was identified in the ash content of cultivated and uncultivated peat. The results showed that peat soil of upper

horizon contained higher ash than that at the greater depth. This is likely due to the accumulation of organic matters at the lower depth and it also signifies the greater extent of humification at the surface peat (Zhenghu et al., 2007).

3.2.4 Elemental analysis

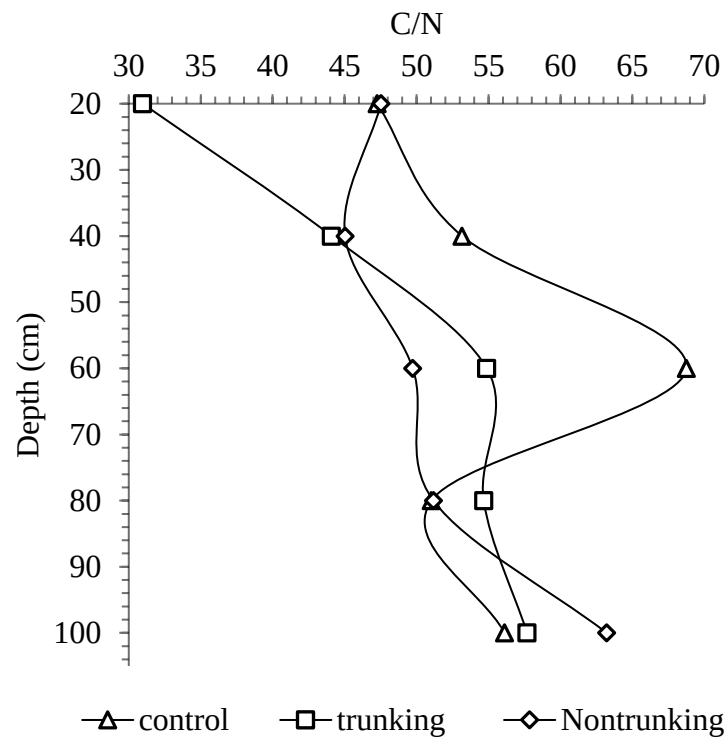


Figure 3.1: The C/N ratio according to peat depth and origin plot demonstrates lower C/N ratio than the control and non-trunking plots.

The carbon-to-nitrogen ratio (C/N) showed a considerable variation from a minimum of 30.96% to a maximum of 68.76%. There is no significant different between the C/N ratio of the cultivated peat with the control (uncultivated) ($p > 0.05$). However, the result shown the trunking has a lowest C/N ratio compared to the control and non-trunking plot.

Figure 3.1 depicts the C/N ratio according to depth and peat origin. The variation in C/N ratio indicates the heterogeneity of humification degree. The profile illustrates an

overall increase in C/N ratio as the depth increases with the surface peat from trunking plot exhibiting the lowest ratio. According to Martin et al., (2011), a lower C/N ratio is an indication of higher degree of humification. This suggests that the surface peat is generally more humified than the horizon peat corroborating the inference deduced based on pH, moisture and ash content. The C/N ratio is also an indicator of soil fertility, corresponding to the nitrogen deposition in soil. The lower C/N ratio suggests a greater mobile nitrogen reserve implying greater fertility. This means the surface peat is likely more fertile than the underlying peat. Continues supplies of new leaves at the trunking plot surfaces soil, accumulate the organic matter and higher N-enrich litterfalls lead to higher nitrogen fixation in the soil (Li et al., 2008). A higher nitrogen reserved in trunking plot increased the nitrate uptake for the sago palm.

Table 3.1: Physiochemical characteristics of peat soil at the sago palm plantation. Data represent mean $\pm$ SD.

Depth (cm)	Sample Origin	Moist. (%)	pH	EC (μ S/cm)	ash content (%)	C/N (%)
20	Control	81.00 $\pm$ 0.54	4.00 $\pm$ 0.01	460.00 $\pm$ 0.10	3.23 $\pm$ 0.01	47.27 $\pm$ 1.56
	Trunking	82.72 $\pm$ 0.09	4.80 $\pm$ 0.01	480.00 $\pm$ 0.00	3.60 $\pm$ 0.00	30.96 $\pm$ 0.92
	Non-Trunking	76.94 $\pm$ 0.25	3.80 $\pm$ 0.01	350.00 $\pm$ 0.00	3.21 $\pm$ 0.01	47.54 $\pm$ 0.30
40	Control	76.90 $\pm$ 0.69	3.21 $\pm$ 0.02	390.00 $\pm$ 0.17	2.46 $\pm$ 0.01	55.13 $\pm$ 1.31
	Trunking	85.50 $\pm$ 0.29	3.50 $\pm$ 0.00	400.04 $\pm$ 0.06	3.00 $\pm$ 0.02	44.09 $\pm$ 0.43
	Non-Trunking	79.54 $\pm$ 0.05	3.37 $\pm$ 0.01	230.00 $\pm$ 0.10	1.92 $\pm$ 0.07	45.03 $\pm$ 0.31
60	Control	84.73 $\pm$ 1.08	3.14 $\pm$ 0.01	220.03 $\pm$ 0.17	1.39 $\pm$ 0.01	68.76 $\pm$ 3.11
	Trunking	82.37 $\pm$ 0.22	3.86 $\pm$ 0.02	310.00 $\pm$ 0.00	2.29 $\pm$ 0.01	54.88 $\pm$ 0.15
	Non-Trunking	82.62 $\pm$ 0.03	3.00 $\pm$ 0.02	190.03 $\pm$ 0.06	1.62 $\pm$ 0.03	49.74 $\pm$ 0.66
80	Control	80.46 $\pm$ 0.14	3.10 $\pm$ 0.02	390.00 $\pm$ 0.00	1.34 $\pm$ 0.01	51.03 $\pm$ 0.67
	Trunking	86.43 $\pm$ 0.45	3.60 $\pm$ 0.02	420.03 $\pm$ 0.15	1.49 $\pm$ 0.01	54.66 $\pm$ 0.82
	Non-Trunking	84.06 $\pm$ 0.02	2.80 $\pm$ 0.02	170.00 $\pm$ 0.00	1.01 $\pm$ 0.02	51.17 $\pm$ 1.45
100	Control	84.19 $\pm$ 0.95	3.12 $\pm$ 0.01	410.00 $\pm$ 0.35	0.80 $\pm$ 0.00	56.13 $\pm$ 0.82
	Trunking	88.42 $\pm$ 0.33	3.39 $\pm$ 0.01	420.00 $\pm$ 0.17	0.99 $\pm$ 0.01	57.68 $\pm$ 0.22
	Non-Trunking	85.85 $\pm$ 0.00	2.80 $\pm$ 0.01	120.00 $\pm$ 0.20	0.65 $\pm$ 0.04	63.22 $\pm$ 0.80

Notes: EC: electrical conductivity; Moist: Moisture Content; C: Carbon; N: Nitrogen.

Table 3.2: Cation exchange capacity and base saturation of cultivate and uncultivated. Data represent mean $\pm$ SD.

Depth (cm)	Sample Origin	CEC (cmol.kg ⁻¹)	Basic cations (cmol.kg ⁻¹)				Sum of bases	BS (%)
			Exch. Mg	Exch.Ca	Exch.Na	Exch.K		
20	Control	10.82 $\pm$ 0.89	1.37 $\pm$ 0.02	2.79 $\pm$ 0.09	0.88 $\pm$ 0.01	0.51 $\pm$ 0.22	5.56 $\pm$ 0.11	51.34 $\pm$ 4.70
	Trunking	9.96 $\pm$ 0.59	1.71 $\pm$ 0.07	1.64 $\pm$ 0.18	0.24 $\pm$ 0.02	0.24 $\pm$ 0.01	3.80 $\pm$ 0.19	38.44 $\pm$ 3.45
	Non-Trunking	13.91 $\pm$ 0.00	1.34 $\pm$ 0.05	1.22 $\pm$ 0.23	0.39 $\pm$ 0.01	0.17 $\pm$ 0.01	2.50 $\pm$ 0.09	18.01 $\pm$ 0.28
40	Control	16.65 $\pm$ 1.07	0.69 $\pm$ 0.27	0.28 $\pm$ 0.19	0.28 $\pm$ 0.07	0.18 $\pm$ 0.11	1.43 $\pm$ 0.46	8.63 $\pm$ 1.30
	Trunking	17.00 $\pm$ 0.10	1.55 $\pm$ 0.05	0.87 $\pm$ 0.02	0.29 $\pm$ 0.01	0.17 $\pm$ 0.01	2.87 $\pm$ 0.07	16.90 $\pm$ 0.47
	Non-Trunking	19.57 $\pm$ 0.89	1.15 $\pm$ 0.04	0.83 $\pm$ 0.07	0.40 $\pm$ 0.02	0.13 $\pm$ 0.01	2.09 $\pm$ 0.10	10.69 $\pm$ 0.57
60	Control	17.17 $\pm$ 1.57	0.80 $\pm$ 0.47	0.19 $\pm$ 0.13	0.42 $\pm$ 0.21	0.27 $\pm$ 0.28	1.67 $\pm$ 0.76	9.75 $\pm$ 2.17
	Trunking	12.53 $\pm$ 0.79	1.12 $\pm$ 0.03	0.42 $\pm$ 0.06	0.24 $\pm$ 0.01	0.11 $\pm$ 0.01	1.89 $\pm$ 0.07	15.06 $\pm$ 0.62
	Non-Trunking	21.29 $\pm$ 1.19	1.00 $\pm$ 0.21	0.56 $\pm$ 0.08	0.35 $\pm$ 0.08	0.10 $\pm$ 0.04	1.73 $\pm$ 0.31	8.14 $\pm$ 0.42
80	Control	19.57 $\pm$ 0.52	0.92 $\pm$ 0.16	0.14 $\pm$ 0.07	0.32 $\pm$ 0.11	0.30 $\pm$ 0.02	1.68 $\pm$ 0.25	8.58 $\pm$ 0.98
	Trunking	14.08 $\pm$ 0.79	1.26 $\pm$ 0.07	0.37 $\pm$ 0.02	0.31 $\pm$ 0.03	0.11 $\pm$ 0.02	2.05 $\pm$ 0.09	14.55 $\pm$ 0.42
	Non-Trunking	21.08 $\pm$ 0.30	0.87 $\pm$ 0.07	0.32 $\pm$ 0.02	0.32 $\pm$ 0.02	0.09 $\pm$ 0.02	1.44 $\pm$ 0.10	6.28 $\pm$ 0.35
100	Control	19.06 $\pm$ 0.52	1.55 $\pm$ 0.09	2.86 $\pm$ 0.36	0.19 $\pm$ 0.00	0.23 $\pm$ 0.01	4.82 $\pm$ 0.32	25.31 $\pm$ 1.40
	Trunking	19.06 $\pm$ 0.15	1.23 $\pm$ 0.02	1.22 $\pm$ 0.07	0.19 $\pm$ 0.03	0.19 $\pm$ 0.02	2.82 $\pm$ 0.03	14.82 $\pm$ 0.64
	Non-Trunking	22.66 $\pm$ 0.00	0.63 $\pm$ 0.02	3.64 $\pm$ 0.22	0.25 $\pm$ 0.01	0.83 $\pm$ 0.03	5.35 $\pm$ 0.16	23.60 $\pm$ 0.39

Notes: Mg: Magnesium; Ca: Calcium, Na: Sodium; K: Potassium; CEC: Cation Exchange Capacity; BS: Base Saturation (Sum of bases/CEC*100); Sum of Bases: Mg+Ca+K+N.

3.2.5 Electrical conductivity (EC)

Soil EC is an index used to delineate site-specific management zones; it is highly correlated to crop yield (Li et al., 2008). When organic substance decomposes, salts and ions in the soil profile and its liquid phase are increased. Such changes exert and influence the soil EC (Peralta & Costa, 2013).

The EC measurements represents the sum of salts and ions in the soil solution. The EC values range from 120.00 $\mu\text{S}/\text{cm}$ to 480.00 $\mu\text{S}/\text{cm}$ (Table 3.2). In order for the plant to grow well the salt content is recommended between 750 and 3490 $\mu\text{S}/\text{cm}$ (Carmo et al., 2016). Apparently, the EC values in both cultivated and uncultivated plots are below the critical range. An EC level below 1000 $\mu\text{S}/\text{cm}$ is typical to peat soil.

Statistically, there is a significant different between EC of trunking vs non-trunking and control vs non-trunking plots ($p < 0.05$). The results showed that the EC of trunking plot was higher than the control and non-trunking; the elevated EC corresponds with its higher pH. This indirectly suggests more humified fraction in trunking plot which in turn allows exchangeable ions to bind with the soil surface. The increasing of salt and positive charges in the soil will improve the nutrient availability which in turn improves soil fertility.

3.2.6 Cation Exchange Capacity (CEC), base saturation, sum of exchangeable cations

CEC determines the amount of nutrients the soil can hold and that is readily available to the plant. Based on Li et al. (2016), the CEC was positively correlated with the presence of humic acid in the soil. Soil humic substances can react with the inorganic matters to stabilize soil nutrient improving microbial activity and soil structures. Furthermore, the CEC is also influenced by the texture and density of soil as well as the pH value.

As shown in Table 3.2, the CEC ranges from 9.96 to 22.66 cmol.kg^{-1} with no significant difference between the cultivated and uncultivated plot. The CEC was observed to increase when moving downward to greater depth. The increase of CEC with depth was due to the lower pH (McCauley et al., 2017). The lower pH suggests a higher concentration of H^+ and lacking of organic matters. Correspondingly, the % BS was found in the range of 6.28 to 51.34 % with no significant difference ($p > 0.05$). A higher % BS value was determined at the surface peat of 20 cm. According to Yong et al. (2018), the base saturation decreases when the CEC increases due to the availability of H^+ ion at the soil surface. Thus, the lower CEC indicates an increasing humification in soil with higher % BS implying greater amount of essential plant nutrient cations of K^+ , Ca^{2+} , and Mg^{2+} (Steven, 2000). The higher % BS at the surface peat of the control may be a result of accumulation of cations as the soil is rendered with no vegetation.

The sum of exchangeable bases reflects the exchange cations in the soil. It ranges from 1.43 to 5.34 cmol.kg^{-1} with no significant difference between the cultivated and uncultivated plots. From Table 3.2, the sum of exchangeable bases observably differs inconsistently between control, trunking and non-trunking plots. A higher exchangeable bases was indicated at the 20 cm of control with higher % BS. The higher sum of exchangeable bases is reported to be related to the accumulation of plant litter and decomposition of organic materials (Akhatuzzaman et al., 2014).

3.2.7 Fourier Transform Infrared (FTIR)

FTIR has been commonly used to evaluate soil humification degree. The frequencies of absorption bands are used to probe the functional groups present in peat soil. The spectra of humic materials are typically characterized by a number of absorption bands, exhibiting variable relative intensities (Artz et al., 2008; Tfaily et al., 2014). Figure 3.2 shows the FTIR spectra of peat soil obtained from the control, uncultivated and cultivated plots.

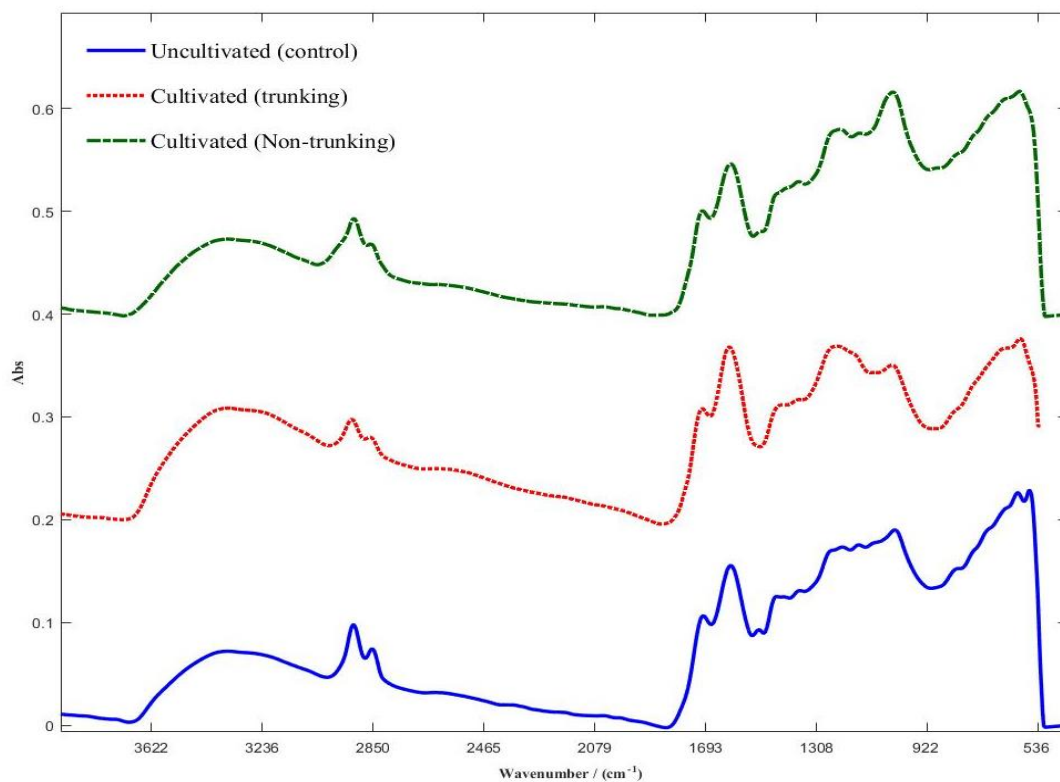


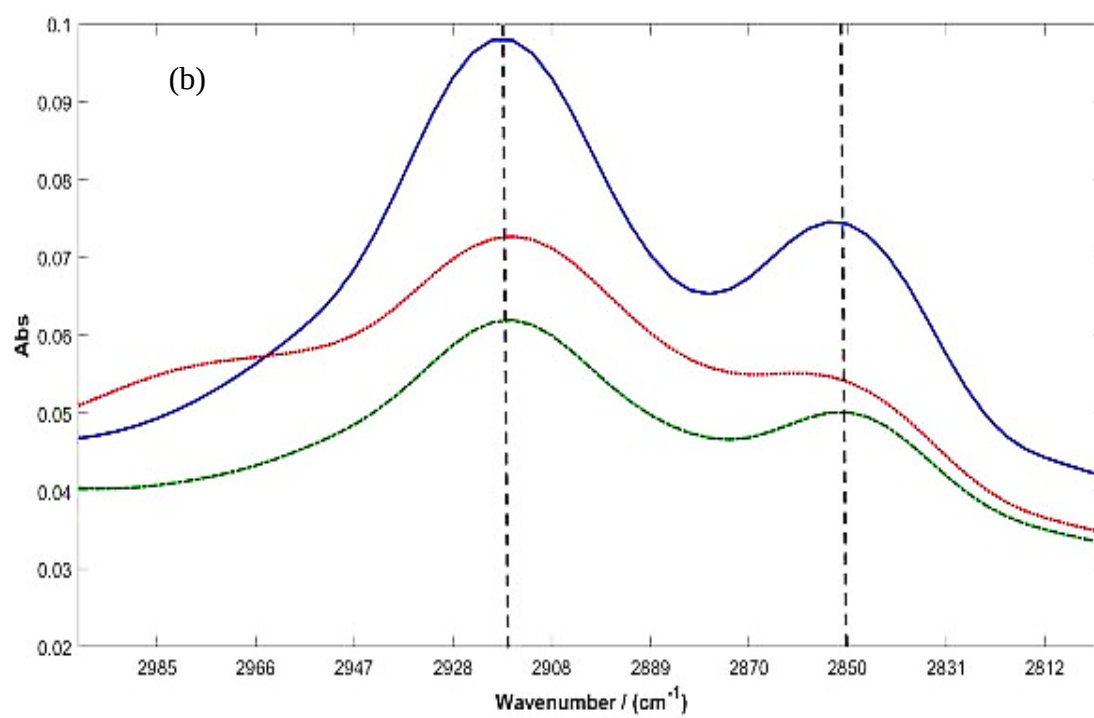
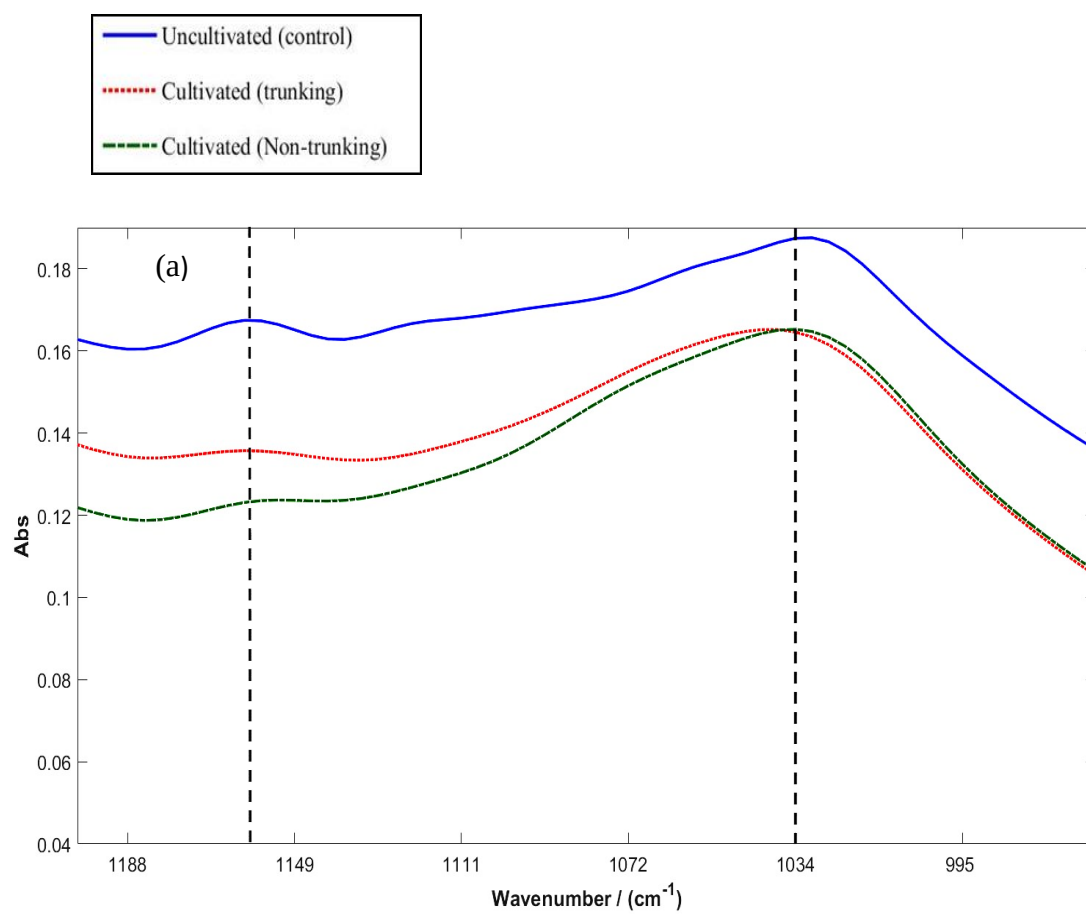
Figure 3.2: The FTIR profiles of uncultivated peat (bottom) and cultivated peat sampled adjacent to trunking (middle) and non-trunking (top) sago palms.

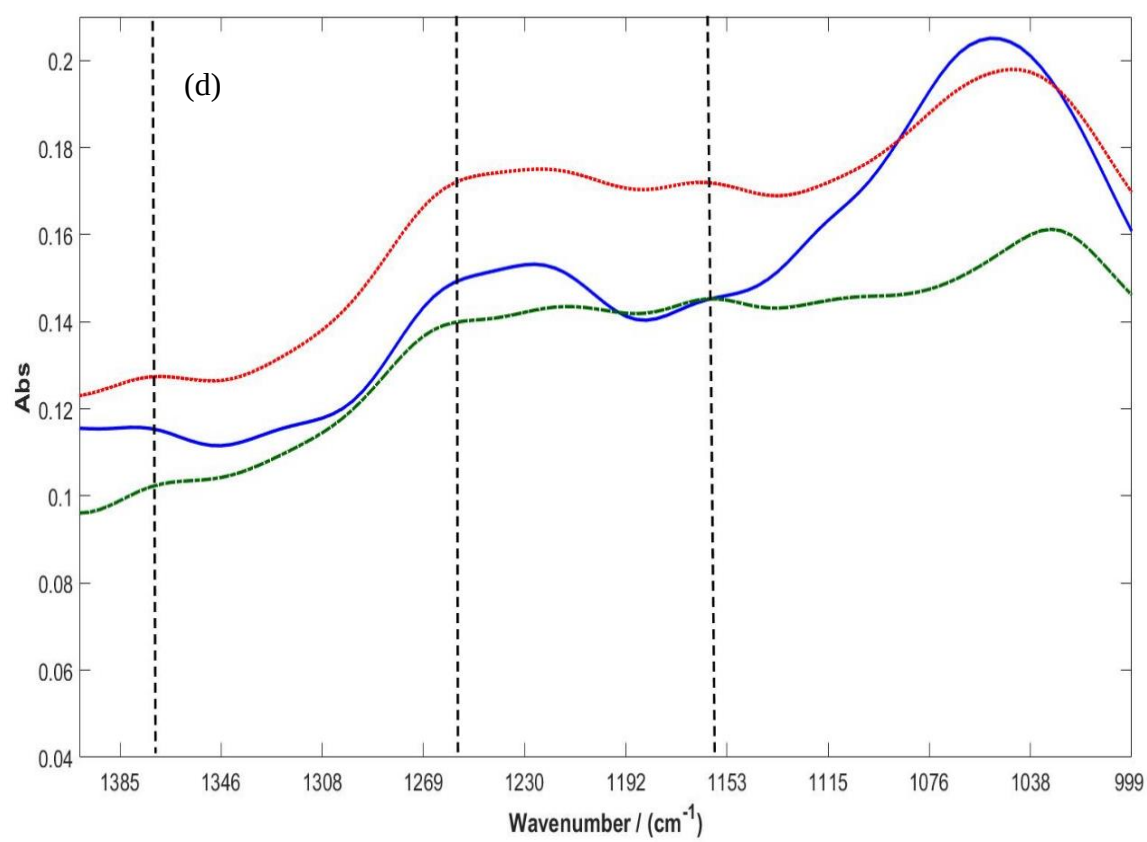
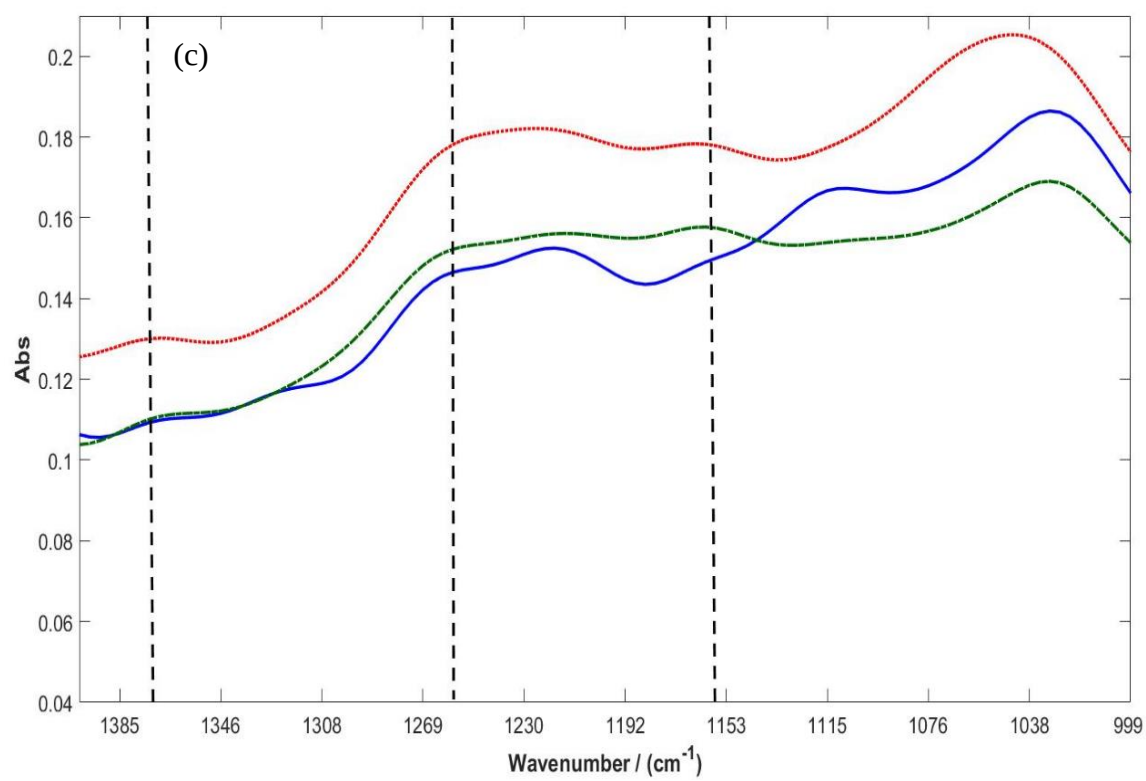
The spectra show similarities with common absorption bands determined at 3400, 2920, 2850, 1700, 1600, 1500, 1458, 1376, 1230, 1159 and 1030 cm^{-1} , in resemblance with the findings of Li et al. (2013) , Sim et al. (2017), Teong et al. (2016) and Zacccone et al. (2007). As observe in Figure 3.2, a broad band at 3400-3300 cm^{-1} attributed to the O-H

stretching vibration is evidenced (alcohols, phenols and organic acid). The spectra also exhibit a strong absorption at 1034 cm^{-1} , suggesting the presence of O-alkyls in polysaccharides. The peak occurring at 1702 cm^{-1} is attributed to the -C=O stretching of carbonyl (aldehydes and ketones), organic acids, and other oxygenated functionalities. Another broad absorption band occurring around 2915 cm^{-1} and 2850 cm^{-1} is associated with asymmetric and symmetric C–H stretching of CH_3 and CH_2 . Moreover, the peak around 1615 cm^{-1} is ascribed to C=C bonds of the aromatic rings and C–O of quinine and amide groups. The small peak occurring at 1508 cm^{-1} reflects the lignin-like residues. These results imply the presence of cellulosic, hemicellulose, lignocellulosic, lignin-derived materials in peat (Xu et al., 2013).

According El Fels et al. (2015), the reduction in absorbance at 1701 cm^{-1} and the shifting of band at 3400 cm^{-1} and 1615 cm^{-1} to lower number indicate the maturity of decomposed materials in soil. Generally, during the humification process, polysaccharides and phenolic moieties of parent materials are transformed into non-lignin aromatic structure. Usually more humified materials are enriched with aromatic groups (Sim et al., 2017). From Figure 11, the bands at 3400 and 1034 cm^{-1} are indicative of polysaccharides while those at $1508, 1450, 1415, 1365, 1242\text{ cm}^{-1}$ are assigned to lignin-like compound.

To determine the humification degree of peat, several important bands were examined. Figure 3.3(a)-(e) show the spectral regions of the selected bands at $1100, 2900$ and 1400 cm^{-1} . The vertical dash line indicate the peak of the bands.





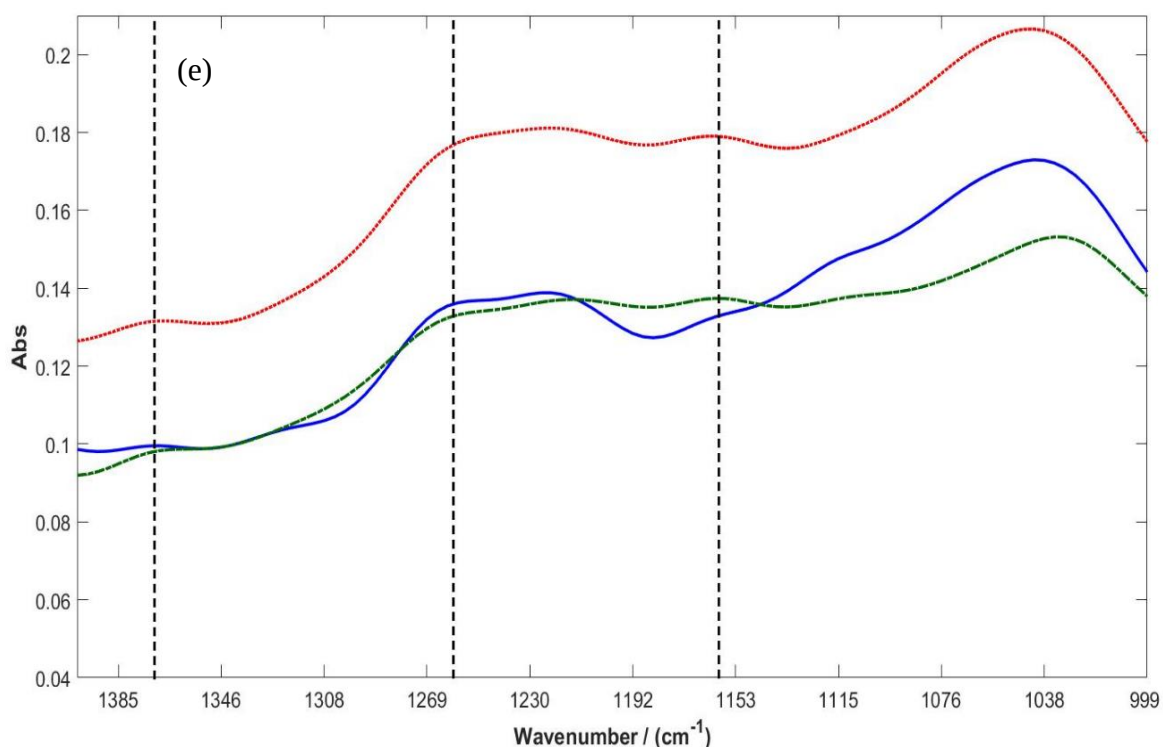


Figure 3.3 (a)-(e): The spectral regions of selected bands for cultivated and uncultivated peat at depth 20 cm to 100 cm.

The band at 1034 cm^{-1} is attributed to polysaccharide compounds; a higher concentration of polysaccharide suggests greater decomposition of carbohydrates in the peat. Figure 3.3(a) demonstrates that absorption at 1034 cm^{-1} was markedly more pronounced in uncultivated peat compared to cultivated peat at 20 cm, indicating greater decomposition degree.

Figure 3.3(b) shows the spectral region of 2915 and 2850 cm^{-1} for peat soil from cultivated and uncultivated plots at 40 cm. This band is assigned to aliphatic compounds; the higher concentration of aliphatic compounds is an indication of greater degree of decomposition (Krumins et al., 2012). As seen, the intensity of the band for uncultivated peat is more prominent. At the depth 60-100 cm, the band of phenolic, C-O lignin and

cellulose at 1365, 1260 and 1161 cm^{-1} (Figure 3.3(c)-(e)) are observably stronger for cultivated peat, a sign of lower decomposition degree.

Furthermore, the intensity of 1701 ($\text{C}=\text{O}$ stretching) and 1161 cm^{-1} (cellulose compound) is relatively less abundant in the uncultivated peat, particularly at 80 cm and 100 cm depth. The band at 1630-1600 cm^{-1} (aromatic compound) was found shifted to higher frequency for the cultivated peat; in uncultivated peat, this band was detected at the lower wavenumber of 1602 cm^{-1} whilst in trunking and non-trunking plots, the band was detected at 1608 cm^{-1} indicating a lower peat maturity.

Based on the FTIR spectra, the uncultivated peat was found to be more humified than the cultivated peat. This is likely because the uncultivated peat is exposed, hence subjected to greater weather conditions that facilitate accelerated decomposition. In addition, the bare uncultivated plot receives much less input of new plant residues. This postulation of greater decomposition rate for the exposed peat was supported by Carlson et al. (2015). An increased decomposition of organic matter was associated with higher temperature and reclamation. Besides, Page et al. (2004) and Yule et al. (2016) revealed that the decomposition of tropical peat was faster when there was less canopy. However, the humification degree of trunking and non-trunking is not distinguishable based on the IR spectra.

3.2.8 E₄/E₆

The UV-Vis spectroscopy has been commonly used for characterisation of humic molecules. The absorbance at various wavelengths such as 280, 465, 540 and 665 nm are widely used (Helms et al., 2008). The UV-Vis characteristics of humic acids can be used to indicate the humification degree of peat and to provide molecular weight information. Table

3.3 shows the E_4/E_6 of humic acid extracted from uncultivated and cultivated peat according to depth.

Table 3.3: The E_4/E_6 values of humic acid extracted from uncultivated and cultivated peat, according to depth. Data represent mean $\pm$ SD.

Depth (cm)	Uncultivated	Cultivated	
		Trunking	Non-trunking
20	5.96 $\pm$ 0.00	6.16 $\pm$ 0.50	5.78 $\pm$ 0.57
40	7.04 $\pm$ 0.31	6.34 $\pm$ 0.54	6.14 $\pm$ 0.35
60	7.07 $\pm$ 0.46	6.09 $\pm$ 0.83	6.47 $\pm$ 0.76
80	6.64 $\pm$ 0.44	6.28 $\pm$ 0.59	7.12 $\pm$ 0.78
100	6.47 $\pm$ 0.55	6.44 $\pm$ 0.50	6.91 $\pm$ 0.53

The highest mean value of E_4/E_6 is 7.12 at 80 cm and the lowest is 5.78 at 20 cm, both from non-trunking plot. There is no significant different in E_4/E_6 between cultivated and uncultivated peat ($p > 0.05$). The E_4/E_6 of humic acid from surface peat is generally lower than that in the deeper horizon for all three peat origins. The lower E_4/E_6 implies greater polymerization of aromatic constituents and a higher molecular weight. The surface peat (0-20 cm) has higher humification degree compared to the deeper peat. The E_4/E_6 values are found to correlate with the C/N ratio; the C/N ratio increases with depths indicating lower degree of decomposition at the deeper horizons.

3.3 Conclusion

The results suggest that deeper peat was overlain by less-humified surface peat indicating that planting on deep peat might not be feasible. The surface soil (20 cm) are found to be loaded with nutrient than the deeper depth (40-100 cm). Higher pH, organic matter, EC, %BS, and lower C/N ratio indicated surface soil is humified than the deeper

depth for both cultivated and uncultivated plot. Moreover, the FTIR spectra shown the uncultivated is humified than that attained at cultivated site. A higher concentration of aliphatic and polysaccharides on surface soil with lower concentration of phenolic and cellulose compound at deeper depth of uncultivated indicating a higher degree of humification. Besides, lower intensity of C=O stretching band and the shifting of aromatic band to lower frequency shown a sign of acceleration in peat maturity. Unfortunately, the trunking and non-trunking plot are indistinguishable. However, a lower ratio of C/N and significant higher of EC in trunking demonstrating of higher availability of nutrient compare to the non-trunking.

CHAPTER 4

HUMIFICATION DEGREE UNDER OIL PALM PLANTATION

4.1 Introduction

Sarawak has a largest peatland and most of it have been converting into oil palm plantation due to highest demand in the market (Jamaludin, 2002). The tropical peat swamp forests are great supplies of terrestrial carbon and host unique biodiversity (Lampela et al., 2014). The clearing and drainage canal led to the oxidic decomposition in the cultivation plantation, previous studies claimed that the conversion of the peatland would bring dreadful climate change impact (page et al., 2016; Carlson et al., 2015). This studies aim to characterizes the degree of humification within the soil profiles of oil palm plantation and forest as well to determine the relationship of the carbon dioxide emission with the degree of humification at the oil palm plantation and forest. The study area will be located at Sebungan Oil Palm Estate and Sabaju 4 Forest. Refer to the chapter 2 for the methodologies.

4.2 Results and Discussion

4.2.1 Ash content, moisture and bulk density

Table 4.1 summarizes the ash content, moisture and bulk density of peat from oil palm plantation and forest at varying depths. The ash content ranged from 4.05 to 4.66% with no significant different between the estate and forest soils ($p > 0.05$). In terms of vertical profile, there was an increasing trend in ash content as the depth increased. The ash content was lower at 15 cm depth and higher at 100-300 cm depth. Besides, the forest soil demonstrated consistently lower ash content than that attained in the estate.

Table 4.1: The ash content, moisture and bulk density of peat from oil palm estate and forest. Data represent mean $\pm$ SD.

Soil depth (cm)	Origin	Ash content (%)	Moisture (%)	Bulk density (g/cm ³)
15	Oil Palm	4.08 $\pm$ 0.17	66.68 $\pm$ 12.78	0.64 $\pm$ 0.24
	Forest	4.05 $\pm$ 0.33	66.10 $\pm$ 15.59	0.72 $\pm$ 0.32
100	Oil palm	4.18 $\pm$ 0.02	90.47 $\pm$ 1.70	0.16 $\pm$ 0.03
	Forest	4.10 $\pm$ 0.01	93.60 $\pm$ 1.18	0.13 $\pm$ 0.07
200	Oil palm	4.38 $\pm$ 0.01	90.70 $\pm$ 4.33	0.10 $\pm$ 0.05
	Forest	4.27 $\pm$ 0.02	92.11 $\pm$ 13.84	0.15 $\pm$ 0.04
300	Oil palm	4.66 $\pm$ 0.01	89.42 $\pm$ 2.79	0.19 $\pm$ 0.06
	Forest	4.40 $\pm$ 0.02	90.08 $\pm$ 2.79	0.17 $\pm$ 0.05

The lower ash content indicated an increasing organic matter content in the soil. The surface soil has greater organic matter compared to the deeper depth as vegetation, root mats and litter falls were accumulated within the soil surface (Rahman et al., 2015). Besides, the high density of biological organisms at the surface soil may create more pore spaces for organic decomposition and nutrient synthesis (Bot & Benites, 2005) which in turn increase surface soil fertility. This suggests that the humification degree of surface soil may be higher due to the continuous supplies of litter to soil and aid from the biological organism in decomposition process.

The physical properties of peat include decomposition degree, water content and bulk density (Prabir & Siti, 2018). According to Lee et al. (2015), physical properties like ash content, bulk density and moisture content is vital for the air and water movement in the soil, which will then influence the ability of the soil in providing essential moisture, air, and nutrient for the plant growth. The soil moisture content assists in transporting nutrients to the plant. In Table 4.1, the top soil from oil palm and forest shows lower moisture content than the core soil. The moisture content ranged from 66.10 to 93.60%; although there were some variations in the moisture content, no statistical different was identified between that

in the oil palm and forest ($p > 0.05$). The moisture of the surface peat was noticeably lower than that attained at sago palm (76-82%). The compaction practice at the oil palm estate could have increased the shear strength of peat resulting in lower moisture content (Tonk et al., 2016). Besides, the higher organic matter suggests greater humification degree at the surface soil; the humified soil encourages the formation of clay fraction leading to reduced moisture content at the surface soil (Putra et al., 2016).

The bulk density of peat from the estate and forest ranged from 0.10 to 0.72 g/cm³; no significant different was observed ($p > 0.05$). However, the result showed that the bulk density of surface peat was generally higher than the horizon peat. The higher bulk density at the surface soil was attributed to the enriched organic matter content. The bulk density reflects the peat porosity, soil aggregate and organic matter content. The results obtained in this study was comparable with the findings of Page et al. (2011) and Firdaus et al. (2010) where the bulk density was reported between 0.02 and 0.21 g/cm³ with decreasing organic matters at greater depth. The lower bulk density at the deeper peat was associated with lower organic matters and higher moisture content. Meanwhile, the higher bulk density in the forest peat may due to higher root density than that at the palm estate. According to Kim (2000), the plant roots could increase the strength of soil at the forest. The lower bulk density at deeper horizon suggests presence of undecomposed woody materials within the soil profiles as claimed by Veloo et al., (2014).

4.2.2 Soil pH

The chemical properties of peat soil at oil palm estate and forest according to depth are shown in Table 4.2. Generally, the pH was found to decrease with increasing depth for soil from both estate and forest. The soil was acidic with pH ranging from 2.96 to 3.84. Comparatively, the surface peat of oil palm estate (0-15 cm) demonstrated higher pH than that at the forest nevertheless no statistical difference was identified ($p > 0.05$). It is postulated that the decomposition of peat soil from the estate is greater than the forest due to lower vegetation density. The decreasing pH with increasing depth was probably caused by the vegetation coverage contributing to higher soil organic matter content (Bot & Benites, 2005). These suggested the formation of humic acid at the surface peat which in turn improving the fertility. Another possible factor of soil acidification was due to the process of nitrogen fixation by microbe activities within the roots (Li et al., 2008). This explains the lower pH at the forest site than the estate.

4.2.3 Electric conductivity (EC)

According to Carmo et al. (2016), the critical range of EC for plant growth is recommended between 750 and 3,490 $\mu\text{S cm}^{-1}$. As shown in Table 4.2, the EC measurements recorded ranging from 240.74 to 456.31 $\mu\text{S cm}^{-1}$, lower than the guideline range. This may due to the acidic condition of the peat which does not hold sufficient cation exchange bases due to pronounce H^+ ion. The H^+ ions prevent the cation bases to be bound to soil colloid which increases nutrient leaching (Yong et al., 2018). The forest was observed with significantly higher EC compared to the oil palm ($p < 0.05$) and the EC declined with increasing depth.

The higher EC in the forest can be explained by the increasing organic matter in the surface forest soil; the higher organic matter content in forest soil facilitates the binding of soil colloidal with cations. In the meantime, the organic matter and EC decrease as the depth increases. The increasing EC suggests improved nutrient availability in forest soil; the existent of large number of cations will contribute to improved fertility (McKenzie et al., 2004).

4.2.4 Cation exchange capacity and exchangeable bases

Another key factor to determine the soil humification is the cation exchange capacity (CEC). The CEC values in this study ranged from 4.40 to 19.66 cmolc.kg⁻¹. There is no significant different between the CEC of peat from oil palm plantation and forest ($p > 0.05$). The CEC of soil from oil palm estate was observably higher than that attained at the forest where the value increased when moving downwards in depth.

The CEC can be affected by the reduction of organic matter in soil (Berry et al., 2007). The CEC were higher not because of the exchangeable base, but because of the H⁺ ions. A high H⁺ ions in the peat soil could lead to plummeting percentage base saturation (%BS) rendering leaching of nutrients (Yong et al., 2018). Typically, the CEC of mineral soil is lower than that of peat; the base saturation, on the contrary, is higher (65%) than peat soil (15%) hence the former comprises greater available nutrients. According to Steven (2000), the %BS is recommended at 70-80% for cropping system. The %BS of peat at oil palm plantation, ranging from 0.41 to 44.17%, is obviously far from the guideline range.

The exchangeable Mg and Na were similar for both study plots. The exchangeable K and Ca on the other hand were found to be significantly higher at the oil palm estate ($p <$

0.05). The exchangeable K of peat at 300 cm of the oil palm estate was higher; the exchangeable Ca was elevated at 100 cm and 300 cm possibly due to the liming practice of oil palm plantation. The liming practices is the liming application to peat soil of calcium- and magnesium-rich materials in various forms, including marl, chalk, limestone, or hydrated lime. In acid soils, these materials react as a base and neutralize soil acidity to increasing the soil pH (Goulding, 2016). This postulation is supported by Rosolem (2011) where the liming effect at the surface is observed at the deeper subsoil based on the experience with corn plantations. The exchangeable Ca^{2+} increased with increasing depth likely due to the formation of soluble salt which was subjected to leaching and followed the water flow to the deeper soil layer. According to Miyamoto et al. (2009), the exchangeable K are found as free cations that tend to be leached and accumulated at the deeper depth of soil. The exchangeable K at the oil palm estate was higher at the surface and at 300 cm depth; this signifies the decomposition of organic matter at the surface soil and leaching of the cations to deeper layer due to rain events. The exchangeable of K and Ca are prone to leaching; this could cause limited available nutrients reducing the soil fertility.

4.2.5 Carbon-to-Nitrogen ratio (C/N)

Carbon and nitrogen are the most vital elements serving as an indicator for plant growth (Kalvins et al., 2013). In general, the total nitrogen in peat is relatively high but the availability fraction for plant uptake is rather low due to high C/N ratio (Othman et al., 2009). From Table 4.2, the %T-C ranged from 47.69 to 57.80% whilst %T-N and C/N ratio ranged from 0.50-2.23% and 21.43-95.15, respectively. However, the total carbon and nitrogen and C/N ratio shows a varied range, statistically no significant different was identified between the estate peat and forest peat ($p > 0.05$).

The percentage of total carbon (%T-C) of oil palm estate was higher than in the forest whilst the percentage of total nitrogen (%T-N) was conversely higher in the latter. The percentage of total carbon increased downward except at 300 cm of the oil palm estate. The percentage nitrogen similarly declined with increasing depth at the forest. The C/N ratio of the forest peat was lower than that of the estate peat. This indicates that the forest has a higher available nitrogen likely due to the litter falls supplies on the surface soil.

According to Li et al., (2018) and Morris et al., (2011), the higher N-enrich litter falls could lead to higher nitrogen fixation in the soil. The higher carbon at the oil palm estate was attributed to the stump and wood debris within the soil profiles and the accumulation of front piles. The lower C/N ratio further indicates a higher degree of humification (Wang et al., 2018). A high C/N ratio with low pH could result in low mineralisation of the soil. An increase in C/N quotient with depth is also reported in several other studies from ombrotrophic peatlands (Lampela et al., 2014).

Table 4.2: Chemical characteristics of peat soil from the oil palm estate and forest. Data represent mean $\pm$ SD.

Soil depth (cm)	Origin	pH	EC (μS/cm)	T-C (%)	T-N (%)	C/N (%)	CEC	Exch. Mg	Exch. Na	Exch. K	Exch. Ca	%BS
								cmolc.kg ⁻¹				
15	Estate	3.84±0.23	317.61±2.14	49.36±0.19	1.45±0.03	34.08±0.61	6.98±1.72	0.14±0.06	0.27±0.06	0.32±0.19	0.55±0.15	44.17±4.87
	Forest	3.51±0.19	451.87±1.49	47.79±0.21	2.23±0.15	21.43±1.55	6.29±1.17	0.38±0.10	0.50±0.09	0.19±0.05	0.26±0.11	32.05±5.02
100	Estate	3.63±0.29	322.09±0.64	57.80±0.14	0.83±0.12	69.72±9.75	9.06±0.06	2.09±0.13	0.73±0.02	0.23±0.01	0.78±0.04	42.56±2.17
	Forest	3.70±0.30	456.31±0.93	51.30±0.15	1.58±0.03	32.48±0.03	4.40±0.07	0.83±0.01	0.28±0.02	0.09±0.01	0.32±0.02	34.23±0.28
200	Estate	3.28±0.20	297.65±1.05	54.43±0.02	0.74±0.11	73.72±10.2	19.66±0.15	4.52±0.66	1.63±0.27	0.21±0.03	0.56±0.09	35.25±5.36
	Forest	3.31±0.18	375.97±0.84	52.16±0.14	1.39±0.14	37.45±3.63	7.04±0.03	1.79±0.05	0.54±0.05	0.09±0.02	0.19±0.04	37.24±2.16
300	Estate	2.96±0.22	240.74±0.83	47.69±0.22	0.50±0.01	95.15±2.65	11.52±0.06	1.10±0.14	0.19±0.03	0.50±0.06	1.19±0.16	25.84±3.42
	Forest	3.05±0.12	316.37±0.71	52.09±0.26	0.88±0.06	59.10±3.92	10.84±0.07	0.01±0.00	0.02±0.00	0.01±0.00	0.01±0.00	0.41±0.00

Notes: EC: electrical conductivity; CEC: cation exchange capacity; %BS: base saturation percentage; C: Carbon; N: Nitrogen.

4.2.6 FTIR

FTIR is commonly used to indicate the changes of the soil humification. Figure 4.1 show the spectra of surface and horizon peat from oil palm estate and forest; the absorption bands found are similar to those identified in peat soil. The common absorption bands determine in Table 4.3, resemblance with the findings of Li et al. (2013), Sim et al. (2017), and Teong et al. (2016). Besides, the shifting of absorbance band at 1701 cm^{-1} , 3400 cm^{-1} and 1615 cm^{-1} to lower number indicate the maturity of decomposed materials in soil (El Fels et al., 2015; Sim et al., 2017).

Table 4.3: The organic compound in the peat soil. (Li et al., 2013; Sim et al., 2017; Teong et al., 2016).

Absorption (cm^{-1})	Functional group
3400-3300	O-H stretching vibration (alcohols, phenols and organic acid).
2920-2850	Asymmetric and symmetric C-H stretching of CH_3 and CH_2 (aliphatic).
1700	C=O stretching of carbonyl (aldehydes and ketones), organic acids, and other oxygenated functionalities.
1600	C=C bonds of the aromatic rings and C-O of quinine and amide groups.
1500	Lignin-like residues.
1400	O-H deformation of phenolic and amino functionalities.
1370	Phenolic.
1260	C-O stretching of ether and carboxyl groups or lignin like.
1160	Hemicellulose.
1070-1030	O-alkyls in polysaccharides or polysaccharide like substances.

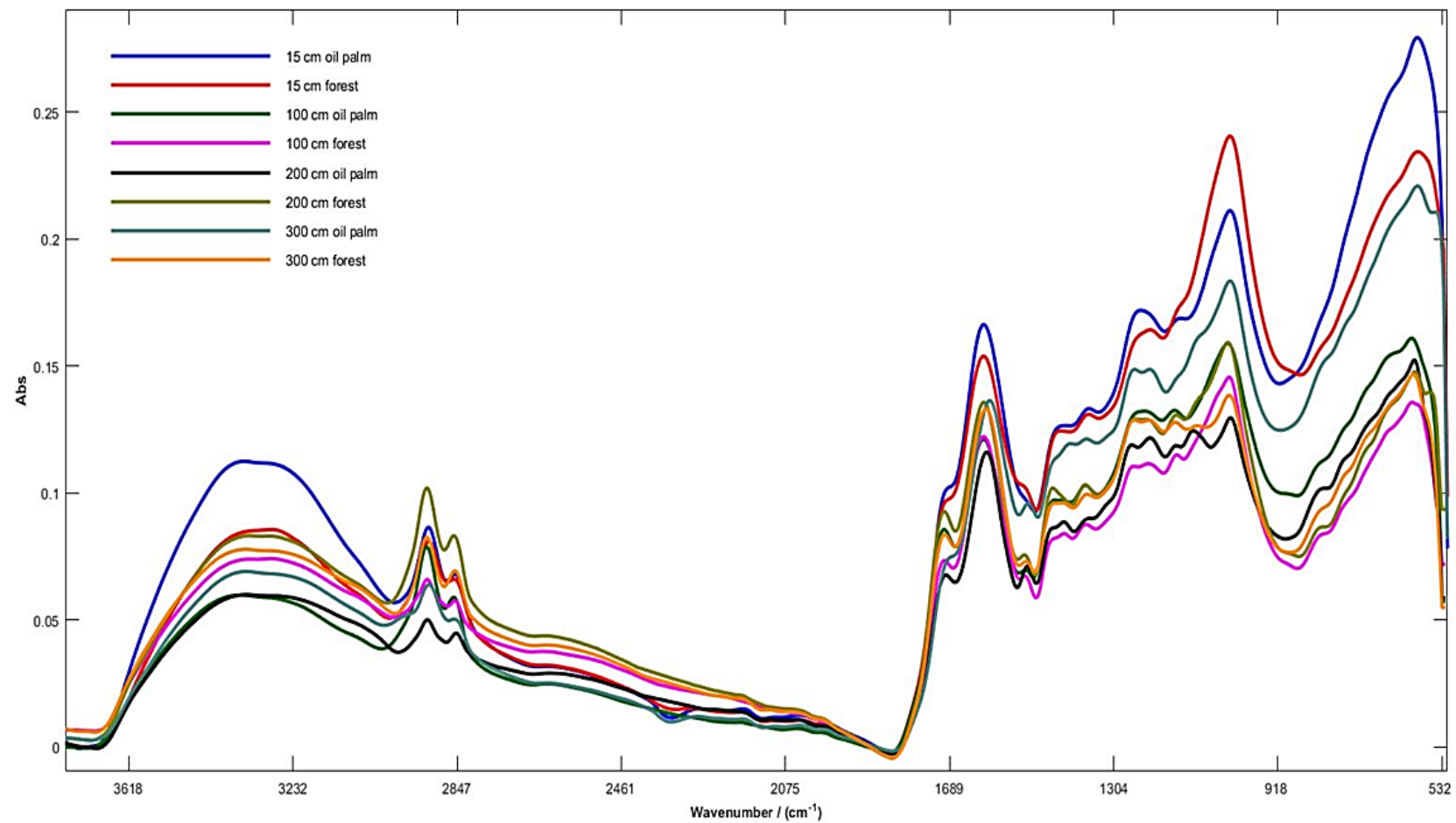
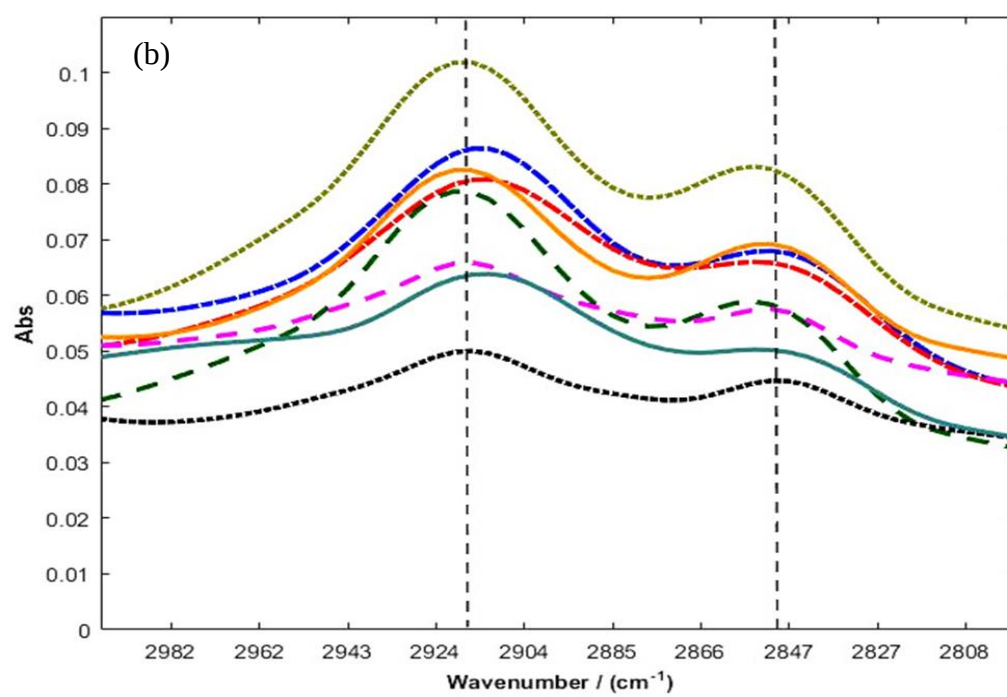
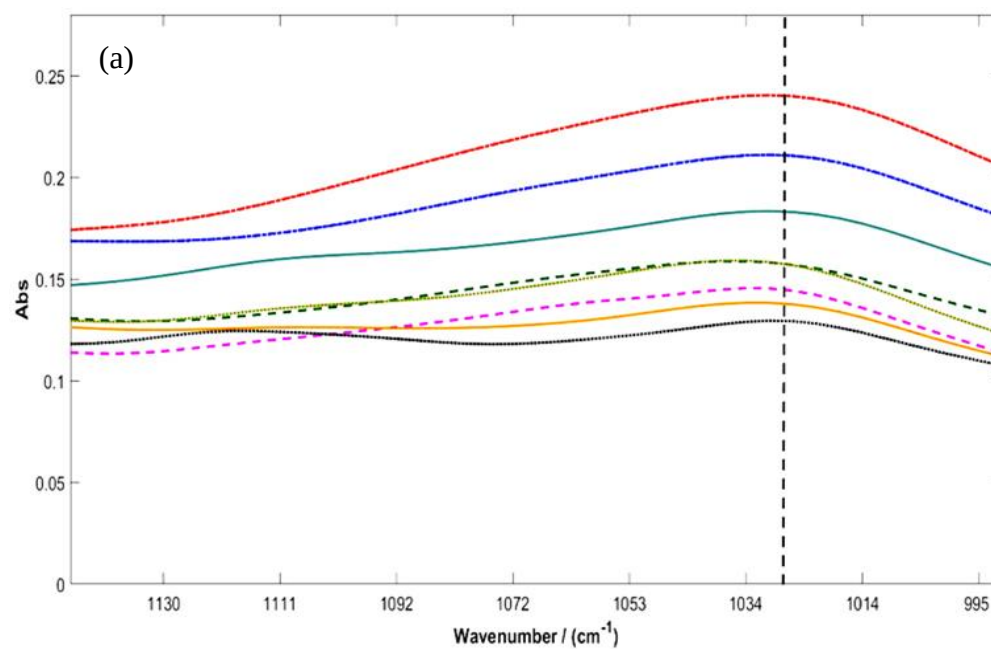


Figure 4.1: The soil profile of oil palm estate and forest at 15 cm to 300 cm.



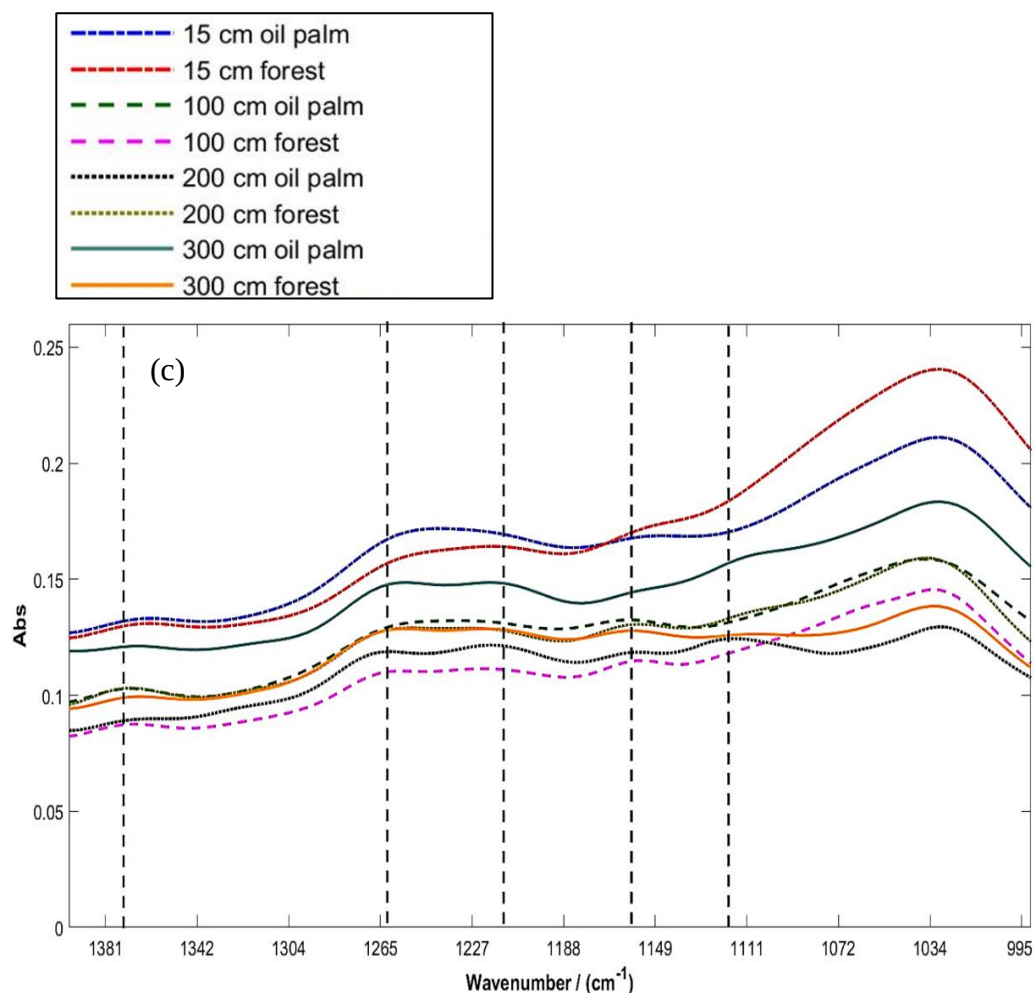


Figure 4.2 (a)-(c): The selected spectra region of selected band of oil palm and forest from 15 cm to 300 cm depth.

The Figure 4.2 (a)-(c) shown the selected spectral regions of several important absorption bands at 1100-1000 cm^{-1} , 3000-2800 cm^{-1} and 1400-1000 cm^{-1} . Figure 4.2(a) indicates the absorption band of polysaccharides at 1033 cm^{-1} on surface soil; comparatively, the intensity of this band is higher in forest peat than the estate peat suggesting greater decomposition degree of the former. Figure 4.2(b) shows the aliphatic absorption band at 2917 and 2853 cm^{-1} ; the band is more prominent for forests peat at 200 cm further corroborating greater extent of humification than the estate peat (Krumins et al., 2012). It is suggested that the presence of biomolecules contributes to the enrichment of aliphatic

compounds in the forest soil; the aliphatic moieties from roots accumulate when decomposition progresses (Nierop et al., 2001).

Figure 4.2(c) shows the spectral region at 1400-1000 cm^{-1} signifying the concentration of phenolic compounds. The phenolic band at 1370 cm^{-1} are prominent at underlying depth possibly due to undecomposed woods in the soil profiles for estate and forest. However, the bands at 1222, 1157 and 1117 cm^{-1} were relatively more abundant at the deeper depth of oil palm estate suggesting greater abundance of C-O lignin and cellulose. The high intensity of 1263 cm^{-1} was attributed to lignin-like compounds that is more abundant at the surface soil of oil palm estate. The absorption band at 1702 cm^{-1} (C=O stretching) on the contrary was weaker for the forest peat and the band was shifted to 1690 cm^{-1} . The band of aromatic compounds at 1615 cm^{-1} (aromatic compound) was found at 1613 for the estate peat and shifted to 1610 cm^{-1} for the forest peat. This suggested that the forest peat is more humified compared to the plantation peat (Sim et al., 2017).

4.2.7 E_4/E_6

The humification degree was characterized based on the index of E_4/E_6 . The index is used to indicate the aromaticity of organic matter present; a high E_4/E_6 value suggests profound aliphatic structures with smaller molecular weight (Purmalis, 2013). Table 4.4 summarizes the E_4/E_6 of humic acid extracted from estate and forest peat; the values ranged from 5.94 to 8.34 with no significant different between the plantation and forest peat ($p > 0.05$). Nevertheless, the result shows the underlying depth was less humified than the surface soil. The underlying depth was submerged in water subjecting to lower decomposition rate hence producing less humified soil than the surface. The lower E_4/E_6 values at the surface

soil (15 cm) implies greater polymerization of aromatic constituents and a higher molecular weight. The surface peat has higher humification degree compared to the underlying peat.

Table 4.4: The E_4/E_6 of oil palm and forest peat samples. Data represent mean $\pm$ SD.

Depth (cm)	Origin	E_4/E_6
15	Oil palm	7.67 $\pm$ 1.43
	Forest	7.44 $\pm$ 0.88
100	Oil palm	6.27 $\pm$ 0.93
	Forest	5.94 $\pm$ 0.56
200	Oil palm	7.63 $\pm$ 1.99
	Forest	6.59 $\pm$ 0.52
300	Oil Palm	8.34 $\pm$ 1.91
	Forest	7.57 $\pm$ 1.06

4.2.8 Soil carbon dioxide flux

The air temperature was found in the range from 26.4 to 33.3 °C with the soil temperature ranging from 25.3 to 28.4 °C. Figure 4.3 shows that the air and soil temperature in the estate was significantly higher than that in the forest ($p < 0.05$). The regulated water table management at 30-40 cm in the oil palm estate causes the surface to be exposed and increases the decomposition of organic substances at the surfaces. According to Könönen et al. (2015), exposed peat with lower vegetation at the surface are prone to effects by high temperature and erosion. The lower canopy at the oil palm estate causes the loss of organic matter at the surface and exposing the underlying organic matter to decomposition. The forest on the other hand was a closed-canopy system and was protected from weather conditions (Melling et al., 2005). Therefore, the lower canopy in the oil palm estate subjected the plantation to weather conditions releasing higher CO₂ flux than the forest.

The carbon dioxide flux was only been measured at the soil surfaces (0-15 cm) for 1 ha plot with 25 subplots from oil palm estate and forest, respectively. Figure 4.4 shows the CO₂ flux of the estate is higher at subplots 7, 11, 14, 17, and 20. While in the forest, the higher flux was detected at subplots 13, 22, and 25. The CO₂ flux ranged from 177.52 to 2472.17 mg CO₂ m⁻² h⁻¹. As seen in Table 4.5, the oil palm is significantly higher than the forest site ($p < 0.05$). The result is comparable to those reported by others using closed chamber techniques (e.g., Husnain et al., 2014; Melling et al., 2007). Melling et al., (2007) reported that the oil palm released 1.54 kg CO₂ m⁻² yr⁻¹ and the emission from the forest is 2.13 kg CO₂ m⁻² yr⁻¹. As shown in Table 4.4, the mean CO₂ at the oil palm are comparable to the findings of Melling et al., (2007) whilst the emission detected at the forest site was somewhat lower.

The higher CO₂ flux at subplots 7, 14, and 17 are because they are near to the secondary drainage canals with access to primary irrigation drainage. Meanwhile, the subplots of 11 and 20 are near to the road. Near the canal, observably there were numerous undecomposed trunks half submerged between subplot 6 and 7 even though the plot has been under cultivation for 10 years. This shows that the wood and trunk residues are recalcitrant in decomposition. The abundant undecomposed woods will attribute to carbon dioxide emission (Veloo et al., 2015b). While the road site the collar was surrounded with the weeds. This might cause the CO₂ flux of soil mix with the roots of the weeds and causes a higher CO₂ flux detected. While, in the forest the subplot 13 has less leaves but near to the fern area, this causes it has a bit warmer temperature. For subplot 20 and 25 it was an open canopy with congong grass and ferns. An error for CO₂ flux might be occur due to the distribution of the fern roots at subplots 13, 20, and 25. The root-related respiration component must be

separated from the peat-based flux, as it is compensated by CO₂ removal from the atmosphere through photosynthesis (Husnain et al., 2014).

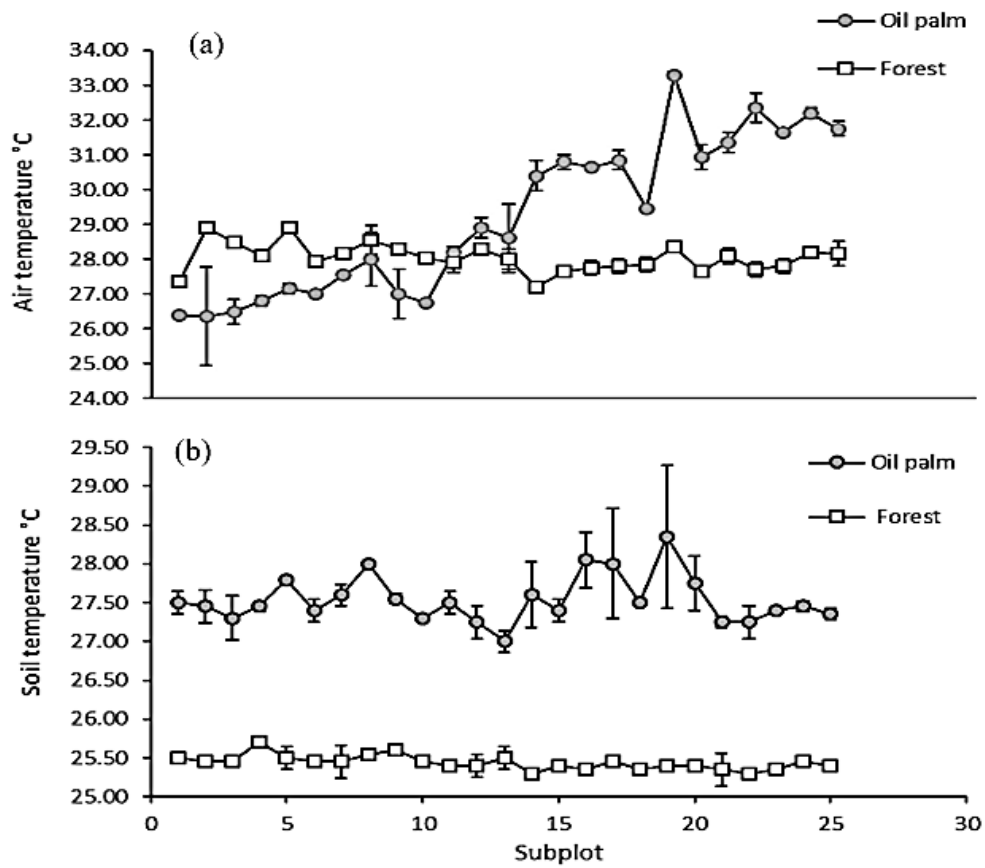


Figure 4.3: Air temperature (a), Soil temperature (b) at surface soil of oil palm estate and forest.

Table 4.5: Soil CO₂ flux and cumulative flux for forest and oil palm estate. Data represent mean $\pm$ SD.

Ecosystem	Carbon dioxide flux rate (mg CO ₂ m ⁻² h ⁻¹)	Cumulative flux (kg CO ₂ m ⁻² yr ⁻¹)
Forest	435.96 $\pm$ 125.90	1.04 $\pm$ 0.30
Oil palm estate	672.74 $\pm$ 569.18	1.61 $\pm$ 1.48

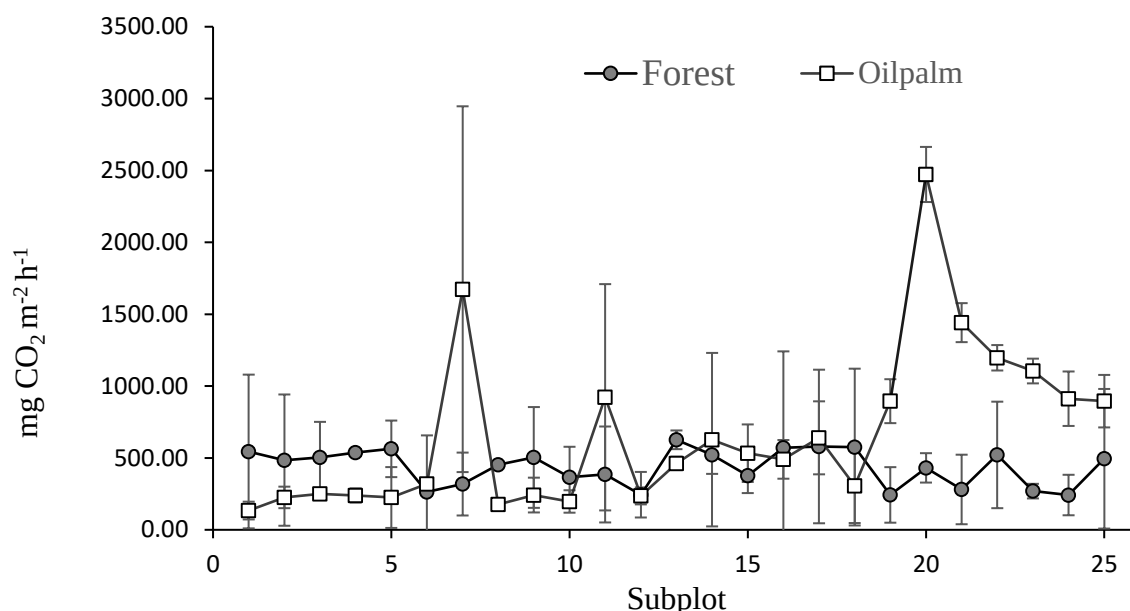


Figure 4.4: The carbon dioxide flux from the 25 subplots in oil palm estate and forest. Data represent mean $\pm$ SD. Error bars indicate SD of the mean. Symbols without SD bars have smaller SD than the symbols.

Pearson correlation coefficient was conducted to examine the relationship between carbon dioxide emission and humification degree (E_4/E_6) in oil palm and forest plot. Table 4.6 summarizes the relationship between both variables; Figure 4.5 shows a weak linear regression between CO_2 flux and E_4/E_6 . Although, the regression is weak with no statistical significance ($P > 0.05$). According to Preston et al., (2012), the length of time since the peat was opened may have distinguished the rate of microbial mineralisation and thus the rate of emissions. The higher CO_2 flux at the oil palm was likely associated with the higher air and soil temperature at the oil palm estate (air temperature: 27.2 ± 0.4 to 33.3 ± 0.0 and soil temperature: 27.0 ± 0.3 to 28.4 ± 0.0) compared to the lower air and soil temperature at the forest (27.2 ± 0.4 to 28.9 ± 0.1 and 25.3 ± 0.0 to 25.7 ± 0.0).

Table 4.6: Correlation table of carbon dioxide and degree of humification in oil palm and forest plot.

Origin	CO ₂ Mg CO ₂ m ⁻² h ⁻¹	E ₄ /E ₆		Df (n-2)	CV
		p	r		
Oil palm	672.74	0.054	0.389	23	0.396
Forest	435.96	0.912	-0.023	23	0.396

*. Correlation is significant at the 0.05 level (2-tailed).

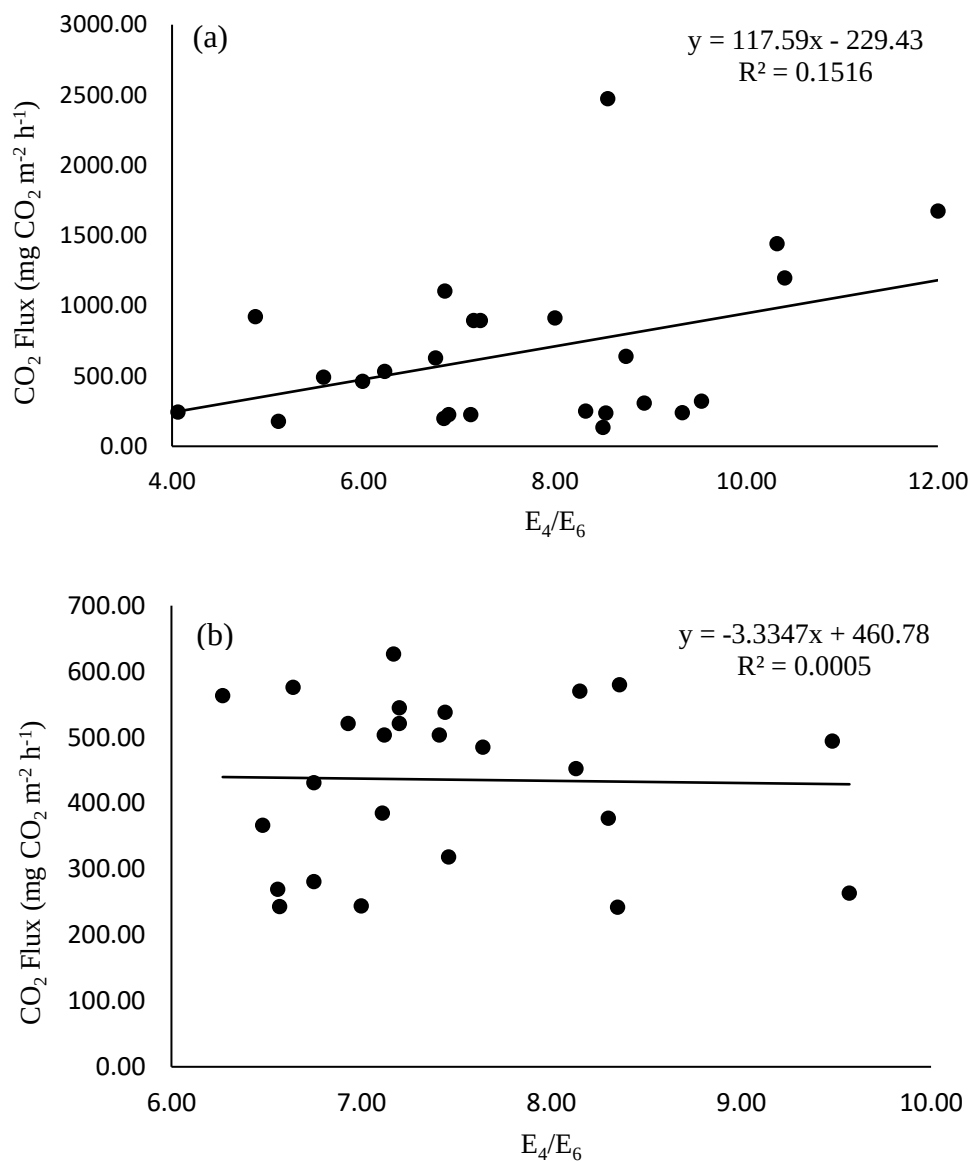


Figure 4.5: The correlation graph of E_4/E_6 with carbon dioxide emission from (a) oil palm estate and (b) forest.

According Minkinen et al. (2007), in temperate and boreal peatlands, temperature is a major factor influencing the peat CO₂ emissions. Similar factor affects the emission in tropical regions although the variation in the temperature is narrow; Torrent et al. (2016) and Bloom et al. (2010) demonstrated that the high temperature of tropical climate combined with peat drainage would increase the decomposition and thus the CO₂ flux. The lower temperature in the forest is due to the high density of canopy which controls the temperature in the forest and the frequently flooding in the forest could also contributes to low CO₂ flux (Melling et al., 2005). According to Inubushi et al. (2003), the flooding at the forest causes the soil to become anaerobic, while methanogenic bacteria produce more CH₄ than CO₂. Moreover, oxidic condition in the oil palm estate acts as a source for the CO₂ emission and the reductive condition in the forest acts as a sink carbon and nitrogen. Hence, the forest is more fertile than the oil palm estate which the decomposition was faster, but the CO₂ emission was releasing slowly. According to Yule & Gomez (2016), the cycling of dissolve organic carbon (DOC) is rapid and occurs before the leaves become part of the peat deposits. This would further explain the presence of the thick, superficial root mat layer that is a key feature of tropical peat forests, since the processes of nutrient cycling would occur in the upper leaf litter layer, rather than the deeper, waterlogged peat.

4.3 Conclusion

Conversion of forest to cultivation plantation exposed the peat surface causes the oxidic decomposition to occur and low canopy of the oil palm with low vegetation cover cause it subjective to the weather changing. The higher organic content, lower moisture, and higher bulk density in the forest indicating the canopy covers the surface soil from the erosion and high temperature. Besides, the chemical characteristic indicating the forest has

a higher nutrient availability than the oil palm estate. Lower EC in oil palm estate, higher %BS and higher C/N ratio with acidic environment indicating a low mineralisation process compared to the forest. The applied of fertilizer in the oil palm management can replace the loss of K and Ca which is easily to be leaching when raining season.

The IR spectra indicted the forest are more humified than the oil palm estate. The lower concentration of cellulose compound and higher aliphatic at the deeper soil of forest, with higher polysaccharides concentration at the soil surface indicates a greater decomposition forest peat. Furthermore, the forest has a weaker band of C=O stretching at 1690 cm^{-1} in the forest with aromatic band shifted to lower band at 1610 cm^{-1} . Whiles, the E_4/E_6 result indicating the humification at the surface soil is more humified than the lower depth. The CO_2 emission is significantly higher in the oil palm estate than that attained in the forest due to the climate alteration. The Pearson correlation shown there is no significant correlation between the CO_2 flux against the degree of humification due to the weak linear correlation. However, the positive correlation of the CO_2 flux with the degree of humification in oil palm estate indicating the higher temperature estimated to increase the decomposition and CO_2 emission while, the negative correlation in the forest was due to the lower temperature and the carbon was stored in the forest. This indicated the forest acted as a sink carbon and nitrogen.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The results suggest that deeper peat was overlain by more-humified surface peat indicating that planting on deep peat might not be feasible. It was observed that the humification degree of soil in cultivated site is lower than that from the forest and uncultivated site for oil palm and sago palm, respectively. Besides, the study shown the surface soil (20 cm) for all of studies plot is enriched with a nutrient. Meanwhile, the E_4/E_6 ratio indicating the surface soil is more humified than the deeper depth.

In sago palm study site a higher pH, organic matter, EC, BS %, and lower C/N ratio indicated surface soil is humified than the deeper depth for both cultivated and uncultivated plot. Besides, the FTIR spectra shown the uncultivated is humified than that attained at cultivated site. A higher concentration of aliphatic and polysaccharides on surface soil with lower concentration of phenolic and cellulose compound at deeper depth of uncultivated indicating a higher degree of humification. Furthermore, lower intensity of C=O stretching band and the shifting of aromatic band to lower frequency shown a sign of acceleration in peat maturity. Unfortunately, the trunking and non-trunking plot are indistinguishable. However, a lower ratio of C/N and significant higher of EC in trunking demonstrating of higher availability of nutrient compare to the non-trunking.

Similarly, the conversion of forest to oil palm plantation exposes the peat surface fostering oxidic decomposition and the low canopy density at the oil palm plantation further subjects the peat to weather conditions. The higher organic content, lower moisture, and higher bulk density in the forest indicates that the canopy covers the surface soil from erosion and

temperature. The chemical characteristic indicates that the forest has higher nutrient availability than that attained at the oil palm estate. The lower of EC, %BS and pH with higher C/N ratio in oil palm estate indicates a low mineralisation process compared to the forest. Besides, the higher exchange bases of K and Ca at estate indicated the nutrient was leaching during raining season.

The IR spectra indicates that the forest is more humified than the oil palm estate. The lower concentration of cellulose compound and higher aliphatic at the deeper soil of forest, with higher polysaccharides concentration at the soil surface indicates a greater decomposition forest peat. Furthermore, the forest has a weaker band of C=O stretching at 1690 cm^{-1} with aromatic band shifted to lower band at 1610 cm^{-1} . Meanwhile, the CO_2 emission is significantly higher in the oil palm estate than that attained in the forest due to the climate alteration. However, the Pearson correlation shown there is no significant correlation between the CO_2 flux against the degree of humification due to the weak linear correlation. Nevertheless, the positive correlation of the CO_2 flux with the degree of humification in oil palm estate indicating the higher temperature estimated to increase the decomposition and CO_2 emission while, the negative correlation in the forest was due to the lower temperature and the carbon was stored in the forest. This indicated the forest acted as a sink carbon and nitrogen. These results are useful in broadening the understanding of interrelationship and association of soil physiochemical properties on the growth performance of sago and oil palms. As well, to be used as a guide for managing soil fertility and choosing a suitable crop for different depth of peat soil at plantation.

5.2 Recommendations

The study shows the humification degree of the soil profiles is not uniform hence the productivity of palm will be uncertain. Besides, the uprooting perennial tree was heavy at the top when its growing causes the palm tree to be collapse due to the soft soil of peat. Thus, the deep peat is more suitable for shallow rooted plant which can utilize the nutrient at the top soil. Suggested that shallow rooted commercialised plant such as sugarcane, pineapple, and mulberry have a very good potential to be planted because it's flourishes in acid conditions prevalent in peat soils. Moreover, it is relatively low growing and not prone to being uprooted at maturity.

The leaching of K and Ca from the oil palm estate can be replaced by fertilizer management. While, the higher CO₂ at the plantation can be reduced by planted more intercropping plant such as banana, sugarcane, pineapple, and sweet potato. These aids covering the exposed top soils from the erosion. Furthermore, by planting a specific cover crops like *Pueraria phaseoloides* which can grow thoroughly under direct sunlight and disappear with increasing of shade or *Desmodium ovalifolium* which is shade tolerant, be able to helping converting the nitrogen to nitrate for the plant uptake and covering the top soils from direct sunlight and heavy precipitation which can break the soil aggregates. Besides, the consistently water table monitoring during the dry and wet season should be consider for the plantation managements to avoids the oxidic condition. For future study, the present study is limited with the carbon dioxide measurement in sago palm. Similarly, the total phosphorous should be analyses for sago palm and oil palm plantations.

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APPENDICES

Appendix 1: Trunking and Non-trunking plot.



Appendix 2: Soil sampling and depth checking at Sago palm plantation.



Appendix 3: Water table checking and soil sampling at reserved forest plot.



Appendix 4: Oil palm tree grow leaning and collapse at deep peat.



Appendix 5: Undecomposed trunk at underlying peat in oil palm plantation.



Appendix 6: Carbon dioxide flux measurement using EGM-4 Infra-Red Gas Analyzer (IRGA) PP system.



Appendix 7: C/N ratio of Sago palm.

Plot	Depth	Rep (Lab)	Total C %	Total N %	C:N
Control	20	1	57.973	1.275	45.47
		2	57.334	1.193	48.07
		3	57.640	1.194	48.27
Control	40	1	59.207	1.147	51.61
		2	59.304	1.095	54.15
		3	59.040	1.101	53.64
Control	60	1	57.543	0.880	65.42
		2	57.784	0.834	69.28
		3	57.307	0.801	71.58
Control	80	1	58.324	1.156	50.47
		2	58.117	1.122	51.78
		3	57.824	1.137	50.85
Control	100	1	58.668	1.032	56.84
		2	58.261	1.055	55.23
		3	58.230	1.034	56.31
Trunking	20	1	55.445	1.732	32.01
		2	55.469	1.815	30.56
		3	55.540	1.832	30.31
Trunking	40	1	57.268	1.314	43.60
		2	57.103	1.286	44.40
		3	57.382	1.296	44.28
Trunking	60	1	57.942	1.054	54.99
		2	57.965	1.055	54.93
		3	57.792	1.056	54.71
Trunking	80	1	58.696	1.070	54.85
		2	58.761	1.093	53.77
		3	58.495	1.056	55.37
Trunking	100	1	59.646	1.031	57.88
		2	59.264	1.032	57.44
		3	59.027	1.022	57.73

Appendix 7: continued

Non-Trunking	20	1	55.670	1.166	47.76
		2	55.704	1.169	47.66
		3	55.855	1.184	47.19
Non-Trunking	40	1	58.802	1.313	44.78
		2	58.579	1.291	45.37
		3	58.923	1.311	44.94
Non-trunking	60	1	58.288	1.182	49.33
		2	58.345	1.182	49.38
		3	58.393	1.156	50.50
Non-trunking	80	1	57.675	1.119	51.55
		2	57.671	1.101	52.40
		3	57.458	1.159	49.57
Non-Trunking	100	1	60.392	0.969	62.30
		2	60.248	0.945	63.78
		3	60.251	0.948	63.57

Appendix 8: C/N ratio of oil palm and forest.

NAME	LOCATION	DESCRIPTION	CARBON %	NITROGEN %	C/N
SB1	A01	0-15	49.303	1.446	34.099
SB1	A02	0-15	49.571	1.481	33.467
SB1	A03	0-15	49.202	1.418	34.688
AVERAGE			49.359	1.449	
SB2	A07	100	57.955	0.809	71.650
SB2	A08	100	57.741	0.955	60.435
SB2	A09	100	57.691	0.723	79.852
AVERAGE			57.796	0.829	
SB3	A10	200	54.445	0.865	62.928
SB3	B01	200	54.429	0.674	80.786
SB3	B02	200	54.409	0.676	80.497
AVERAGE			54.428	0.738	
SB4	B03	300	47.725	0.517	92.27393
SB4	B04	300	47.892	0.492	97.44842
SB4	B05	300	47.455	0.495	95.88031
AVERAGE			47.691	0.501	
SBF 1	B06	0-15	47.924	2.074	23.10593
SBF 1	B07	0-15	47.889	2.241	21.37139
SBF 1	A08	0-15	47.548	2.375	20.02358
AVERAGE			47.787	2.230	
SBF2	B02	100	51.336	1.553	33.04751
SBF2	B03	100	51.134	1.615	31.65996
SBF2	B04	100	51.415	1.570	32.74841
AVERAGE			51.295	1.580	
SBF3	A05	200	52.311	1.557	33.59083
SBF3	A06	200	52.023	1.286	40.46908
SBF3	A07	200	52.155	1.336	39.03817
AVERAGE			52.163	1.393	
SBF4	A08	300	51.831	0.946	54.76185
SBF4	A09	300	52.345	0.855	61.17714
SBF4	A10	300	52.098	0.842	61.86897
AVERAGE			52.091	0.881	

Appendix 9: Soil pH for 15 cm depth of 25 Subplot in oil palm.

Subplot	Trial 1	Trial 2	Trial 3	Average	SD
1	3.63	3.63	3.6	3.62	0.02
2	3.43	3.38	3.41	3.41	0.03
3	3.38	3.36	3.36	3.37	0.01
4	3.2	3.18	3.21	3.20	0.02
5	4.02	4.03	4.01	4.02	0.01
6	3.45	3.47	3.5	3.47	0.03
7	3.49	3.51	3.46	3.49	0.03
8	3.53	3.48	3.53	3.51	0.03
9	4.01	4.02	4	4.01	0.01
10	3.59	3.58	3.6	3.59	0.01
11	3.72	3.67	3.7	3.70	0.03
12	3.52	3.53	3.5	3.52	0.02
13	3.41	3.39	3.41	3.40	0.01
14	3.22	3.19	3.23	3.21	0.02
15	3.16	3.11	3.18	3.15	0.04
16	3.68	3.6	3.63	3.64	0.04
17	3.17	3.18	3.16	3.17	0.01
18	3.5	3.48	3.53	3.50	0.03
19	3.7	3.68	3.66	3.68	0.02
20	3.43	3.4	3.43	3.42	0.02
21	3.36	3.33	3.35	3.35	0.02
22	3.65	3.66	3.68	3.66	0.02
23	3.2	3.25	3.2	3.22	0.03
24	3.3	3.32	3.31	3.31	0.01
25	3.29	3.26	3.28	3.28	0.02

Appendix 10: Soil pH for 15 cm depth of 25 subplots forest.

Subplot	Trial 1	Trial 2	Trial 3	Average	SD
1	3.46	3.49	3.48	3.48	0.02
2	3.61	3.62	3.59	3.61	0.02
3	3.75	3.74	3.75	3.75	0.01
4	3.78	3.78	3.77	3.78	0.01
5	3.67	3.67	3.69	3.68	0.01
6	3.3	3.28	3.3	3.29	0.01
7	3.53	3.53	3.5	3.52	0.02
8	3.42	3.42	3.42	3.42	0.00
9	3.57	3.58	3.58	3.58	0.01
10	3.31	3.31	3.31	3.31	0.00
11	3.6	3.61	3.61	3.61	0.01
12	4.07	4.03	4	4.03	0.04
13	3.31	3.32	3.32	3.32	0.01
14	3.54	3.56	3.53	3.54	0.02
15	3.53	3.54	3.52	3.53	0.01
16	3.33	3.34	3.33	3.33	0.01
17	3.32	3.33	3.32	3.32	0.01
18	3.63	3.63	3.63	3.63	0.00
19	3.58	3.58	3.6	3.59	0.01
20	3.55	3.56	3.55	3.55	0.01
21	3.5	3.46	3.5	3.49	0.02
22	3.42	3.43	3.43	3.43	0.01
23	3.38	3.38	3.39	3.38	0.01
24	3.32	3.32	3.33	3.32	0.01
25	3.2	3.18	3.18	3.19	0.01

Appendix 11: Electric conductivity of 15 cm depth for 25 subplots in oil palm.

Subplot	Trial 1 ($\mu\text{s}/\text{cm}$)	Trial 2 ($\mu\text{s}/\text{cm}$)	Trial 3 ($\mu\text{s}/\text{cm}$)	Average	SD
1	326	326	326	326.0	0.00
2	536	542	542	540.0	3.46
3	447	448	453	449.3	3.21
4	516	513	516	515.0	1.73
5	439	443	443	441.7	2.31
6	510	512	513	511.7	1.53
7	513	515	515	514.3	1.15
8	423	426	430	426.3	3.51
9	450	449	450	449.7	0.58
10	499	501	503	501.0	2.00
11	414	418	414	415.3	2.31
12	377	376	376	376.3	0.58
13	430	431	430	430.3	0.58
14	450	450	450	450.0	0.00
15	565	564	566	565.0	1.00
16	516	519	520	518.3	2.08
17	448	447	450	448.3	1.53
18	500	502	502	501.3	1.15
19	448	447	450	448.3	1.53
20	250	251	249	250.0	1.00
21	461	465	465	463.7	2.31
22	407	409	405	407.0	2.00
23	345	346	345	345.3	0.58
24	450	451	451	450.7	0.58
25	552	552	551	551.7	0.58

Appendix 12: Electric conductivity of 15 cm depth for 25 subplot forest.

Subplot	Trial 1 ($\mu\text{s}/\text{cm}$)	Trial 2 ($\mu\text{s}/\text{cm}$)	Trial 3 ($\mu\text{s}/\text{cm}$)	Average	SD
1	345	347	347	346.3	1.15
2	271	272	274	272.3	1.53
3	228	229	228	228.3	0.58
4	332	331	331	331.3	0.58
5	441	445	443	443.0	2.00
6	574	579	581	578.0	3.61
7	209	212	212	211.0	1.73
8	367	368	369	368.0	1.00
9	293	295	298	295.3	2.52
10	470	469	471	470.0	1.00
11	495	502	505	500.7	5.13
12	309	309	311	309.7	1.15
13	207	210	212	209.7	2.52
14	321	322	326	323.0	2.65
15	393	396	400	396.3	3.51
16	212	211	212	211.7	0.58
17	295	296	301	297.3	3.21
18	204	207	208	206.3	2.08
19	160.3	162.4	162	161.6	1.12
20	230	230	234	231.3	2.31
21	559	562	565	562.0	3.00
22	217	215	218	216.7	1.53
23	182.2	185.4	186.5	184.7	2.23
24	218	220	221	219.7	1.53
25	360	368	370	366.0	5.29

Appendix 13: Ash content of 15 cm depth for 25 Subplot at oil palm.

Subplot	weight Ash (g)	weight Ash (g)	weight Ash (g)	Average	STDEV
1	4.574	4.777	4.387	4.580	0.19
2	4.111	4.249	3.980	4.113	0.13
3	4.202	4.035	4.382	4.206	0.17
4	4.178	4.271	4.088	4.179	0.09
5	4.003	3.912	4.098	4.004	0.09
6	4.208	4.367	4.060	4.212	0.15
7	4.260	4.338	4.184	4.261	0.08
8	4.517	4.626	4.414	4.519	0.11
9	4.418	4.328	4.512	4.419	0.09
10	4.365	4.373	4.356	4.365	0.01
11	3.642	3.174	4.276	3.697	0.55
12	3.702	3.798	3.610	3.703	0.09
13	3.992	4.167	3.831	3.997	0.17
14	3.340	3.689	3.049	3.359	0.32
15	3.740	3.744	3.736	3.740	0.00
16	3.728	3.948	3.524	3.734	0.21
17	3.761	3.589	3.957	3.769	0.18
18	3.899	4.132	3.684	3.905	0.22
19	3.772	3.644	3.914	3.777	0.14
20	4.184	4.298	4.073	4.185	0.11
21	4.626	4.645	4.607	4.626	0.02
22	4.056	4.311	3.821	4.063	0.24
23	4.458	4.777	4.171	4.469	0.30
24	3.884	4.333	3.511	3.909	0.41
25	4.283	4.357	4.209	4.283	0.07

Appendix 14: Ash content of 15 cm depth for 25 subplots of forest.

Subplot	weight Ash (g)	weight Ash (g)	weight Ash (g)	mean	SD
1	3.83	4.78	4.39	4.332	0.476
2	3.13	4.25	3.98	3.787	0.584
3	3.18	4.04	4.38	3.867	0.616
4	3.48	4.27	4.09	3.946	0.416
5	3.50	3.91	4.10	3.836	0.307
6	4.32	4.37	4.06	4.250	0.166
7	4.38	4.34	4.18	4.299	0.101
8	4.08	4.63	4.41	4.374	0.275
9	3.94	4.33	4.51	4.259	0.294
10	4.43	4.37	4.36	4.387	0.040
11	4.67	3.17	4.28	4.040	0.776
12	4.15	3.80	3.61	3.853	0.274
13	4.32	4.17	3.83	4.108	0.252
14	4.15	3.69	3.05	3.630	0.553
15	4.62	3.74	3.74	4.032	0.505
16	4.14	3.95	3.52	3.872	0.317
17	3.79	3.59	3.96	3.779	0.184
18	4.13	4.13	3.68	3.982	0.258
19	3.62	3.64	3.91	3.727	0.163
20	4.09	4.30	4.07	4.152	0.126
21	4.22	4.64	4.61	4.492	0.234
22	3.81	4.31	3.82	3.982	0.284
23	4.06	4.78	4.17	4.337	0.385
24	3.65	4.33	3.51	3.831	0.440
25	3.72	4.36	4.21	4.096	0.333

Appendix 15: Bulk density for 15 cm depth of 25 Subplots in oil palm.

Subplots	Dry soil	Bulk density g/cm ³
1	100.8	0.67
2	104.2	0.69
3	115.6	0.77
4	133.8	0.89
5	169.3	1.13
6	34.7	0.23
7	66.8	0.45
8	73.6	0.49
9	55.1	0.37
10	45.4	0.30
11	124.8	0.83
12	82.5	0.55
13	76.9	0.51
14	98.3	0.66
15	49.8	0.33
16	130.2	0.87
17	72.9	0.49
18	114.9	0.77
19	123.0	0.82
20	155.2	1.03
21	90.4	0.60
22	43.6	0.29
23	89.3	0.60
24	138.0	0.92
25	92.8	0.62

Appendix 16: Bulk density for 15 cm depth of 25 subplots in forest.

Subplots	Dry soil	Bulk density g/cm ³
1	146.8	0.98
2	68.1	0.45
3	249.1	1.66
4	65.4	0.44
5	122.5	0.82
6	197.2	1.31
7	108.9	0.73
8	106.8	0.71
9	93.4	0.62
10	43.4	0.29
11	94.2	0.63
12	53.8	0.36
13	157.2	1.05
14	92.3	0.62
15	112.7	0.75
16	90.1	0.60
17	148.5	0.99
18	62.4	0.42
19	64.3	0.43
20	123.3	0.82
21	105.9	0.71
22	117.6	0.78
23	142.6	0.95
24	82.7	0.55
25	34.1	0.23

Appendix 17: Publication

Sim, S.F., Wasli, M.E., Yong, C.M.R., Howell, P.S., Jumin, C., Safie, N.A., & Samling, B. (2017). Assessment of the humification degree of peat soil under sago (*Metroxylon sagu*) cultivation based on Fourier Transform Infrared (FTIR) spectroscopic characteristics. *Mires and Peat*, 19(24), 1-10. doi:10.19189/MaP.2017.OMB.296