



Faculty of Resource Science and Technology

Mapping the Humification Degree for Sustainable Development of Peat

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Mapping the Humification Degree for Sustainable Development of Peat

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DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.



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ABSTRACT

Tropical peatlands in the Southeast Asia are commonly deforested, burned, and drained due to the increase of economic and social pressures for peatlands to be converted into agricultural sites for economic development. The state of Sarawak, Malaysia has the largest peat area of approximately 1.6 Mha in which an extensive proportion of it has been developed into agricultural plantations such as oil palm estates. However, the cultivation of these crops on peatlands in Malaysia has been a divisive subject; previous studies hypothesized that peat humification degree is a significant factor in controlling palm growth (i.e., lower yield is observed when the crops are planted on less humified peat), whereas other reports highlighted the importance of good water table management as one of the main factors in ensuring positive plant growth. Additionally, the conversion of tropical peat forest into agricultural plantation has also caused the latter to undergo extreme changes affecting soil moisture dynamics, vegetation composition, organic matter decomposition process, nutrient availability, and carbon fluxes. Considering the environmental impacts of peatland alteration due to anthropogenic disturbances, it is crucial that existing cultivated peatlands be managed, developed, and utilized in a more sustainable manner. Therefore, this study was set out to investigate peat characteristics (soil moisture, elemental content, pH, EC, momentary total CO₂ emission), as well as to map out peat soil moisture and humification degree using atomic C/N ratio, in cultivated peat under oil palm plantation in contrast to that of an uncultivated secondary forest peat. Peat soil samples were collected from one-hectare plots of 25 20 m × 20 m subplots in Sebungan Oil Palm Plantation and Sabaju Secondary Forest at two depths: 0 – 50 cm and 50 – 100 cm. These samples were dried in the oven at 55 °C and sieved into fine particles. Samples were then subjected to elemental analysis, FTIR, pH and EC analyses. Momentary total CO₂ emission was also measured during

sampling. Peat soil moisture and C/N ratio data were spatially interpolated using the QGIS software. The oil palm plantation clearly showed lower moisture content at both peat profiles (0 – 50 cm and 50 – 100 cm) compared to the secondary forest. The growth of oil palm trunks showed a significant positive correlation with the topsoil moisture; observed through the soil moisture map, oil palms showing negative growth in trunk diameter were in relatively drier subplots or near to the drain. C/N ratio in the secondary forest was substantially lower (i.e., lower C/N ratio indicates more humified peat) than the oil palm plantation as the former was characterized with higher N content. Contrastingly, the humification index calculated based on the functional group characteristics in FTIR indicated that the plantation peat was enriched with carboxyl and carbonyl groups suggesting that plantation peat was at the more advanced stage of humification. These results give an indication that C/N ratio as a humification degree indicator of the two ecosystems cannot be compared directly due to their differences in N-cycling ecology. In the oil palm plantation, the topsoil C/N ratio map highlighted that oil palms which grow on peat with lower C/N ratio (more humified) produced more fronds with greater diameter size, whereas palms producing lower number of fronds were in areas with relatively higher C/N ratio (less humified). pH value in the topsoil profiles in both plantation and forest were significantly lower than at 50 – 100 cm while EC was observably higher in the oil palm plantation as a result of decreased organic matter input. Lastly, the momentary total CO₂ emissions in the secondary forest was observed to be significantly higher than the oil palm plantation. Overall, this study confirms that changes in land use, especially drainage and vegetation removal, modify the soil-water dynamic and rate of humification in tropical peatlands. The use of maps in this study has also provided better insights into the spatial heterogeneity of

peat characteristics at a local scale and could be useful for a more effective management of tropical peatlands in the future.

Keywords: Tropical peatland, soil moisture, humification degree, elemental compositions, GIS

Pemetaan Ciri-ciri Tanah Gambut di Ladang Kelapa Sawit Sebungan dan Hutan Gambut Sekunder Sabaju.

ABSTRAK

Kebanyakan tanah gambut tropika di Asia Tenggara telah ditebang, dibakar dan dikeringkan akibat daripada peningkatan tekanan ekonomi dan sosial yang bertujuan untuk menjadikan tanah gambut sebagai tapak pertanian. Negeri Sarawak mempunyai kawasan tanah gambut yang terbesar di Malaysia (kawasan sebesar 1.6 Mha) di mana sebahagian besar daripadanya telah dijadikan kawasan pertanian seperti ladang kelapa sawit. Walau bagaimanapun, penanaman and penjagaan tananam seperti kelapa sawit di atas tanah gambut adalah tidak mudah. Kajian terdahulu telah melaporkan bahawa hasil pengeluaran pokok kelapa sawit berkurangan apabila pokok-pokok tersebut ditanam di atas tanah gambut yang mempunyai kadar penghumusan yang lebih rendah. Selain itu, terdapat juga kajian terdahulu yang menekankan kepentingan pengurusan paras air bawah tanah sebagai salah satu faktor utama dalam memastikan pertumbuhan tumbuhan yang positif. Tambahan pula, penukaran kawasan tanah gambut tropika kepada ladang kelapa sawit telah menyebabkan kawasan ladang mengalami perubahan melampau yang menjejaskan dinamik kelembapan tanah, komposisi tumbuh-tumbuhan, proses penguraian bahan organik, ketersediaan nutrien dan fluks karbon. Oleh sebab itu, ianya amat penting untuk tanah gambut yang telah ditanam kelapa sawit diurus, dibangunkan dan digunakan dengan cara yang lebih mapan. Justeru, kajian ini telah dilaksanakan untuk mengkaji ciri-ciri tanah gambut (kelembapan tanah, kandungan elemen, pH, kekonduksian elektrik, pelepasan karbon dioksida keseluruhan) di kawasan tanah gambut yang ditanam kelapa sawit dan kawasan hutan tanah gambut sekunder. Pemetaan kelembapan tanah dan kadar penghumusan menggunakan nisbah C/N juga telah dibuat menggunakan sistem maklumat

geografi (SMG). Sampel tanah gambut telah diambil dari Ladang Kelapa Sawit Sebungan dan Hutan Gambut Sekunder Sabaju (kedua-dua kawasan merupakan plot satu hektar yang mempunyai 25 subplot yang berukuran $20\text{ m} \times 20\text{ m}$) pada dua kedalaman iaitu $0 - 50\text{ cm}$ dan $50 - 100\text{ cm}$. Sampel tersebut telah dikeringkan di dalam ketuhar pada suhu $55\text{ }^{\circ}\text{C}$ dan ditapis menjadi zarah halus. Sampel kemudiannya digunakan untuk analisis kandungan elemen, FTIR, pH dan kekonduksian elektrik. Jumlah pelepasan karbon dioksida telah diukur semasa proses pengambilan sampel tanah gambut. Kawasan ladang kelapa sawit menunjukkan kelembapan tanah yang lebih rendah pada kedua-dua kedalaman ($0 - 50\text{ cm}$ dan $50 - 100\text{ cm}$) berbanding dengan kelembapan hutan gambut. Pertumbuhan batang pokok kelapa sawit menunjukkan korelasi positif dengan kelembapan tanah pada kedalaman $0 - 50\text{ cm}$; pertumbuhan batang pokok kelapa sawit yang negatif telah didapati berada di kawasan yang mempunyai kelembapan tanah yang lebih rendah atau berdekatan dengan longkang/saluran air di ladang. Seterusnya, nisbah C/N di hutan gambut adalah lebih rendah daripada kawasan ladang kelapa sawit kerana hutan gambut menunjukkan kandungan N yang lebih tinggi. Namun begitu, pengiraan indeks penghumusan melalui penentuan kumpulan berfungsi menggunakan FTIR menunjukkan bahawa tanah gambut di ladang telah diperkayakan oleh kumpulan karboksil dan karbonil. Ini membuktikan bahawa tanah gambut di ladang mempunyai kadar penghumusan yang lebih tinggi. Pemerhatian ini menandakan bahawa penggunaan nisbah C/N sebagai penunjuk kadar penghumusan di kedua-dua ekosistem ini tidak boleh dibandingkan secara langsung disebabkan oleh perbezaan kitaran N. Tambahan pula, peta nisbah C/N pada kedalaman $0 - 50\text{ cm}$ menunjukkan bahawa pokok kelapa sawit mempunyai batang pokok yang lebih besar serta mengeluarkan lebih banyak pelepah apabila ditanam di atas tanah gambut yang mempunyai nisbah C/N yang lebih rendah (kadar penghumusan tanah lebih tinggi). Pokok yang ditanam

di atas tanah gambut yang mempunyai nisbah C/N yang lebih tinggi (kadar penghumusan tanah lebih rendah) pula mengeluarkan jumlah pelepah yang lebih sedikit. Nilai pH pada kedalaman 0 – 50 cm di ladang kelapa sawit dan hutan sekunder adalah lebih rendah berbanding dengan nilai pH pada kedalaman 50 – 100 cm. Nilai kekonduksian elektrik pula adalah lebih tinggi di ladang kelapa sawit pada kedua-dua kedalaman. Nilai pelepasan karbon dioksida di hutan sekunder pula lebih tinggi daripada pelepasan karbon dioksida di ladang kelapa sawit. Secara keseluruhannya, kajian ini mengesahkan bahawa perubahan dalam penggunaan tanah gambut, terutamanya melalui pembuatan saluran air untuk menurunkan paras air bawah tanah serta penyingkaran tumbuh-tumbuhan, akan mengubah dinamik kelembapan tanah dan kadar penghumusan tanah gambut tropika. Penggunaan peta dalam kajian ini juga telah memberikan gambaran yang lebih baik mengenai keheterogenan ruangan ciri-ciri tanah gambut pada skala tempatan, di samping dapat digunakan untuk pengurusan tanah gambut tropika yang lebih berkesan pada masa hadapan.

Kata kunci: Tanah gambut tropikal, kelembapan tanah, kadar penghumusan, komposisi elemen, GIS

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LIST OF ABBREVIATIONS

Al	Aluminium
ANOVA	Analysis of Variance
As	Arsenic
ASTM	American Society for Testing and Materials
ATR	Attenuated Total Reflectance
C	Carbon
Ca	Calcium
CH ₄	Methane
CI	Confidence interval
CO ₂	Carbon dioxide
CSV	Comma-separated values
Cu	Copper
DOC	Dissolved organic carbon
DOM	Dissolved organic matter
DON	Dissolved organic nitrogen
EC	Electrical conductivity
Fe	Iron
FP	Frond pile
FTIR	Fourier Transform Infrared
GAP	Good agricultural practices
GIS	Geographical Information System
GPS	Global Positioning System

Gt	Gigatonnes
H	Hydrogen
HP	Harvest path
IDW	Inverse distance weighted
K	Potassium
Mg	Magnesium
Mn	Manganese
MPIC	Ministry of Plantation and Commodity
MPOB	Malaysian Palm Oil Board
MSPO	Malaysian Sustainable Palm Oil
N	Nitrogen
N ₂ O	Nitrous oxide
NH ₂	Amino radical
NH ₄ ⁺	Ammonium
NMR	Molecular fluorescence and nuclear magnetic resonance
NO ₃ ⁻	Nitrate
NPP	Net primary production
O	Oxygen
P	Phosphorus
PB	Palm base
POC	Particulate organic carbon
PSF	Peat swamp forest
PVC	Polyvinyl chloride
QGIS	Quantum Geographical Information System

RSPO	Roundtable for Sustainable Palm Oil
SE	Standard error
SMG	<i>Sistem maklumat geografi</i>
SPSS	Statistical Package for the Social Sciences
SRTM 90	Shuttle Radar Topography Mission 90
STD	Standard deviation
UV-Vis	Ultraviolet-visible
WRB	World Reference Base

CHAPTER 1

INTRODUCTION

1.1 Study Background

Peatlands store over 600 – 650 gigatonnes (Gt) of organic carbon (C), forming the greatest terrestrial pool of organic C in the biosphere. In the Southeast Asia, tropical peatlands form more than half of the global C store, ranging between 57 – 66 Gt of C (Page et al., 2011; Miettinen et al., 2016; Dargie et al., 2017). The complex formation of peat occurs when the rate of organic matter decomposition is lower than the accumulation rate; commonly occurring in water-saturated, anoxic conditions (Hoyt et al., 2019).

Peat soil comprises of complex aromatic macromolecules which constitutes up to 60 % of soil organic matter (Trevisan et al., 2010; Verbeke et al., 2021). The physical, chemical and microbial transformation of organic matter into humic substances is known as humification (Goel & Dhingra, 2021). The process involves microbial use of labile fractions (i.e., carbohydrates and amino acids) for energy and biosynthesis. Plant litter is then turned into precursors of organic matter, forming compounds of aromatic structures with increasing carboxyl and carbonyl groups while phenolic, alcoholic and methoxyl moieties are replaced. Essentially, the fertility and productivity of peat is governed by the degree of humification (Calvo et al., 2014; Veloo et al., 2015; Sim et al., 2017). Humic substances with more condensed structures act to stimulate the activity of plasma membrane H^+ -ATPase (Canellas & Façanha, 2004) whilst carboxyl groups form complexes of metal ions improving their bioavailability (Kuhn & Maurice, 2014). At the same time, microbial decomposition instigates nitrogen assimilation which enriches humic matter with NH_2 and NH_4^+ (Kulikova & Perminova, 2021).

Undisturbed, peatlands act as C sinks as peat deposits continuously accumulate C at constant rates (Dargie et al., 2017; Fatoyinbo, 2017). Peatlands also play an important role in nutrient cycling, water supply regulation and biodiversity support in the ecosystem (Page et al., 2022). However, direct anthropogenic disturbances such as land use change, drainage and deforestation have altered the biogeochemical cycle of tropical peatlands, resulting in the reduction of peat water-storage capacity and porosity, peat subsidence, release of C in the form of CO₂, CH₄ and fluvial C, reduced peat substrate quality as well as changes in nutrient cycling dynamics (Anshari et al., 2004; Domain et al., 2010; Hooijer et al., 2012; Cook et al., 2018; Könönen et al., 2018; Girkin et al., 2019; Melton et al., 2022).

In the Southeast Asia, tropical peatlands are commonly deforested, burned, and drained due to the increase of economic and social pressures for peatlands to be converted into agricultural sites for economic development (Hirano et al., 2009; Miettinen et al., 2012). In Malaysia, a large proportion of the 2.5 million hectares of peatlands have been cleared, converted, and developed into agricultural sites for sago palms (*Metroxylon Sagu* Rottb.) and oil palms (*Elaeis guineensis* Jacq.), (Purwanto et al., 2002; Miettinen et al., 2012; Carlson et al., 2015). Palm oil, a by-product of oil palm fruits, is one of the world's most prominent vegetable oils. This oil accounts for 60% of global vegetable oil trade and accounts for one-fourth of global oil consumption (Alam et al., 2015).

Palm oil production is concentrated in Malaysia and Indonesia, with Malaysia seeing an increase in the number of oil palm plantations established as one of the country's driving forces in the agro-industry (Alam et al., 2015; World Bank, 2016). In fact, Malaysia oil palm cultivation has grown from 54,700 ha in the early 1960s to 5.64 Mha in 2015. This figure is expected to rise as Malaysia's Ministry of Primary Industry proposes to cap the area of oil palm plantations to 6.5 Mha by 2023 (Yusof, 2019). The total area planted with oil palm

area in Sarawak, Malaysia, has increased from 14,091 ha in 1975 to 839,748 ha in 2009 (Veloo et al., 2014). In a recent study (Miettinen et al., 2016), this total area was estimated to have increased to 0.7 Mha in 2015. Initially, oil palms were primarily planted on mineral soils because peat was deemed less favourable due to poor initial cultivation. Nonetheless, cultivated peatlands under oil palms have expanded significantly in the last two decades and are still expanding due to the development of new agronomy and water management technologies, as well as government support (Lim et al., 2012).

1.2 Problem Statement

The state of Sarawak, Malaysia has the largest peat area of approximately 1.6 Mha (Mutalib et al., 1991; Miettinen et al., 2016); however, similar to peatlands in other parts of Malaysia, Sarawak peatlands have been extensively developed into agricultural plantations. Nevertheless, the cultivation of crops such as oil palms and sago palms on peatlands in Malaysia has been a divisive subject as both crops were found to grow slower when planted on deep peat (Sim et al., 2005; Veloo et al., 2015). Studies have shown that sago palms planted on deep peat in Mukah, Sarawak showed retarded growth where only 20 % of the palms were trunk-producing with none attaining maturity in 10 – 15 years, whereas palms which were planted on shallow peat performed better with more than 80% trunking within 5 to 6 years, besides obtaining maturity in 10 years (Purwanto et al., 2002; Jong et al., 2006). Other studies observed lower oil palm yield when the crop is planted on deep peat (Veloo et al., 2015; Woittiez et al., 2017; Rauf et al., 2019; Awang et al., 2021). Veloo et al. (2015) suggests that humification degree is a significant factor controlling the crop yield; lower yield is observed when the crops are planted on less humified peat. The maturity and fertility of peat has been reported to be closely associated to its humification degree (Domeizel et al.

2004; Sim et al., 2017). These observations suggest that there is considerable spatial heterogeneity in humification degree within the same area of peat.

In addition, studies have shown that plant growth and crop yield on peat soil is affected by the management of water table (Lim et al., 2012). For example, Hashim et al. (2019) further highlighted the importance of water table management in nutrient regulation since the rate of nutrient leaching in peat is dependent on the water table depth. In four-month-old oil palm seedlings planted in lysimeters, mimicking natural conditions of drained tropical peat, the peat with water table of 25, 40, 55, 70 and 85 cm displayed significant differences in nutrient concentrations (Ca, Cu, K, Mg, P), (Hashim et al., 2019). The highest water table (25 cm) showed greatest nutrient losses while the lowest (85 cm) showed the least nutrient losses. At water table depth of 55 cm, oil palm seedlings had fastest growth corroborating the findings by Melling et al. (2007). In oil palm plantations, the water table at 40 – 60 cm is currently recommended to ensure that the palm roots are not waterlogged. Most oil palm roots are found in the upper 50 cm of peat soil profile (Henson & Chai, 1997; Melling et al., 2016). Water table within the rooting zone that is above or below the recommended range may negatively impact the nutrient uptake as well as the production of fresh fruit bunches (Henson et al., 2008; Lim et al., 2012).

Besides the challenges faced in palm growth on peat, the conversion of tropical peat forest into agricultural plantation has also caused the latter to undergo extreme changes affecting soil moisture (i.e., water table level) dynamics, vegetation composition, organic matter decomposition rates, nutrient availability, and carbon fluxes (Dommain et al., 2010; Hirano et al., 2014; Baird et al., 2017; Dargie et al., 2017). Considering the environmental impacts of peatland alteration and the possibility of additional peatland degradation in the

future due to anthropogenic disturbances, it is crucial that existing cultivated peatlands be managed, developed, and utilized in a more sustainable and effective manner.

1.3 Objectives

The objectives of this study were:

- i. To evaluate and compare the peat soil characteristics (soil moisture, humification degree, pH, electrical conductivity, and total carbon dioxide emission) in cultivated peat under oil palm plantation and uncultivated secondary forest.
- ii. To visualize the spatial heterogeneity of peat soil moisture and C/N ratio in both cultivated and uncultivated peat using geographical information system (GIS).

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Peatlands are wetland ecosystems that form when waterlogged, anoxic conditions limit the decomposition and respiration of organic matter. They are often characterised by the accumulation of incompletely decomposed organic matters (Vitt, 2013). According to Xu et al. (2018), the ultimate definition of ‘peat’ or ‘peatland’ has not been agreed on as the definition varies in regards to the interest of various research groups (Xu et al., 2018). Commonly, the high carbon (C) and nitrogen (N) content as well as organic matter composition of at least 30 % in peat distinguishes it from mineral soils (Sorensen, 1993; Joosten & Clarke, 2002; Reiche et al., 2010). Other studies reported organic matter content up to 50 % (Gumbrecht et al., 2017), 65 % (Dargie et al., 2017) or more than 90 % (Frolking et al., 2001; Tarnocai et al., 2009). Peat is also characterised by its minimum thickness (i.e., depth) of 30 – 40 cm up to several meters (Tarnocai et al., 2009; Page et al., 2011; Page & Baird, 2016; Dargie et al., 2017). Additionally, peat is also known as histosols in multiple regions and is defined as “soils which contains at least 20 % organic material or, at least 18 % organic material if the soils have been saturated with water for 30 consecutive days” as reported in the World Reference Base (WRB) for soil resources in 2006 (Michéli et al., 2006).

2.2 Distribution of Peat

Peatlands account for about 3 % of the terrestrial surface and occurs predominately in the mid to high northern latitudes (i.e., arctic, boreal and temperate ecosystems) with lesser proportion in tropical regions (Leifeld & Menichetti, 2018). Figure 2.1 shows the global

distribution map of peatlands according to Yu et al. (2010). Recently, Xu et al. (2018) pointed out that peatlands cover about 185 – 423 million hectares (Mha) of land globally (1.2 % to 2.8 % of the earth's total land area).

Global distribution of peatlands

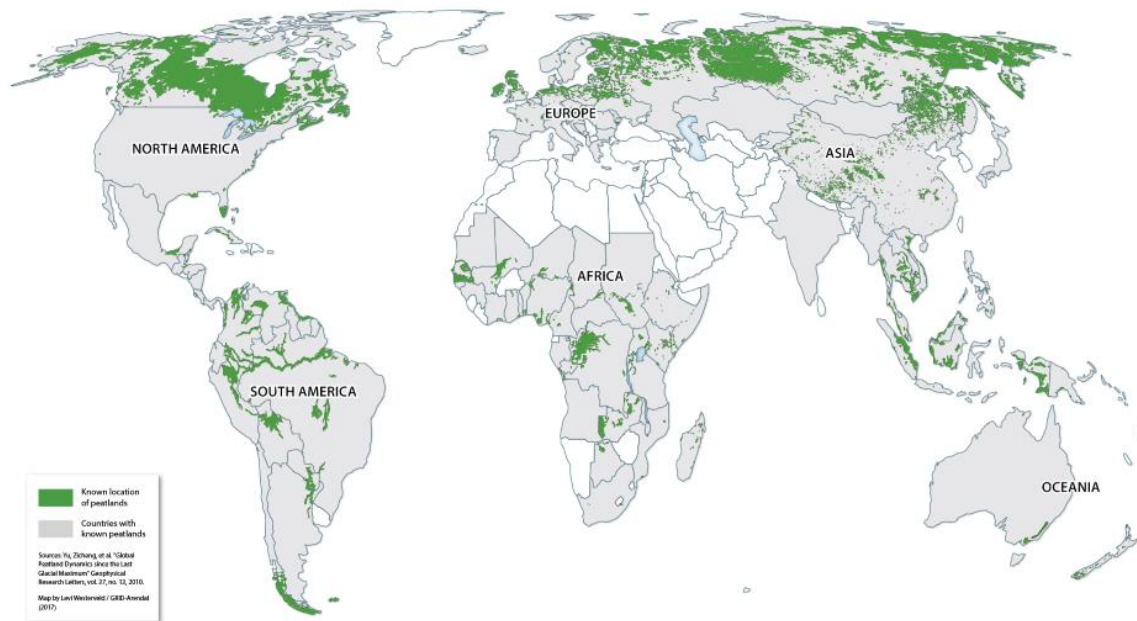


Figure 2.1: Global distribution of peatlands according to Yu et al. (2010). Map retrieved from GRID-Arendal (2017a).

Peatlands in tropical regions are currently estimated in the range of 90 – 170 Mha (23 % to 30 % of the global peatland area), which is double or triple of the size of previous estimates (56 Mha) as addressed in Page et al. (2011). Previously, the largest distribution of tropical peatlands was mainly reported in the Southeast Asia; East Sumatra, Indonesia, Kalimantan, Malaysia and Papua New Guinea (Lähteenoja et al., 2009; Miettinen & Liew, 2010; Miettinen et al., 2016; Dargie et al., 2017). The Southeast Asian peatlands have been examined in scientific studies ever since the early 20th century (Osaki & Tsuji, 2016; Omar et al., 2022) whereas peatlands in other tropical regions have only been recorded since 2010.

Recently, extensive intact tropical peatlands in Central Africa and South America have been reported (Draper et al., 2014; Dargie et al., 2017; Gumbrecht et al., 2017) contributing to the revised estimates of tropical peatlands in the world. For instance, peatland in the Congo Basin which covers over 14.6 Mha was only documented in 2017 (Dargie et al., 2017). Most tropical peatlands are found in low-latitude areas, nonetheless some are found at high altitudes such as in the African, South American, and Papua New Guinea mountains (Page et al., 2011; Apers et al., 2022). According to the aforementioned study, peatlands cover approximately 25 Mha in Southeast Asia; however, this figure has been reduced to 21 Mha in a recent article (Xu et al., 2018). Most tropical peatlands are located in Indonesia (15 Mha), Malaysia (2.2 Mha), Thailand (40000 ha) as well as in smaller areas like Brunei and the Philippines (Ribeiro et al., 2020).

According to reports in the 1990s, the state of Sarawak, Malaysia, covered a total of 1.6 to 1.7 million ha of peatlands (Mutalib et al., 1991; Melling et al., 1999). However, it is believed that the size of peatland in its original state has decreased significantly over the years due to the high rate of Sarawak peatland conversion through extensive logging and continuous agricultural expansion (Miettinen et al., 2016; Jaafar et al., 2020). To the best of our knowledge, the most recent precise peatland distribution in the state has not been widely reported in literature. Miettinen et al. (2016), on the other hand, used maps to estimate the land cover and agricultural plantation distribution in the peatlands of Peninsular Malaysia, Borneo (including the states of Sarawak and Sabah), and Sumatra in 2015, and compared these estimates to corresponding maps in 1990, 2000, 2007, and 2010. According to the findings of the aforementioned study, Sarawak covered approximately 1.4 Mha of peatlands in 2015, with only 0.5%, 10.5%, and 0.9% of that total area being pristine peat swamp forest, secondary forest with tall shrubs, and ferns or low shrub-covered peat, respectively. Over

389 000 ha of peat forest in Sarawak were lost between 2007 and 2015, primarily due to agricultural development, with an annual deforestation rate of 8.3%. Over 0.7 million hectares of Sarawak peatlands are covered by oil palm plantations, accounting for more than 80% of the peat swamp forest lost since 2007.

2.3 Formation of Tropical Peat

The intricate formation of peat occurs “when the amount of photosynthetically-produced organic matter exceeds the loss of organic matter through decomposition, fire or lateral loss” (Hodgkins et al., 2018; Hoyt et al., 2019). Tropical peatlands are known as carbon (C) sinks in their natural form holding an estimated 105 Gt C, with over 57 Gt C in the Southeast Asia (Dargie et al., 2017; Cook et al., 2018). Carbon accumulation that occurs in peat soil takes place when the litter deposition rate exceeds the litter decomposition rate in waterlogged, anoxic conditions. If this process is reversed, C would be released instead (Page & Baird, 2011; Könönen et al., 2016; Tubiello et al., 2016). Tropical peatlands are mainly formed from rainforest trees under conditions of consistent high humidity, temperature and rainfall, and are woody-remains dominated, whereas temperate, boreal and (sub)arctic peatlands commonly form from the remains of grasses, mosses, sedges, shrubs and trees growing in cold temperatures (Page & Baird, 2016). Besides that, peat is usually found to have a pH value of less than 4 (average 3.3) denoting its acidic nature (Hashim et al., 2019).

Based on multiple studies, peat formation is reported to be influenced by several causes such as climatic characteristics (precipitation and temperature), geology, hydrological dynamics (groundwater, river dynamics and seasonality), nutrient pool, topography as well as vegetation dynamics (Yu, 2012; Hapsari et al., 2017; Ribeiro et al.,

2020). Hydrological dynamics is considered as one of the main factors in regulating and controlling peat formation and organic matter decomposition processes (Blodau, 2002; Limpens et al., 2008). Soil in tropical peatland is seasonally flooded due to large rivers containing intense sediment deposition with high nutrient content. This condition is attributable to high precipitation rates and temperatures which “favours the growth of dense tree coverage, with high floristic diversity and high net primary productivity” (Page et al., 2022). The constant high-water table level in peatlands affects the peat decomposition rate as it limits oxygen availability for microbial decomposition of organic materials (Clymo, 1984; Laiho, 2006; Könönen et al., 2016). Figure 2.2 summarizes the process of tropical peat formation.

In general, peatlands located along the coastlines of the Southeast Asia mostly originated during the middle Holocene era (Page et al., 2004; Rieley et al., 2008). Subagjo and Driessen (1972) further explains the peat formation process in these areas; initially, coastal plains are traversed by a number of rivers with low and heavily-textured levees that rise slightly above the nearly permanently-waterlogged coastal plain. Dense vegetation, including reeds and sedges, will develop in the natural depressions of the coastal plains under wet conditions, followed by the formation of partly humidified mesotrophic or eutrophic topogenous peatlands caused by plant debris build-up.

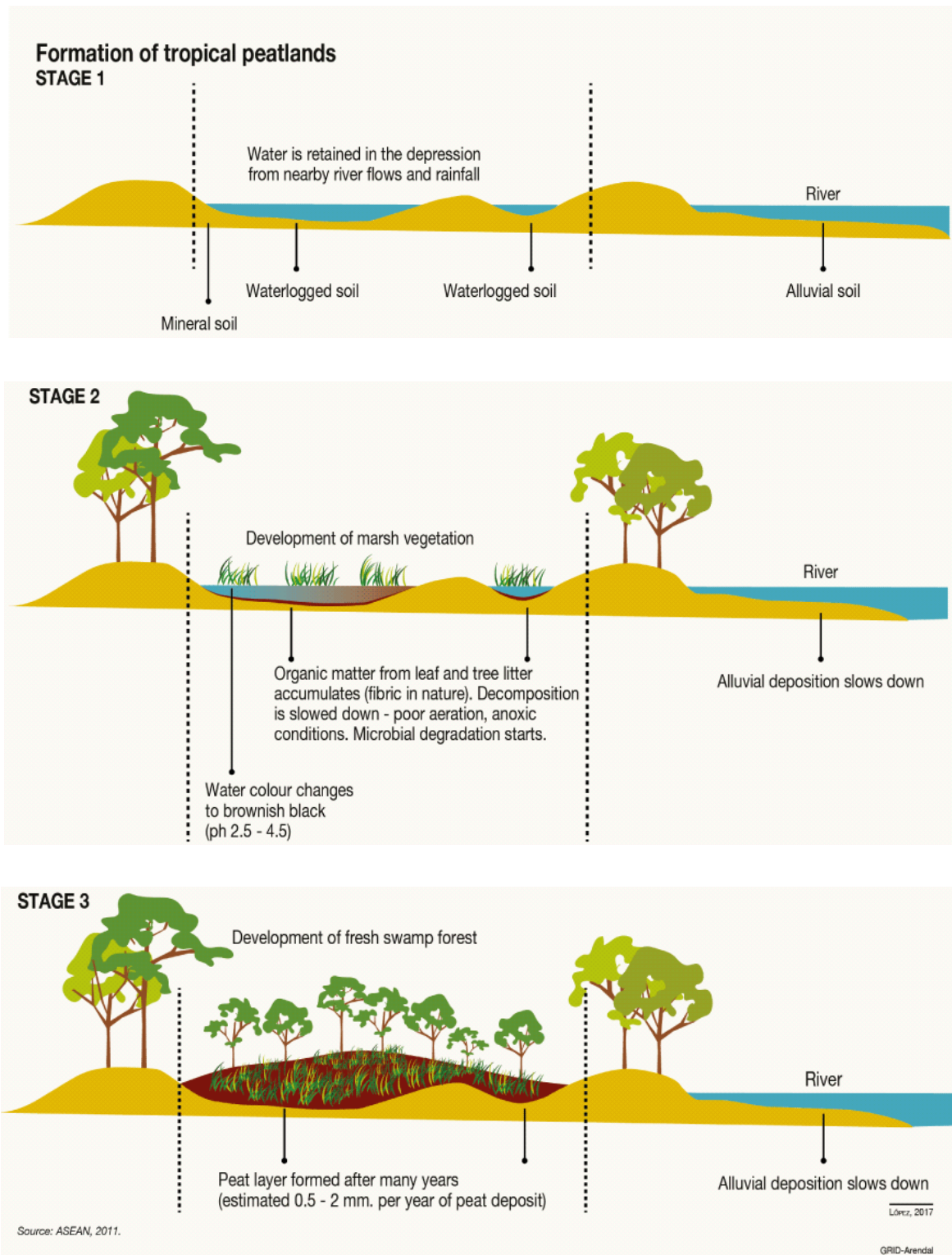


Figure 2.2: Formation of tropical peat (GRID-Arendal, 2017b).

The inflow of relatively mineral-rich river water decreased with increasing peat thickness, causing the soil to become drier and the peat to rise above groundwater level. A progressive growth of marsh forest vegetation occurs, resulting from the growing vegetation which are adapting to the changing environmental conditions. This forest spreads out over time, eventually covering substantial tracts of peat that were by this point well above the initial groundwater level. However, a sizeable portion of the organic material produced by the forest did not decay despite the relatively deep-water table. This was due to the forest's tight canopy maintaining a perpetually moist environment (Anderson, 1961; Osaki & Tsuji, 2016).

2.4 Carbon Stock of Tropical Peatlands

Although peatlands only cover about 3 % of total land area, they contain about a tenth of surface freshwater and a third of the global soil carbon (Joosten & Clarke, 2002; Jackson et al., 2017). Peatlands store about 600 – 650 gigatonnes (Gt) C, making them the largest terrestrial pool of organic C in the biosphere (Yu et al., 2010; Page et al., 2011; Dargie et al., 2017). Page et al. (2011) and Miettinen et al. (2016) reported that the Southeast Asian peatlands form a significant C store of 57 – 66 Gt C (11 – 14 %) of the global peat C.

In undisturbed tropical peatlands, the rate of carbon accumulation ranges between 24 to 300 g C m⁻² year⁻¹ and has been reported much higher in comparison to that in undisturbed boreal and temperate peatlands which has been described in the range of 2 to 271 g C m⁻² yr⁻¹), (Olefeldt et al., 2012; Renou-Wilson et al., 2019). Moreover, the rate of C accumulation in undisturbed tropical peatlands is much more than that of mineral soil-based, intact, old-growth tropical forests in the African and Amazonian region (C accumulation rate in the range 40 – 91 and 0 – 47 g C m⁻² year⁻¹, respectively), (Hubau et al., 2020). Even though C

accumulation rate varies according to peatland types, according to Craft et al. (2008), this variation is dependent on peat formation, hydrology and vegetation type. Other than that, C accumulation rates have been mainly greater in lower latitude areas in the tropical regions (Sjögersten et al., 2014).

2.4.1 Carbon Cycling of Tropical Peatlands

In tropical peatlands, carbon enters the ecosystem photosynthetically and exits as carbon dioxide (CO₂) in a few ways; through autotrophic respiration by plants, CO₂ emission through heterotrophic respiration by microbial organisms, methane (CH₄) emission through anaerobic respiration by methanogenic microorganisms, as dissolved organic carbon (DOC), and, to a minor extent, as particulate organic carbon (POC) which are transported into drainage channels and rivers (Stumm et al., 1996; Billett et al., 2015; Page et al., 2022).

As described thoroughly in Page et al. (2022), carbon accumulation in living biomass, plant litter and peat occur when the photosynthetic C input through net primary production (NPP; photosynthesis minus autotrophic respiration) exceeds the sum of gaseous and fluvial C losses. This condition thus allows the peatland ecosystem to become a C sink. To further elaborate, as the peat is waterlogged, heterotrophic respiration by microbial organisms will occur under anaerobic conditions at a decreased rate, resulting in the release of CH₄ through the methanogenesis process. As a result, organic materials that are not fully decomposed or are just partially digested enter the peat ecosystem (Page et al., 2022). Nevertheless, a greater amount of organic matter will be aerobically decomposed when an aerobic layer forms at the top of the peat column as a result of reduced rainfall or anthropogenic disturbances like drainage. This condition releases C as CO₂ and fluvial C to the atmosphere and surrounding waterways, respectively, causing a potential net ecosystem

C loss (Carlson et al., 2015; Cook et al., 2018). Figure 2.3 shows a diagram of the C cycle in tropical peatlands under various land uses; pristine/near pristine peat swamp forest (PSF), slashed and burned peat forest, peatland developed under monoculture crops, and secondary, restored, or rewetted forest.

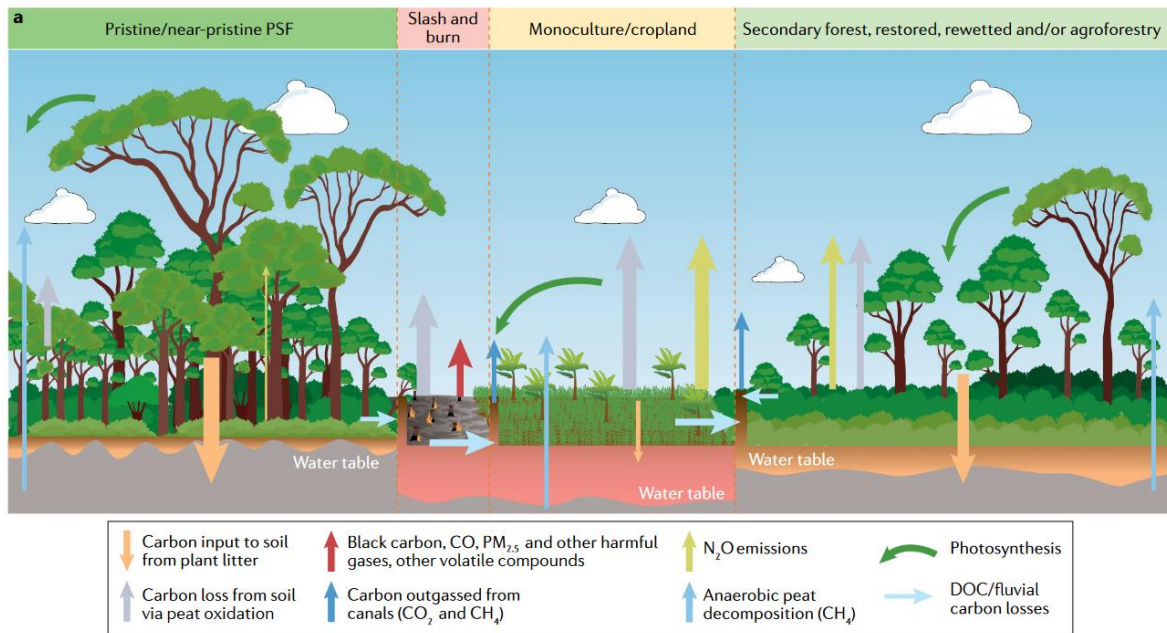


Figure 2.3: The biogeochemical cycling in tropical peatlands of different land uses (Page et al., 2022). The authors in the aforementioned study states that the thickness of the arrows in this diagram indicates the relative flux magnitude in each land use.

2.5 Consequences of Land Use Changes on Tropical Peatlands

Tropical peat deposits constantly build up carbon in steady states in the absence of anthropogenic disturbances (Dargie et al., 2017; Fatoyinbo, 2017). On the other hand, C sink in tropical peatlands is reported vulnerable to human disturbances such as drainage and land use change (i.e., burning, logging, deforestation), as well as climate change (Melton et al., 2022). Changes in temperature, total precipitation, sea level, and the frequency of extreme events all have an impact on hydrology, vegetation composition, net primary

production, substrate quality, decomposition, lateral C fluxes, and peat C accumulation rates. These factors together determine how tropical peat is affected by climate change. However, more research is required to properly establish the connection between the effects of climate change on tropical peatlands (Frey & Smith, 2005; Rieley et al., 2008; Hirano et al., 2012; Hodgkins et al., 2018; Ribeiro et al., 2020).

The dynamics of tropical peatland ecosystems are currently altering more as a result of direct anthropogenic influences. Since the 1990s, land use in tropical peatlands has actively changed especially in emerging nations (Hooijer et al., 2010). Due to social and economic demands to increase agricultural output and economic development, peatlands in Southeast Asia frequently experience deforestation, burning and draining (Hirano et al., 2009; Miettinen et al., 2012; Könönen et al., 2015). Since primary and secondary forests no longer cover 36 % of the original Southeast Asian peat, just 6 % of the surviving peat swamp forests are regarded as being pristine (Miettinen et al., 2016). This is a significant decrease from the estimate made in 2010 (Miettinen et al., 2012). Consequently, the rate of C emissions from peatlands used for agriculture has been large and rising worldwide (Wijedasa et al., 2017). Page et al. (2011) contends that despite the fact that agriculture and forestry development and expansion have increased economic and industry prospects, they have also given significant detrimental effects on the environment.

2.5.1 Hydrological Changes due to Drainage

The cultivation of peatlands requires the removal of original vegetation on peat surface through deforestation and lowering of water table depth through draining. Water table depth, expressed as soil moisture profile, is the distance between ground surface of peat and water table (Carlson et al., 2015). Lowering the water table depth is done to ensure

sufficient aeration of the crops rooting zone (Könönen et al., 2018). For example, in the case of oil palm plantations, it has been recommended that water table depth be maintained effectively in the range of 40 – 60 cm to prevent the oil palm active roots from being waterlogged. Water table within the rooting zone that is too low or high will negatively affect the nutrient uptake and fresh fruit bunches production of the palms (Henson et al., 2008; Lim et al., 2012).

Tropical peatlands have high to extremely high hydraulic conductivity (i.e., permeability) in their natural, undrained state, allowing for saturated or nearly-saturated conditions in the presence of heavy rainfall and rough peat surface (i.e., hummock and hollow microtopography), (Kelly et al., 2014; Baird et al., 2017). However, when peatland is deforested, drained and compacted using heavy machineries prior to crop planting, peat subsurface flow (i.e., water flow beneath the soil surface) increases greatly. Vegetation and forest removal decreases evapotranspiration rates and results in soil surface runoff, whereas drainage has been reported to reduce peat water-storage capacity and porosity (Anshari et al., 2004; Dommain et al., 2010; Baird et al., 2017). These changes are believed to result in an over-supply of water during wet seasons but under-supplied during dry seasons in peatlands which have been converted into agriculture sites, in which the latter would increase the risk of peat soil drying and fire (Mezbahuddin et al., 2015; Baird et al., 2017).

2.5.2 Peat Subsidence

According to Hooijer et al. (2012), hydrological changes in drained peatlands is also responsible for the long-term subsidence of peat, increasing the risk of flooding in these areas. To elaborate, peat subsidence is a result of both physical and biological processes. It happens when drainage lowers the water table causing the peat to compact, and then peat

above the water line oxidises. Once microbial breakdown is stimulated by these mechanisms, CO₂ is eventually released into the atmosphere (Hooijer et al., 2012; Lauren et al., 2021). It has been noted that the initial peat sinking in tropical peatlands is rapid even in the first two years of peatland conversion. During this time, the peat surface might lower by up to one metre (Hooijer et al., 2012). In the Southeast Asia plantation landscapes, subsidence rates have been measured in the range of 3 to 5 cm year⁻¹ after the first subsidence. When peat decomposition process became more prevalent, subsidence rates were reported a mean value of 2.2 cm year⁻¹ across all degraded and converted peatlands (Hooijer et al., 2012; Evans et al., 2019; Anshari et al., 2021; Evans et al., 2021).

In addition to decreasing the ability of tropical peatlands to store carbon (Evans et al., 2019), drainage-driven peat subsidence over time also carries the risk of eventually exposing underlying sands or previously waterlogged pyrite-rich marine clays to aerobic conditions (Wösten et al., 1997; Osaki & Tsuji, 2016). According to Grealish et al. (2013), the oxidation of pyrite (iron sulphide) produces sulphuric acid, which may significantly acidify drainage waters as well as peat. Additionally, metals like aluminium (Al), iron (Fe), manganese (Mn), and arsenic (As) may mobilise into their respective solution forms at lower pH levels (pH 2 or lower). This would cause drainage waters in converted peatlands to be toxic for aquatic life, plants and humans besides bringing about negative impacts on crop production (Klepper et al., 1992; Shamsuddin & Muhrizal, 2000; Suwardi, 2019).

2.5.3 Changes in Carbon Balance and Emission of Greenhouse Gases

The carbon balance of peat has significantly changed as a result of drainage, deforestation, and conversion of peat natural forests into agricultural fields (Miettinen & Liew, 2010). Studies on forested peatlands in Kalimantan, Sumatra, and Sarawak that have

been impacted by logging and plantation development show that peatland C balance is very sensitive to even low levels of disruption (Tang et al., 2020; Deshmukh et al., 2021). This observation was determined through the net ecosystem exchange measurement using eddy covariance technique (i.e., a method for calculating the land-atmosphere C flux [net ecosystem exchange]); the measurements of the net ecosystem exchange showed values between 1.7 and $4.2 \text{ t C ha}^{-1} \text{ year}^{-1}$ (Hirano et al., 2012; Tang et al., 2020; Deshmukh et al., 2021). In comparison, these values were significantly greater than the net ecosystem exchange in a natural peat swamp forest in Sarawak, Malaysia, which stored C at a lower rate of $-1.4 \pm 0.5 \text{ t C ha}^{-1} \text{ year}^{-1}$ (negative value represents peatland as a C sink), (Kiew et al., 2018). Additionally, research in Sumatra found that C emission rates were higher after a forest had been drained and cleared of vegetation ($10.8 \pm 1.1 \text{ t C ha}^{-1} \text{ year}^{-1}$) as compared to before disturbances ($4.2 \pm 2.4 \text{ t C ha}^{-1} \text{ year}^{-1}$). Similarly, rising C loss has been seen along a gradient of forest degradation in Central Kalimantan, where C emissions increased starting from moderately drained, selectively logged forest ($1.7 \pm 2.0 \text{ t C ha}^{-1} \text{ year}^{-1}$) < heavily drained forest ($3.2 \pm 2.0 \text{ t C ha}^{-1} \text{ year}^{-1}$) < drained, burned forest ($5.0 \pm 0.7 \text{ t C ha}^{-1} \text{ year}^{-1}$), (Hirano et al., 2012).

At the same time, heterotrophic emission rate has also been used to compare peat surface carbon effluxes between natural peat ecosystems and cultivated peat. CO_2 fluxes in undisturbed peat swamp forests range between $9 - 14 \text{ t CO}_2 \text{ ha}^{-1} \text{ year}^{-1}$ (Jauhiainen et al., 2005; Swails et al., 2019). Drainage of peat forests accelerates microbial decomposition promoting C loss from deeper peat layers by causing aerobic decomposition to occur deeper in the peat profile (Freeman et al., 2001; Hirano et al., 2014; Ishikura et al., 2019). The majority of this C loss is emitted as CO_2 into the environment (Carlson et al., 2015; Hoyt et al., 2019). According to Mishra et al. (2014) and Dhandapani et al. (2020), a higher land use

intensity, such as from diversified cropping systems to intensively maintained monoculture plantations, further amplifies heterotrophic CO₂ output. According to Lee et al. (2018), drained peatlands in Southeast Asia have contributed to 1.3 – 3.1 % of global CO₂ emissions, whereas Carlson et al. (2015) estimated that agricultural peatlands have CO₂ fluxes of 14 – 20 t CO₂ ha⁻¹ year⁻¹. In the aforementioned study, connections between water table and C loss in cultivated peat under oil palm plantations were also modelled. It was shown that for every centimetre of water table depth increase, heterotrophic respiration rates rose by 0.25 t CO₂ ha⁻¹ year⁻¹.

Peatland drainage and agricultural conversions provide peat surface CH₄ emissions in addition to CO₂ emissions (Girkin et al., 2019). According to published research, the Southeast Asia annual CH₄ fluxes from drained and plantation regions range from 1 to 4 kg CH₄ ha⁻¹ year⁻¹ (Deshmukh et al., 2020; Prananto et al., 2020). Given that CH₄ has a great potential for warming, even if its fluxes are significantly lower than those of CO₂, they are still significant (IPCC, 2019). In tropical peatlands, CH₄ emission rates vary and are frequently impacted by water table dynamics and land use (Sjögersten et al., 2014). For instance, in Terengganu, Malaysia, and North Selangor, Malaysia, a logged forest produced 328 230 kg CH₄ ha⁻¹ year⁻¹, but an undisturbed forest produced 151 100 kg CH₄ ha⁻¹ year⁻¹ (Dhandapani et al., 2019; Cooper et al., 2020).

Fluvial carbon losses may account for a sizable portion of the tropical peat carbon balance, according to recent studies (Evans et al., 2014; Yupi et al., 2016; Cook et al., 2018). Dissolved organic carbon (DOC) makes up the majority of the organic C in rivers and streams, while particulate organic carbon (POC) makes up less than 10 % of the overall flux (Moore et al., 2013; Yupi et al., 2016). According to various studies (Koehler et al., 2014;

Catalán et al., 2015; Logue et al., 2016; Evans et al., 2017), dissolved organic matter (DOM) is made up of a complex mixture of aromatic and aliphatic organic compounds with varying susceptibilities to different physico-chemical and biological processes. These processes include flocculation, microbial respiration, and photochemical degradation. The majority of tropical peat's river C losses are discharged to the ocean. In intact, forested peatlands, this loss is predicted to be $0.6 \text{ t C ha}^{-1} \text{ year}^{-1}$; however, in drained peatlands, the loss can reach $0.9 \text{ t C ha}^{-1} \text{ year}^{-1}$ (Moore et al., 2013; Hiraishi et al., 2014; Yupi et al., 2016). Moreover, according to Wit et al. (2015), over 50 % of the organic C that is leached from tropical peat goes on to mineralize and escape into the atmosphere as CO_2 . This suggests that fluvial losses represent a significant potential indirect source to greenhouse gas emissions.

2.5.4 Changes in Nutrient Cycling

Essentially, tropical peatlands are ombrotrophic ecosystems (i.e., rain-fed), acidic (pH 3.0 – 4.5) and have limited nutrient availability (Weiss et al., 2002; Page et al., 2011). According to Weiss et al. (2002), the availability of nutrients in ombrotrophic peatlands depends on external inputs like rainfall, dust, and marine aerosol, whilst the microbial breakdown of organic waste at or near the peat surface contributes to nutrient stocks inside the system. These nutrient sources are quickly re-bound to microbial and plant biomass (Page et al., 1999; Sjögersten et al., 2011). Due to the near proximity of the water table to the surface, nutrients are therefore most concentrated in the surface peat (Andriessse, 1988; Page et al., 1999; Lampela et al., 2014). In ombrotrophic peatlands, surface nitrogen (N) content is in the range of 1 – 2 % (Page et al., 1999; Weiss et al., 2002; Lampela et al., 2014), slightly lower than N content in minerotrophic peatlands (2.0 – 2.5 %), (Lähteenoja & Page, 2011). In forested peatlands, nutrient contents of nitrogen (N), phosphorus (P), calcium (Ca), magnesium (Mg), and potassium (K) are observed to be 50 or 100 times higher in the upper

peat profiles than those 200 cm below the peat surface; this was linked to biological accumulation in plant roots and litter. A rapid decline in nutrient concentrations is seen below the bioaccumulation zone (Weiss et al., 2002; Lampela et al., 2014).

When tropical peatlands are converted to other land covers, the loss of nutrient stock within the forest biomass occurs due to the decreased input of litter on converted peatlands. Long-term reports also point to changes in nutrient availability and cycling dynamics. According to Lauren et al. (2021), greater organic matter decomposition rates following drainage led to enhanced nutrient release, supplying crops and tree stands with nutrients like P and K. However, due to nutrient leakage and export into drains or other water courses, this rise in nutrient availability may be followed by a nutrient capital decline over a longer period (Könönen et al., 2015).

In comparison to altered sites, where the maximum nitrogen content was found in the topmost peat, the N concentration in peat swamp forest was observed to be higher and more consistent at various depths (Könönen et al., 2018). In addition, the mineralization of organic N is promoted after drainage; N is mineralized into ammonium (NH_4^+) which can be nitrified to form nitrate (NO_3^-), while producing partially oxidized conditions for the production of nitrous oxide (N_2O), (Martikainen et al., 1993; Davidson et al., 2000; Golovchenko et al., 2007; Rubol et al., 2012). Although N_2O emissions are commonly low in intact peatlands, these emissions are deemed sensitive to peat moisture conditions as well as addition of substrate (i.e., addition of plant litter). Fertilizers used in cultivated peatlands may also enhance N_2O emissions, however this is highly dependent on agricultural practices and fertilization application rates (Jauhiainen et al., 2012; Oktarita et al., 2017). For instance, fertilized sites ($178 - 218 \text{ kg N}_2\text{O ha}^{-1} \text{ year}^{-1}$) emit more N_2O than unfertilized sites ($8 - 16$

kg N₂O ha⁻¹ year⁻¹), (Hatano, 2019; Prananto et al., 2020). In contrast, another study, showed that the N₂O emissions were relatively low (3.3 ± 0.4 kg N₂O ha⁻¹ year⁻¹ to 5.0 ± 0.8 kg N₂O ha⁻¹ year⁻¹) although the site was converted from a peat swamp forest to a rice plantation (Hoyos-Santillan, 2016).

2.5.5 Changes in Peat Substrate Quality

A study in Könönen et al. (2018) found that the alteration of water table level and litter deposition rates through drainage and deforestation, respectively, have resulted in poorer tropical peat substrate quality (i.e., peat decomposability). The biological environment that peat provides for microbial decomposers is also influenced by the quality of the peat substrate; alterations in land usage led to a general decrease in microbial biomass and enzyme activity.

One of the primary factors affecting carbon dynamics is litter deposition reduction since it lowers the rates at which C accumulates in converted or cultivated peatlands. Furthermore, it may result in contrasting soil respiration patterns between peat swamp forest and cultivated sites. For example, a higher soil respiration rate was observed in peat under oil palm cultivation compared to peat secondary forest attributable to the lowering of water table level in the former (Melling et al., 2007; Gronlund et al., 2008; Sim et al., 2019). In contrast, some research found higher soil respiration rates in unmanaged swamp forests that had a greater volume of decaying litter, and lower soil respiration rates at peat areas that had undergone intense land management (Hirano et al., 2014; Jauhiainen et al., 2016).

High amounts of labile carbon compounds, as well as nitrogen and phosphorus, are present in peat swamp forests because of the constant litter deposition rate and high-water table (Sjögersten et al., 2011; Hoyos-Santillan et al., 2016; Könönen et al., 2016; Sangok et

al., 2017). When a peat swamp forest is drained, accelerated C loss happens, especially in the first few years after the forest is drained and vegetation is removed. Over time, the rate of C loss then gradually declines (Hooijer et al., 2012). Peat becomes richer in recalcitrant compounds (aromatic and aliphatic compounds) as enhanced C loss takes place (i.e., enhanced decomposition process), but poorer in more labile compounds (polysaccharides, DOC, nutrients like total N, NO_3^- , NH_4^+ , and DON). This results in lower microbial biomass and enzyme activity and, consequently, lower decomposition rate (Page et al., 1999). However, it was determined that additional in-depth research is still needed on the microbial biomass and their activities in tropical peatlands (Könönen et al., 2018).

2.6 Humification Degree of Peat

The conversion of organic matter in various stages of decay into complex, heterogeneous mixes of polydisperse components known as humic compounds is known as the humification process (Sim et al., 2017; Zacccone et al., 2018). In its broadest sense, humification is defined as the conversion of various groups of substances and individual molecules present in living organic matter into humic substances, and ultimately into mineral carbon compounds (Klavins et al., 2008). To be more specific, humic compounds (humins, fulvic acid, and humic acid) are parts of humus (i.e., dark-coloured organic matter in soil).

Understanding how organic matter is changed during mineralization is crucial, particularly in the creation of humic compounds (humification), as this process explains the biogeochemical carbon cycle in peat (Francisco et al., 2003; Perez et al., 2004). The nature of organic matter transformations affects humic substance composition and properties. Numerous studies have adopted humification indices, also referred to as humification indicators, to more accurately determine the properties and rate of degradation of humic

compounds (Lu et al., 2001). Additionally, the maturity of the compost produced has been described using these indicators (Jerzykiewicz et al. 1999; Domeizel et al. 2004).

Usually, indirect measurements are used to analyze the humification process by describing the corresponding structural changes. The study on peat humification degree has been conducted since the 19th century (Aaby & Tauber, 1975). Peat humification degree has been measured using a variety of chemical and physical techniques over the years. Some of the more well-known techniques includes the von Post scale method and the pyrophosphate test. The von Post scale method divides the degree of peat decomposition into 10 grades (H1-H10) based on the colour of the manually squeezed peat pore water and remaining solid material (von Post, 1992). The pyrophosphate test, on the other hand, examines the proportion of peat that is soluble in pyrophosphate (Kaila, 1956). Other methods include examining the quantity and size of the fibre material to morphologically define the decomposition scale (fibric, mesic and sapric), (Farnham & Finney, 1965), as well as through atomic ratio analyses (mainly using C/N, O/C and H/C ratios) and spectroscopic approaches which typically uses Fourier Transform Infrared (FTIR), molecular fluorescence and nuclear magnetic resonance (NMR) spectroscopy, ultraviolet-visible (UV-Vis) spectroscopy and isotope ratio mass spectroscopy (IRMS), (Biester et al., 2014; Philben et al., 2015; Zaccone et al., 2018).

2.6.1 The Relation between Peat Maturity and Humification Degree

Peat maturity and fertility are closely related to the degree of humification (Jerzykiewicz et al., 1999; Domeizel et al., 2004; Sim et al., 2017). Although peatlands, specifically those in the tropics, have been converted into agriculture sites for the growth of various crops (Hooijer et al., 2010), the growth rate and yield potential of these crops grown

on peatlands has been a divisive subject. In Malaysia, studies have shown that the cultivation of oil palms and sago palms on peat have been problematic, in which both of these crops were found to grow slower when planted on deep peat (Sim et al., 2005; Veloo et al., 2015). In another study, it was observed that only 20% of sago palm produced trunk in deep peat. These palms grew better on shallow peat with more than 80% trunking in 5 to 6 years, attaining maturity in 10 years (Jong et al., 2006). Meanwhile, 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, leading to poor rooting and nutrient uptake. Overall, one of the main causes of these challenges is believed to be a result of crops planted on the less humified peat in deeper soil horizon (Veloo et al., 2015).

In the study conducted in a cultivated peat under oil palm plantation and uncultivated peat in secondary forest (Sim et al., 2019), it was observed that the atomic C/N ratio offered a conclusive indication that peat of lower horizons was less decomposed compared to that of surface peat. Moreover, there were significant differences between the oil palm plantation and forest, with the latter demonstrating a lower value at all depths. A lower C/N ratio implies higher humification degree which suggests a larger mobile nitrogen reserve (Sari & Forro, 2008). As deep peat exhibits a relatively higher C/N ratio than surface peat, it suggests that deeper peat was less humified than the latter. Lim et al. (2013) mentioned that the lower horizon of tropical peat in Sarawak consists of a large amount of undecomposed woody materials as well as plant remains. Therefore, as oil palms are planted on deep peat, its growth may be affected by roots which are in contact with undecomposed woody and plant materials (Veloo et al., 2015). These results support the findings obtained in the determination of humification degree using E_4/E_6 ratio of the Fourier Transform Infrared (FTIR) spectroscopy in the same study.

FTIR spectroscopy uses frequencies of absorption bands to probe the functional groups present, besides integrating the abundance and ratios of relative intensities to provide information on the degree of humification. Polysaccharides and phenolic moieties of parent materials are transformed into non-lignin aromatic structures during the humification process, hence, more humified materials as they contain more aromatic groups (Zech et al., 1997; Sim et al., 2017). E_4/E_6 absorbance ratio, which demonstrates the degree of condensation and aromaticity of humic chemicals in peat soil, is a measurement of absorbance at 465 nm and 665 nm. Viegra et al. (2009) reported that with greater E_4/E_6 value, the soil will be less humified. In a study conducted in Sim et al. (2017) on sago palms, it was found that the E_4/E_6 ratio of humic acid from surface peat (0 – 20 cm) was consistently lower compared to those from deeper horizons, even though there were no specific pattern in humification degree between 40 – 100 cm. This result suggests the presence of lower condensation structure (higher humification degree) on the surface peat.

Besides these observations, enhanced nutrient uptake by blackberry (*Rubus* spp.) when grown on more humified substrate (Venegas-Gonzalez et al., 2013) has been reported, whereas Requena (1997) observed improve growth performance of lettuce in association with humification degree.

2.7 Palm Oil Production in Malaysia

The by-product of oil palm fruits, palm oil, is one of the world's most prominent vegetable oils. This oil accounts for 60% of global vegetable oil trade and accounts for one-fourth of global oil consumption (Alam et al., 2015). In tandem with the increase in global population, the global demand for palm oil has also increased due to its competitive prices compared to other vegetable oils and its versatility as an ingredient in various products such

as processed foods, cosmetics, and biofuel (Paspi, 2018; Destiarni & Jamil, 2021; Majid et al., 2021). Palm oil production is concentrated in Malaysia and Indonesia, with Malaysia seeing an increase in the number of oil palm plantations established as one of the country's driving forces in the agro-industry (Alam et al., 2015; World Bank, 2016). In fact, Malaysia oil palm cultivation has grown from 54,700 ha in the early 1960s to 5.64 Mha in 2015. This figure is expected to rise as Malaysia's Ministry of Primary Industry proposes to cap the area of oil palm plantations to 6.5 Mha by 2023 (Yusof, 2019). The total area planted with oil palm area in Sarawak, Malaysia, has increased from 14,091 ha in 1975 to 839,748 ha in 2009 (Veloo et al., 2014) whereas in a recent study (Miettinen et al., 2016), this total area was estimated to have increased to 0.7 Mha in 2015.

In 2004, the establishment of the Roundtable on Sustainable Palm Oil (RSPO) became a turning point for the global palm oil industry. RSPO is a multi-stakeholder initiative and certification scheme which brings together stakeholders of every stage of the global commodities chain with a goal to reduce the negative socio-environmental impacts of oil palm expansion, as well as to promote the growth and usage of sustainable palm oil products through credible international standards (Wijaya & Glasbergen, 2016; Majid et al., 2021; Roundtable on Sustainable Palm Oil, 2023). Following increase in demand for certified sustainable palm oil (CSPO), palm oil-producing nations such as Malaysia and Indonesia have taken the initiatives to establish their own sustainability standards. In 2015, the Malaysian Ministry of Plantation and Commodity (MPIC), together with the country's palm oil industry and the Malaysian Palm Oil Board (MPOB), introduced the Malaysian Sustainable Palm Oil (MSPO) as a national standard to demonstrate the country's commitment towards sustainable palm oil production (Kuntom et al., 2015; Senawi et al., 2019). Through the MSPO, MPOB is involved in the maintenance of, and mitigating the

impact on, environmental ecosystems for the safe and healthy production of palm oil-based products. The compliance with MSPO became mandatory for all Malaysian oil palm producers on 31 December 2019 (Kuntom et al., 2015; Senawi et al., 2019; Sivanandam, 2019).

According to reports, Malaysia has also enforced a strict non-conversion of peatlands and enacted environmental oil palm cultivation rules on existing peat lands; this was in line with the national action plan for peatland development to strengthen the competitiveness of the palm oil industry as well as to inculcate good agricultural practices (GAP) for oil palm cultivation (Khusairi et al., 2018; Ishak et al., 2020; Qaim et al., 2020). As mentioned in Awang et al. (2021), GAP for oil palm cultivation is defined as “the guidance covering field operations in the plantation to transportation of oil palm bunches to the collection centre or mill in order to increase production efficiency and to ensure good quality and safe raw material of oil palm bunches or fresh fruit bunches suitable for palm oil production”, while also taking into consideration the economic, social, and environmental sustainability.

2.7.1 Challenges in Managing Peat in Oil Palm Plantations

In Malaysia, oil palms were originally planted primarily on mineral soils because peat was deemed less favourable due to poor initial cultivation. Nonetheless, cultivated peatlands under oil palms have expanded significantly in the last two decades and are still expanding due to the development of new agronomy and water management technologies, as well as government support (Lim et al., 2012). The cultivation of peat under oil palm plantations have been a divisive subject due to several reasons. Peatland conversions have been reported to bring about negative impacts on the environment such as biodiversity loss and emission of greenhouse gases (for further elaborations, refer to Section 2.5). On the other

hand, the production of optimal oil palm yield is highly dependent on the proper management of peat in oil palm plantations which includes good water table management, good irrigation, and drainage as well as effective methods of fertilization (Sumarga et al., 2016; Manning et al., 2019; Tang et al., 2020; Qaim et al., 2020). Other than that, peat soil fertility and humification degree have been suggested as one of the main factors in controlling oil palm yield (Veloo et al., 2015; Awang et al., 2021).

According to previous studies, soil-water content plays a critical role in decomposition of peat, regulating the carbon loss and influencing its nutrient availability (Teh et al., 2005; Jauhiainen et al., 2008; Carlson et al., 2015; Hashim et al., 2019). Lim et al. (2012) regarded water table as the most important factor affecting plant growth and crop yield on peat and Hashim et al. (2019) further highlighted the importance of water table management in nutrient regulation since the rate of nutrient leaching in peat is dependent on the water table depth. In four-month-old oil palm seedlings planted in lysimeters, mimicking natural conditions of drained tropical peat, the peat with water table of 25, 40, 55, 70 and 85 cm displayed significant differences in nutrient concentrations (Ca, Cu, K, Mg, P), (Hashim et al., 2019). The highest water table (25 cm) showed greatest nutrient losses while the lowest (85 cm) showed the least nutrient losses. At water table depth of 55 cm, oil palm seedlings had fastest growth corroborating the findings by Melling et al. (2007). In oil palm plantations, the water table at 40 – 60 cm is currently recommended to ensure that the palm roots are not waterlogged. Most oil palm roots are found in the upper 50 cm of peat soil profile (Henson & Chai, 1997; Melling et al., 2016). Water table within the rooting zone that is above or below the recommended range may negatively impact the nutrient uptake as well as the production of oil palm fresh fruit bunches (Henson et al., 2008; Lim et al., 2012).

In the case of sago palms planted on peat in Mukah, Sarawak, palms which were planted on deep peat showed retarded growth where only 20 % of the palms produced trunks with none attaining maturity in 10 – 15 years (Purwanto et al., 2002; Jong et al., 2006). Similar issue of lower yield was observed in oil palm planted on deep peat (Veloo et al., 2015; Woittiez et al., 2017; Rauf et al., 2019; Awang et al., 2021). Oil palm planted on deep peat soil with appropriate water management produces the highest yield of 23 – 25 t fruit bunches ha⁻¹ year⁻¹, compared to 30 – 35 t fruit bunches ha⁻¹ year⁻¹ on mineral soils (Tohiruddin et al., 2006; Othman et al., 2011).

CHAPTER 3

MATERIALS AND METHODS

3.1 Study Sites

Peat soil samples were collected from Sebungan Oil Palm Plantation (hereafter also referred as Sebungan Estate; coordinates N 03° 09' 58.32" E 113° 21' 15.43") and Sabaju Secondary Forest (hereafter also referred as Sabaju Forest; N 03° 09' 58.32" E 113° 24' 21.32"), which are located in Sebauh district, East of the town of Bintulu, Sarawak, Malaysia (Figure 3.1 Inset). The climate in this region has generally high temperature (mean temperature of 26 °C to 27 °C) and humidity with precipitation rate over 3000 mm per annum (MET Malaysia, 2019). Peat soil in Sebungan Oil Palm Plantation was established between two rivers, Batang Kemena and Sungai Sebungan (Cook et al., 2018) and was drained prior to oil palm planting in 2007. In Sebungan Estate, semi-matured palms had partially closed canopies that provided some shade for the peat surface. Sabaju Forest was a closed-canopy forest which has undergone up to two cycles of logging in the past. In the Sabaju Forest, the distance between study site and the closest drain, next to the access road was approximately 500 m to the east of the forest (Figure 3.1).

In both sites, one-hectare plots consisting of 25 subplots of 20 m × 20 m, respectively were studied (Figure 3.2). The peat in Sebungan Oil Palm Plantation ranged in depth from 1 m to more than 3 m. The water table was kept between 30 cm and 60 cm below the soil surface by establishing an artificial drainage network in the plantation. This management was based on previous studies in the plantation (Cook et al., 2018; Sim et al., 2019), meanwhile the water table in Sabaju Forest was expected to be higher given the unregulated condition.

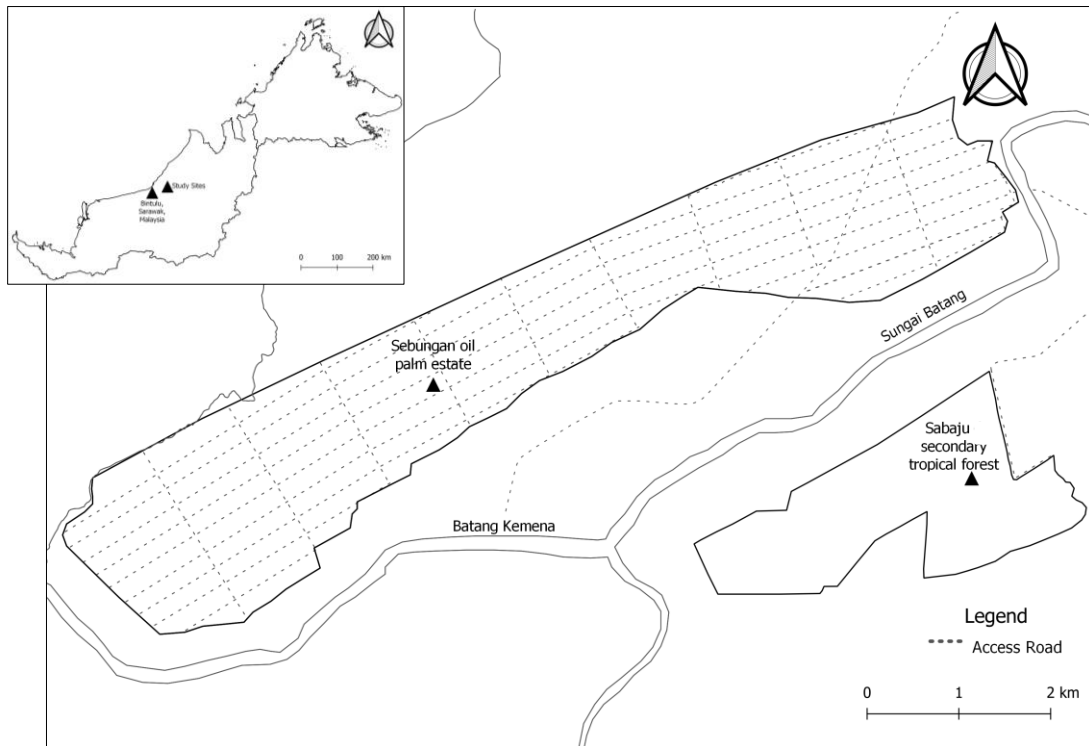
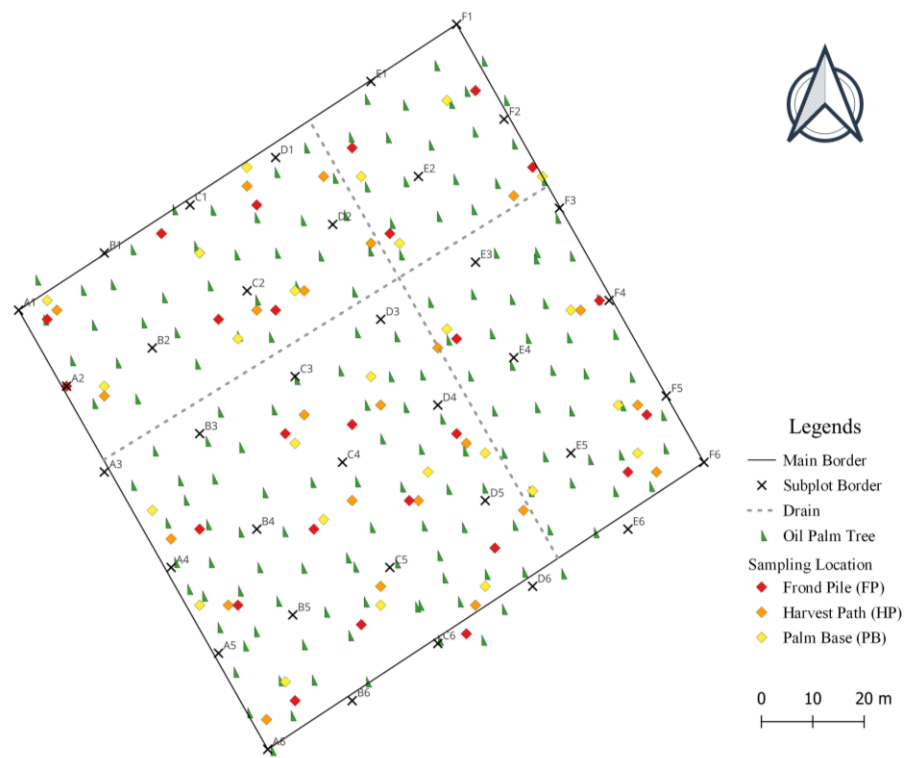
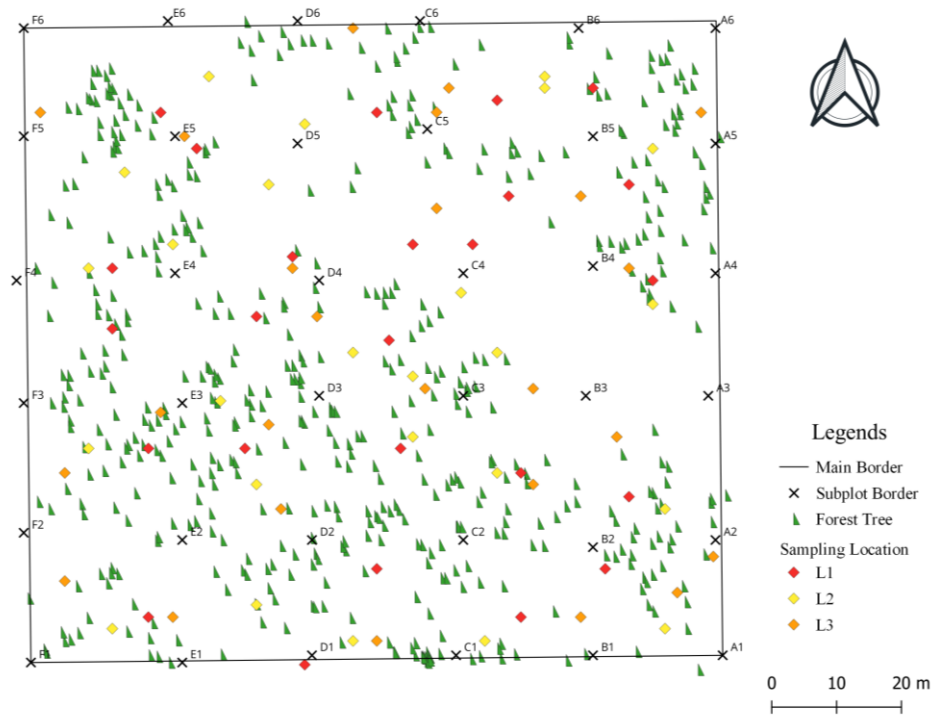


Figure 3.1: Map showing the locations of the two study plots in relation to access road. Inset: location of the study area within Sarawak, Malaysia.



(a)



(b)

Figure 3.2: Map of (a) Sebungan Oil Palm Plantation and (b) Sabaju Secondary Forest.

3.2 Peat Sampling and Preparation

Peat soil sampling was conducted over the course of 4 weeks in July 2019, during the influence of the Southwest monsoon (May to August) which was comparatively drier to the Northeast monsoon (October to January), (Malaysian Palm Oil Board [MPOB], 2006). Peat samples were taken from two depths: 0 – 50 cm and 50 – 100 cm for both sites using a peat auger (Eijkelkamp, core diameter 5.2 cm, length 50 cm) with an extension rod. The samples were removed from the auger, sealed tightly in zip-lock bags and kept below 4 °C before analyses in the laboratory.

Samples in Sebungan Oil Palm Plantation were taken from each of the 25 subplots at three management zones: harvest path (HP), frond pile (FP) and palm base (PB). The

distance between sampling points between the three management zones in each subplot ranged from 2 to 10 metres. Samples from Sabaju Forest were taken from three random points, labelled as L1, L2 and L3 from each subplot. Here, the distance between neighbouring sampling points in each subplot ranged from 5 to 12 metres. To reduce the possibility of contacting impenetrable woody materials, soil sampling in the forest was preferred at flat and open surfaces rather than right next to or between forest trees. Peat core samples obtained at 50 – 100 cm depth (i.e., mineral soil was not hit during sampling). Each cored sample was removed from the auger, sealed tightly in zip-lock bags, and kept below 4 °C before analyses in the laboratory. A total of 300 samples were collected from Sebungun Oil Palm Plantation and Sabaju Forest (2 samples $\times$ 3 sampling points $\times$ 25 subplots $\times$ 2 study sites; i.e., 75 samples from each depth at each site).

During sampling, the geographical coordinates of subplot borders, locations of oil palm and forest tree as well as the sampling points were recorded using a GPS (Garmin GPSMAP 64s, Olathe, KS). Only trees with diameters greater than 10 cm were mapped in the forest; tree diameters ranged from 10.0 to 63.7 cm and tree heights ranged from 7.8 to 31.4 m. Tree diameter and height data were obtained MPOB. Elevation data used in this study was obtained from Google Earth.

3.3 Soil Moisture Content

Peat soil samples were weighed and dried in the oven at 55 °C until a constant weight was achieved. The final weight was taken for the calculation of soil moisture content with reference to the standard method in ASTM D 2974-87 and Sim et al. (2019).

$$\text{Moisture Content (\%)} = \frac{(A-B)}{A} \times 100 \quad \text{Equation 3.1}$$

∴ where A = mass of as-received peat soil, g

B = mass of the oven-dried peat soil, g

Dried peat samples were grinded into fine particles and sieved through 2 mm sieve.

3.4 Elemental Analyses

Total carbon, hydrogen, nitrogen and sulphur of peat soil samples were analysed using the CHNS Elemental Analyzer (Thermo Scientific Flashmart 2000 CHNS Elemental Analyzer, Waltham, MA). Approximately 2.5 – 3.0 mg of soil samples and a similar weight of vanadium pentoxide (V_2O_5), an oxidizer, were transferred into designated tin boxes. Each sample was combusted in a reactor of 1000 °C and analysed in duplicates. The humification degree indicator, C/N ratio was determined using the formula below:

$$\text{C/N ratio} = \frac{\frac{C \text{ percentage}}{C \text{ atomic mass}}}{\frac{N \text{ percentage}}{N \text{ atomic mass}}} \quad \text{Equation 3.2}$$

The same calculation to Equation 4.1 was used to determine the molar ratios of H/C and O/C, respectively. The percentage of O is determined by difference (Zaccone et al., 2007) where % O = 100 – (% ash + % C + % H + % N + % S) in which the ash content is assumed at 4% based on our previous study at the same sites (Sim et al., 2019).

3.5 Fourier Transform Infrared (FTIR) Analyses

Fourier Transform Infrared (FTIR) was used to characterize the functional groups in peat. A composite sample was prepared from triplicate samples of each subplot from Sabaju Forest and Sebungan Estate, giving a total of 100 samples (2 sites × 25 subplots × 2 depths).

The samples were scanned with a ThermoScientific ATR-FTIR (Thermo Nicolet Analytical Instruments, Madison, WI) at a resolution of 0.4821 cm^{-1} in the $4000 - 525\text{ cm}^{-1}$ range. Each spectrum was rationed against a newly recorded background spectrum from the bare ATR crystal. To remove any residuals, the ATR crystal was cleaned with ethanol. The .csv spectra were saved and processed with the automated peak detection and matching algorithm to generate a peak table with rows and columns representing samples and variables (cm^{-1}), (Sim & Ting, 2012). For brevity, the algorithm detects and computes the area of each peak in each spectrum using the first derivative. The identified peaks across all samples are then matched to a pre-defined wavelength window.

3.6 pH and Electrical Conductivity

A 1:10 soil-to-water ratio was used; one gram of peat soil and 10 mL of deionized water were added to a centrifuge tube and thoroughly shaken before being left overnight (Griffiths et al., 2009). A portable pH/conductivity metre (EXTECH ExStixII) was used to measure the pH and EC in sequence.

3.7 Peat Momentary Total Carbon Dioxide Emission Monitoring

Polyvinyl chloride (PVC) collars (diameter 12.5 cm, height 10 cm) for total CO_2 emission measurements had been established in 2017 by MPOB in both study sites. Three collars (refer to Appendix 13) had been placed in every subplot of Sebungun Estate at each of the management zones: harvest path (HP), frond pile (FP), palm base (PB), totalling 25 collars on each management zone and 75 collars ($3\text{ management zones} \times 25\text{ subplots}$) throughout the 1 ha site. Collars at FP management zones were located right next to the frond pile (frond pile was previously moved to expose soil during PVC collars installation), whereas collars at palm bases were located 1 to 2 metres away within the palm trunk circle.

There was only one CO₂ collar in every subplot of Sabaju Forest (i.e., 25 collars in total). Collars were freed from vegetation and litter (bare peat was exposed) to minimize the influence of litter decomposition prior to measurement (Hergoualc'h & Verchot, 2013). CO₂ was measured from the collars by using build-in program in EGM-4 CO₂ Gas Analyzer (PP Systems) and the manufacture's headspace. The distance between the upper rim and the soil surface of each collar was recorded. Soil moisture at depth 15 cm, air moisture and air temperature were recorded prior to each measurement using a soil moisture probe and a thermometer. CO₂ emission measurements were taken on 8 and 9 July 2019, between 7 am to 11 am in Sebungun Estate, and on 18 July 2019 at a similar time in Sabaju Forest. Three rounds of measurements were done at each collar in both study sites. CO₂ emission data obtained from the EGM-4 Analyzer were transferred and organized in Microsoft Excel, and a linear graph of CO₂ concentration versus time (seconds) was plotted for each emission measurement data. Data selection for further processing based on the following criteria:

- 1) The first two recorded CO₂ concentration readouts were not taken into consideration for the linear graph to minimize potential pressure disturbance caused by attaching the chamber to a collar.
- 2) Only plots with $R^2 > 0.9$ were taken into consideration.
- 3) The plot had to include over ten CO₂ concentration data points. The momentary peat total CO₂ emission, CO_{2tot} per unit area was then calculated using the formulae below:

Total CO₂ emission, CO₂_{tot} per unit area:

Equation 3.3

$$\left[\left(\frac{(CO_2 Ref_f - CO_2 Ref_i)}{(Time_f - Time_i) (s)} \times \frac{atmospheric\ pressure\ (mbar)}{1000} \times \frac{273\ (K)}{(Temperature\ (^{\circ}C) + 273K)} \right) \times \frac{44.01\ \frac{g}{mol}}{22.41} \times \frac{SRC\ Chamber\ volume\ (m^3)}{enclosed\ area\ (m^2)} \right] \times \frac{1}{1000} \times 3600\ (s)$$

Chamber volume correction:

Equation 3.4

$$\frac{enclosed\ area\ (m^2)}{SRC\ chamber\ volume(m^3)} \times A$$

$$\therefore \text{ where } A = \left[\left\{ enclosed\ area\ (m^2) \times \left(\frac{height\ of\ collar\ connected\ to\ chamber\ (cm)}{100\ (cm/m)} \right) \right\} + SRC\ Chamber\ volume\ (m^3) \right]$$

3.8 Data Analysis

Statistical analyses on peat elemental analysis, soil properties, palm growth and carbon dioxide emission monitoring were conducted using the Statistical Package for the Social Sciences (SPSS) for Pearson product-moment correlation and Analysis of Variance (ANOVA) with the mean data compared using Tukey's test at $p < 0.05$. The average CO₂_{tot} emission data in Sebungun Estate were calculated for each of the three management zones (HP, FP and PB), whereas in both Estate and Sabaju Forest, the average CO₂_{tot} emission data were calculated according to subplots. The average CO₂_{tot} emission data according to subplots in the forest was used to correlate with the number of trees.

3.9 Spatial Interpolation

In comma-separated values (CSV) files, the study site and peat soil characteristics, such as subplot borders, trees, soil depth, sampling points, moisture, and elevation, were

assigned as attribute features to corresponding geographical coordinates. The corresponding csv files were uploaded to the Quantum Geographical Information System (QGIS) 3.20 software, which displayed the study sites and sampling points as point layers. The inverse distance weighted (IDW) interpolation tool in QGIS was used to spatially interpolate peat soil moisture. IDW interpolation predicts the values of unmeasured points by using points with known values. The closer the known value points are to the prediction locations, the greater the influence in comparison to points further away (Liu et al., 2021). The distance coefficient, p , was kept constant at $p = 2$ for all maps in this study to measure the influence of known values.

In order to determine the soil moisture range in the maps, the minimum and maximum soil moisture values at depths of 0 – 50 cm and 50 – 100 cm were determined and set as the moisture minimum and maximum values in QGIS software. The “Discrete” and “Continuous” classification modes were used to interpolate the maps. In the case of C/N ratio range in Sebungan Oil Palm Plantation and Sabaju Forest, the minimum and maximum value at both depths (0 – 50 cm and 50 – 100 cm) in each study site were determined and was set separately. This was done as the C/N ratio range in Sebungan Oil Palm Plantation was much higher compared to that in Sabaju Forest; when the same C/N ratio range was used for both study sites, the heterogeneity in Sabaju Forest maps could not be visualized clearly. Similar “Discrete” and “Continuous” classification modes were used to interpolate the C/N ratio maps.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Variation of Soil Moisture with Land Use and Peat Depth

In Sebungan Oil Palm Plantation, the average soil moisture at 0 – 50 cm and 50 – 100 cm was 83.9 % and 86.9 % respectively (Table 4.1; refer to Appendices 1 and 2). Across depths, soil moisture from 0 – 50 cm was significantly different from that of 50 – 100 cm ($p < 0.05$). In Sabaju Forest, the average soil moisture was 89.6 % and 91.2 % with increasing soil depth (Table 4.1; refer to Appendices 4 and 5). Similar to the oil palm plantation, differences in soil moisture were significant between forest samples at 0 – 50 cm and the deeper soil profile. The increase in soil moisture with depth in both Sebungan Estate and Sabaju Forest indicates that deeper peat is submerged in water, supporting previous findings of Sim et al. (2019) that peat soil is fully submerged at a depth of 100 cm and below in both sites.

Table 4.1: Average soil moisture in Sebungan Oil Palm Plantation and Sabaju Secondary Forest peat from the surface downwards.

Location	<i>n</i>	Depth (cm)	Soil moisture (%)
			Mean $\pm$ STD
Sebungan Oil Palm Plantation	75	0 – 50	83.88 $\pm$ 3.91 ^a
	75	50 – 100	86.86 $\pm$ 2.10 ^b
Sabaju Secondary Forest	75	0 – 50	89.57 $\pm$ 2.85 ^a
	75	50 – 100	91.24 $\pm$ 1.84 ^b

Same superscript letters between depths in each location indicate no significant differences ($p > 0.05$)

Soil moisture at individual layers between the two land uses showed significant differences for both depths ($p < 0.05$). Overall, soil moisture values in the oil palm plantation were significantly lower than in the secondary forest. The values measured in Sebungan Estate (range 83.9 – 86.9 % at depth range 0 – 100 cm) were all lower than the value for topsoil in Sabaju Forest (89.57 % at 0 – 50 cm).

The available water table data of Sabaju Forest in 2017 and 2018, provided by the Malaysian Palm Oil Board (MPOB), was examined. Water table data collected at Sebungan Oil Palm Plantation in 2018 and 2019 and at Sabaju Forest in 2017 and 2018 were available from MPOB (Figure 4.1). These showed that water table depth varied seasonally, fluctuating within the range 17 – 95 cm (below soil surface) in Sabaju Forest and 52 – 179 cm in Sebungan Oil Palm Plantation. The water table recorded in both the forest and oil palm plantation was at its lowest level in June – September 2018 and 2019 respectively, which are typically the driest months in Malaysia. The annual range of water table level seemingly varied. The average water table depth recorded at Sabaju Forest in 2017 (April to December) was 31.3 ± 19.2 cm and in 2018 it was 66.3 ± 28.4 cm, suggesting that climate conditions, such as precipitation rate and soil surface temperature, affect water table fluctuation in the forest (Wakhid et al., 2018). Water table in Sebungan Oil Palm Plantation recorded water table depth of 58.86 ± 12.28 cm in 2018 and 93.55 ± 43.18 cm in 2019. The average water table at the time of peat soil sampling in July 2019 was 151.98 ± 12.43 cm below the soil surface, which was much lower than the target range of 30 – 60 cm. This may have resulted in very dry soil in even the lower horizon investigated during this study.

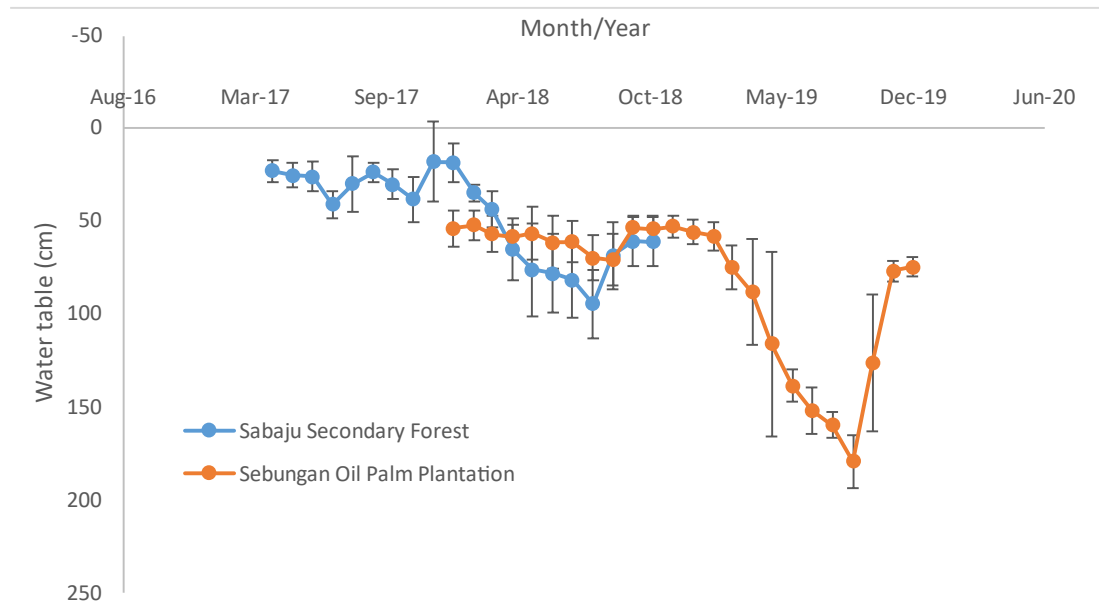


Figure 4.1: Monthly water table data collected in Sebungan Oil Palm Plantation (2018 – 2019) and Sabaju Secondary Forest (2017 – 2018).

The observation of lower moisture data in Sebungan Oil Palm Plantation in comparison to Sabaju Forest was consistent with the findings in Tonks et al. (2017), who reported higher moisture content in surface layer of a secondary forest compared to a mature 10 – 15-year-old oil palm site. Oil palm plantation has larger gaps in the canopy and lower cover of ground vegetation than secondary forest (Hooijer et al., 2012; Dommain et al., 2018). This in turn exposes the ground to more intense solar radiation, leading to increased surface soil temperature (Wosten et al., 2008; Jauhiainen et al., 2014; Wang et al., 2014). Thus, it is likely that the lower moisture levels in the shallowest soil layer at Sebungan Oil Palm Plantation compared to Sabaju Forest was a result of drier and hotter microclimate in the former (Anamulai et al., 2019). A similarly drier microclimate in cultivated peatland was observed by Ludang et al. (2007) in Central Kalimantan, Indonesia. The wetter soil in Sabaju

Forest would be fostered by the greater cover of ground vegetation and the microtopography of the forest floor.

Another reason for drier soil in the oil palm plantation is attributed to the lowering of water table by drainage and compaction of the soil. This contributes to increasing the bulk density of the peat (which results in lower moisture content), especially in the topmost soil layer (Wösten et al., 1997; Huat et al., 2011; Tonks et al., 2017). The bulk density data collected from the same plots in Sebungan Estate and Sabaju Forest in 2017 (Sim et al., 2019) was examined to demonstrate its relationships with the gravimetric soil moisture. The bulk density, y against moisture, x from four depths (0 – 100, 100 – 200, 200 – 300, 300 – 400 cm) comprising of 200 data points were plotted yielding an inverse relationship, $y = -0.01986x + 1.9728$ with $R^2 = 0.94$ (Figure 4.2). The bulk density of the surface soil (0 – 100 cm) from forest (0.64 g cm^{-3}) and oil palm plantation (0.65 g cm^{-3}) were comparable. Moving down the profile, the bulk density was lower with the estate showing higher density than the forest. The surface soil of forest (69.3 %) and oil palm estate (66.7 %) collected in 2017 were drier than the moisture recorded in current study. This can be due to environmental factors such as the precipitation distribution and the dynamics of groundwater level (Qiu et al., 2001; Lee et al., 2018). The plantation soil was drier at 300 – 400 cm (89.4%) than the forest soil at 100 – 200 cm (93.6 %), similar to the trend attained in current study where oil palm plantation peat at deeper horizon was drier than the forest surface peat.

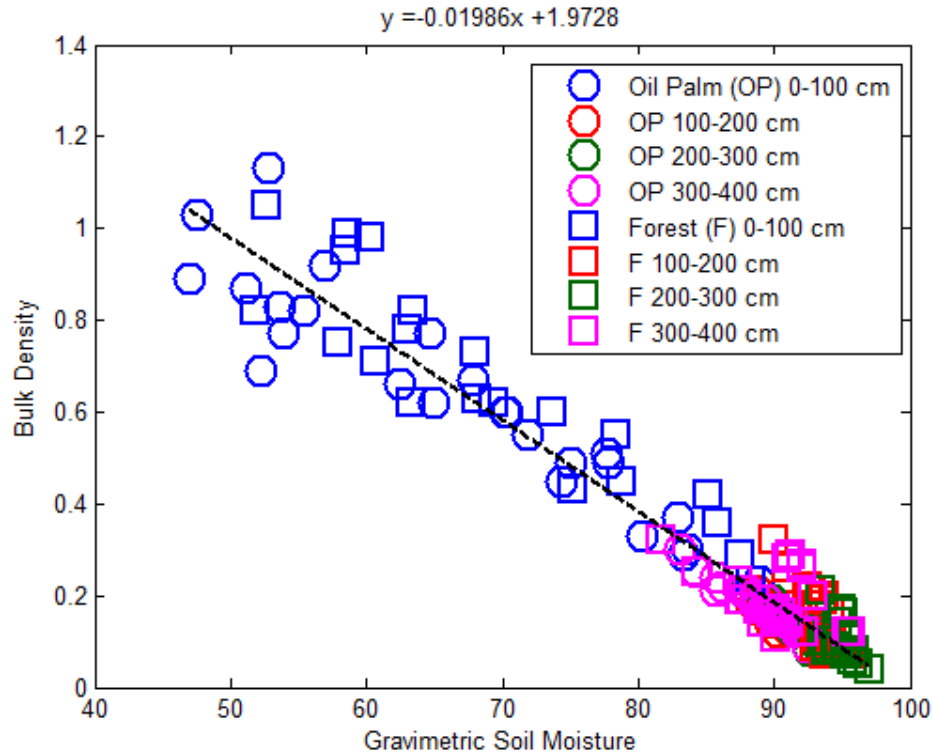
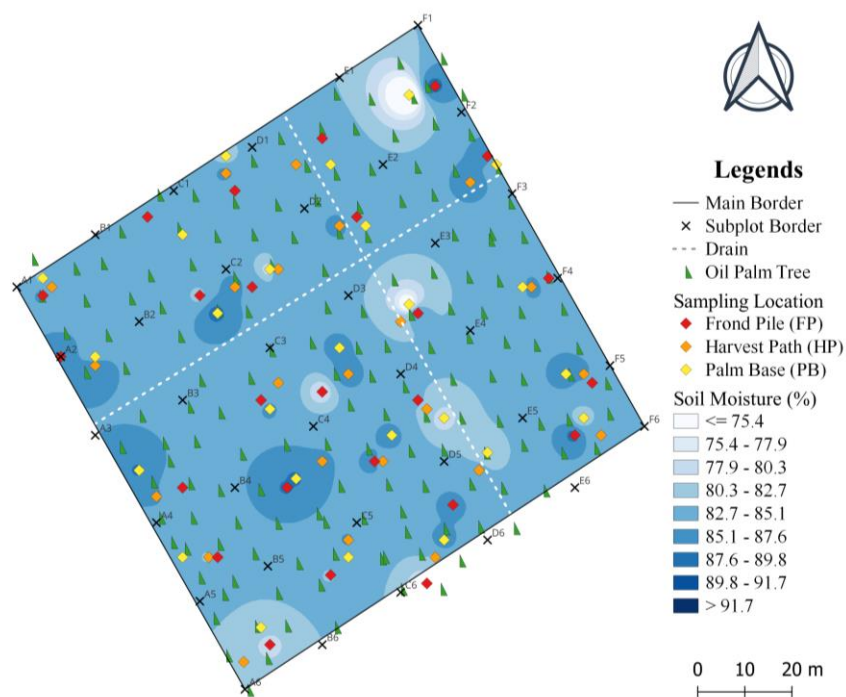


Figure 4.2: Inverse relationship between bulk density and gravimetric soil moisture based on data of Sim et al. (2019).

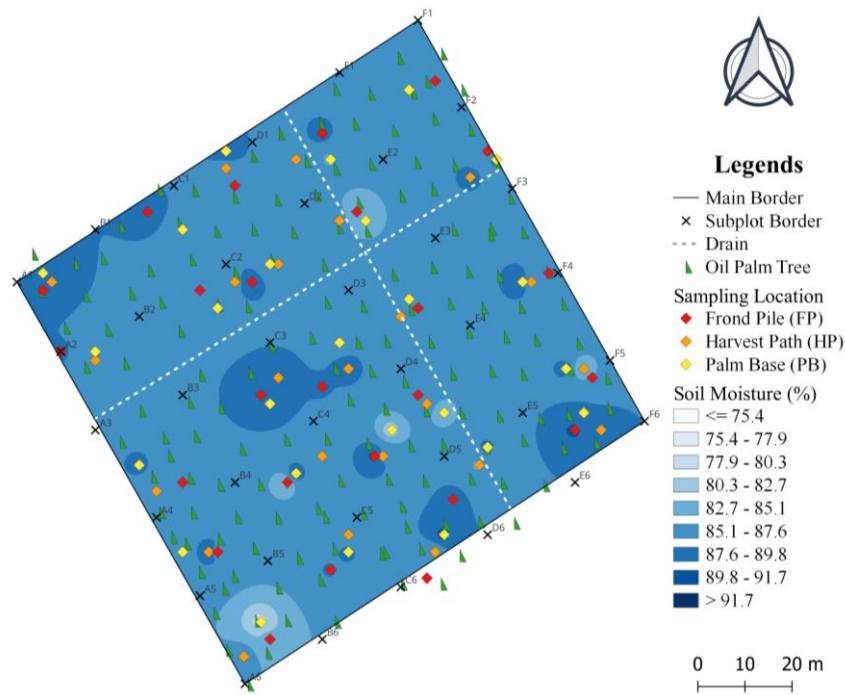
The soil moisture at the different management zones of oil palm plantation, namely harvest path (HP), frond pile (FP) and palm base (PB) throughout the 1 ha plot were compared. The average soil moisture across the 25 subplots at HP, FP and PB were $84.9 \pm 1.7 \%$, $84.3 \pm 3.14 \%$ and $82.5 \pm 5.6 \%$, respectively. The order of moisture content in HP, FP and PB (HP > FP > PB) agrees well with that reported by Manning et al. (2019) but these differences were not significant. Peat soil near PB was drier compared to that at HP and FP, which might be due to higher water uptake from surrounding soil by the palm roots (Safitri et al., 2018).

4.2 Spatial Variation of Soil Moisture and Elevation

The spatial soil moisture in Sebugan Oil Palm Plantation was mapped (Figure 4.3). The profile map of 0 – 50 cm shows that soil moisture ranged between 82 % and 87 % in most areas. The moisture distribution at 50 – 100 cm was relatively more homogenous compared to the surface profile where the soil moisture was between 85 % and 91 % throughout the study site.



0 – 50 cm



50 – 100 cm

Figure 4.3: Maps of vertical soil moisture in Sebungun Oil Palm Plantation.

It is believed that the spatial moisture distribution is controlled by the topographic elevation (Qiu et al., 2001), and the results based on Google Earth data in this study are consistent with this contention. Higher elevated areas may be better drained and thus be characterised by lower soil moisture. A study conducted by Wang et al. (2017) in the roadways of United States of America reported the accuracy of Google Earth elevation was satisfactory and comparable to other sources of elevation data (root mean square error = 2.27 m, standard deviation = 2.27 m, mean absolute error = 1.32 m). Rusli et al. (2014) verified that the elevation data of flat surfaces extracted from Google Earth demonstrate a strong positive correlation with the satellite elevation obtained from the Shuttle Radar Topography Mission 90 (SRTM 90). The average elevation (above mean sea level) in Sebungun Estate was 16.8 ± 0.5 m (SE = 0.046, 95 % CI = 16.86 – 16.86) with a minimum and maximum of

16 m and 18 m, respectively. The average elevation at the three different management zones of HP, FP and PB were 16.7 ± 0.5 m, 16.8 ± 0.7 m, 16.7 ± 0.5 m, respectively and showed no significant differences. Based on the elevation map of Sebungun Estate (Figure 4.4), the spatial elevation distribution was rather homogenous in most parts of the oil palm plantation. Pearson product-moment correlation was estimated to assess the relationship between the average moisture at 0 – 50 cm and elevation in the plantation; an inverse correlation between the two variables was established although they were not statistically significant ($r = -0.169$, $p = 0.147$, $n = 75$).

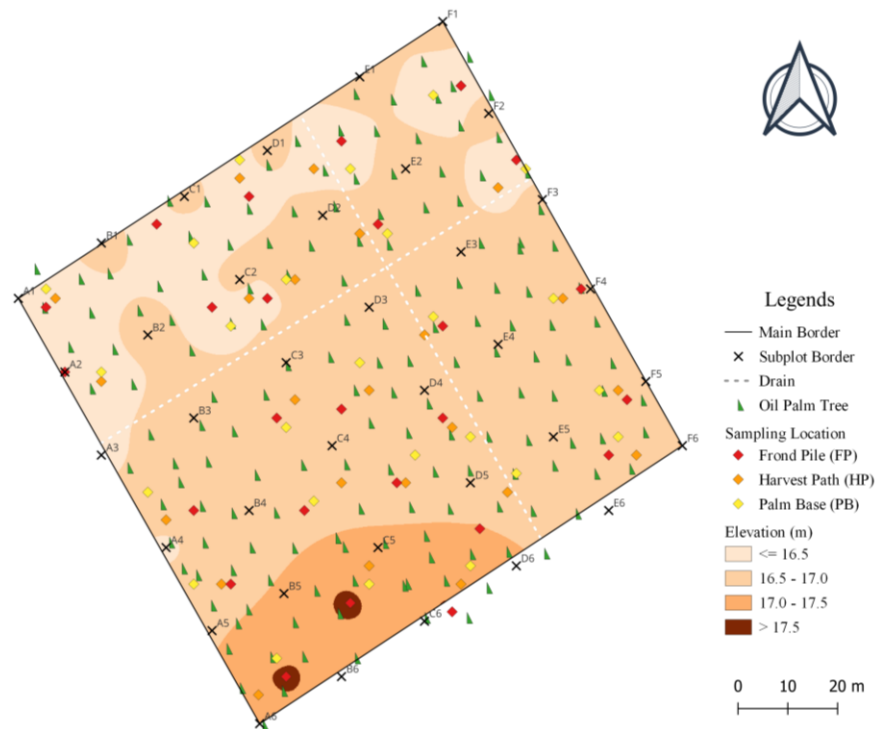


Figure 4.4: Map of elevation in Sebungun Oil Palm Plantation.

The spatial variation of soil moisture in Sabaju Forest was mapped (Figure 4.5). Soil below 50 cm in Sabaju Forest had a moisture between 85 % and 94 %. The top layer (0 – 50 cm) had a slightly lower moisture content of 76 % to 88 % with a few areas showing wetter

properties up to 94 %. Overall, the spatial maps revealed more heterogeneous moisture distribution in the forest. This is likely due to the random distribution of aboveground vegetation and its microtopographic heterogeneity. Forest peat samples in this study were mostly taken from flat, open surfaces rather than next to or in between trees where depressions would be present nevertheless in some subplots this was unavoidable. This sampling strategy was taken during sampling as the peat auger often landed on hard, undecomposed tree trunks in deeper peat profiles.

The average elevation in the forest was 20.01 ± 1.62 m above mean sea level ($SE = 0.153$, 95 % $CI = 19.71 - 20.31$), which differed significantly from the estate. In agreement with the role of topography in controlling the spatial distribution of soil moisture (Qiu et al., 2001; Yang et al., 2017), a higher moisture percentage at 0 – 50 cm profile was in areas with relatively lower elevation (Figure 4.6). Correlation analysis confirmed this observation as the average soil moisture at 0 – 50 cm was inversely correlated to elevation in Sabaju Forest. Similar to the estate, however, the values were not statistically significant ($r = -0.124$, $n = 75$, $p = 0.289$). Similar results were obtained for the correlation between average soil moisture and number of trees by subplot ($r = -0.09$, $n = 25$, $p = 0.966$). In addition, a significant inverse correlation was observed between the average elevation and number of trees by subplot ($r = -0.561$, $n = 25$, $p = 0.003$).

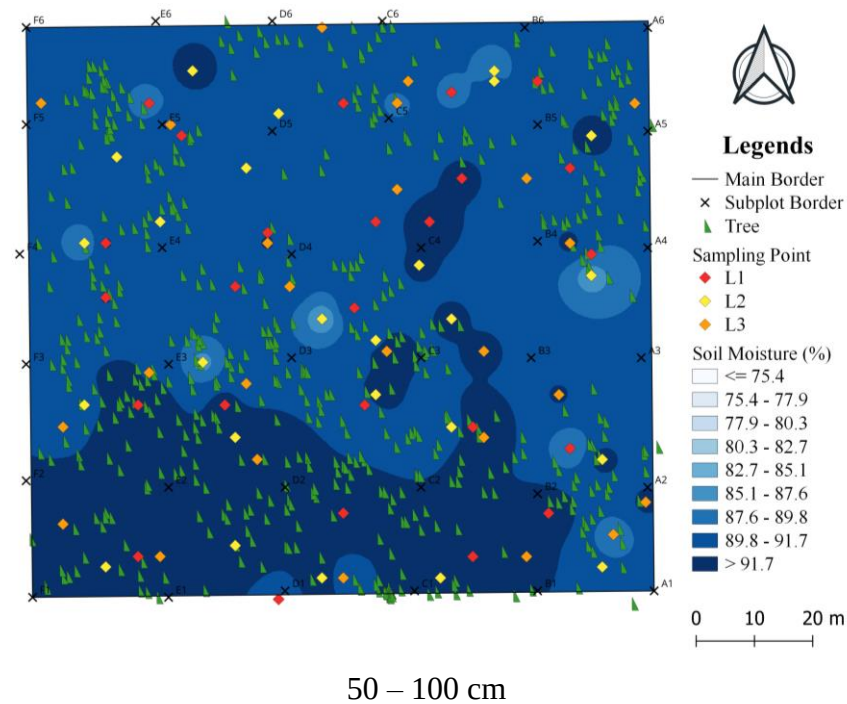
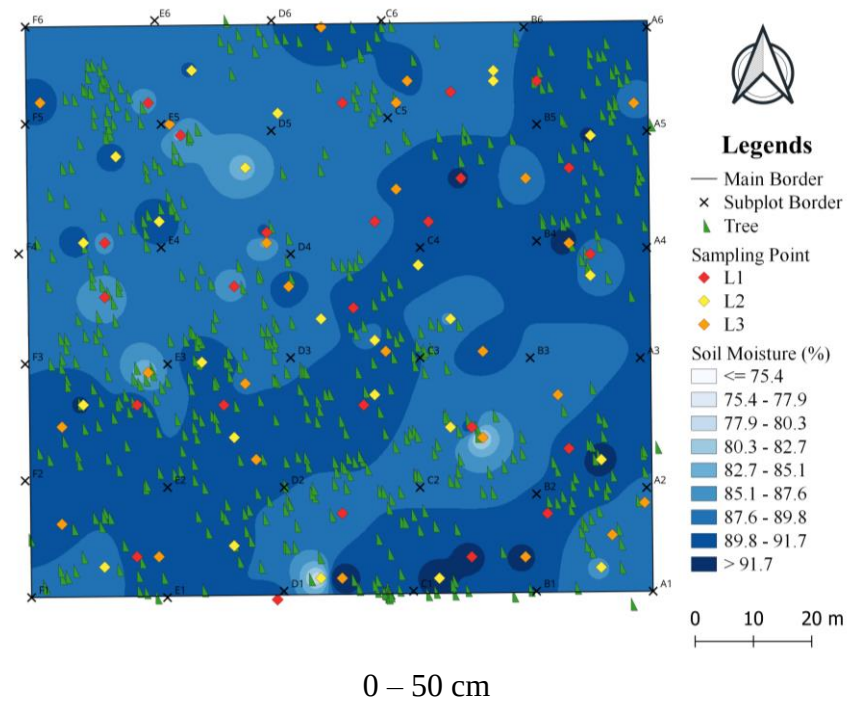


Figure 4.5: Maps of vertical soil moisture in Sabaju Secondary Forest.

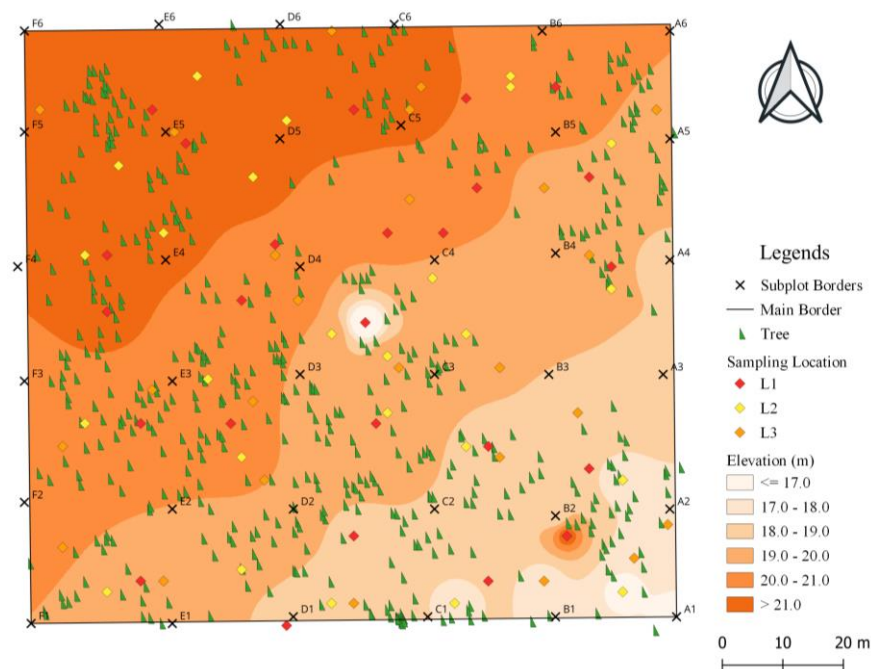


Figure 4.6: Map of elevation in Sabaju Secondary Forest.

4.3 Correlation of Soil Moisture with Oil Palm Growth

In this study, the soil moisture has a direct effect on the palm growth. The spatial moisture map was correlated with the palm growth data obtained from MPOB for 2014 to 2018 (i.e., oil palm growth measurements were not continuously conducted, hence unavailable for 2019). A significant positive correlation was established between the soil moisture at 0 – 50 cm with the average trunk diameter of 156 oil palms ($r = 0.413$, $n = 25$, $p = 0.04$). Figure 4.7 illustrates the percent growth in diameter of palms and the average soil moisture of subplots. Through the map in Figure 4.8, it was observed that some palms which exhibited negative growth in trunk diameter were mostly located in relatively drier subplots or near to the drain.

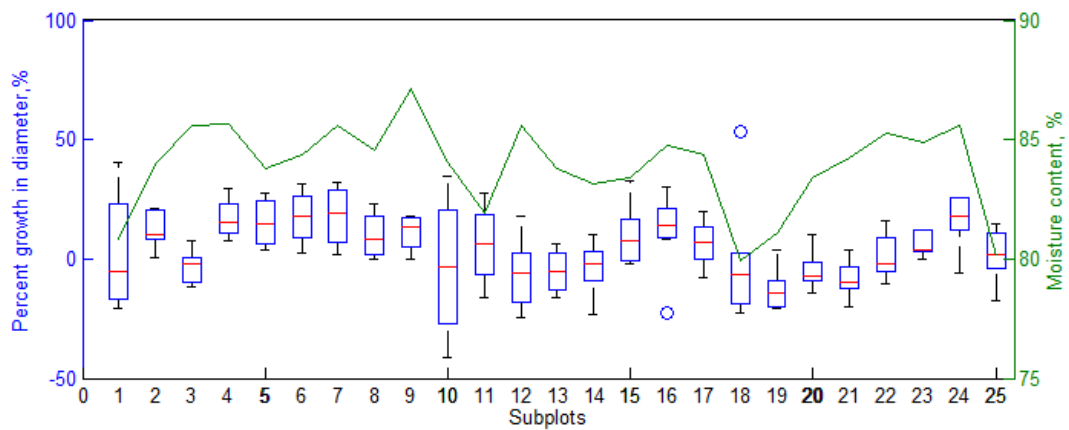


Figure 4.7: Percent growth of trunk diameter based on data from 2014 – 2018. Percent growth of trunk diameter and 0 – 50 cm soil moisture content in 25 subplots. The number of oil palms in the subplots range from 4 – 10.

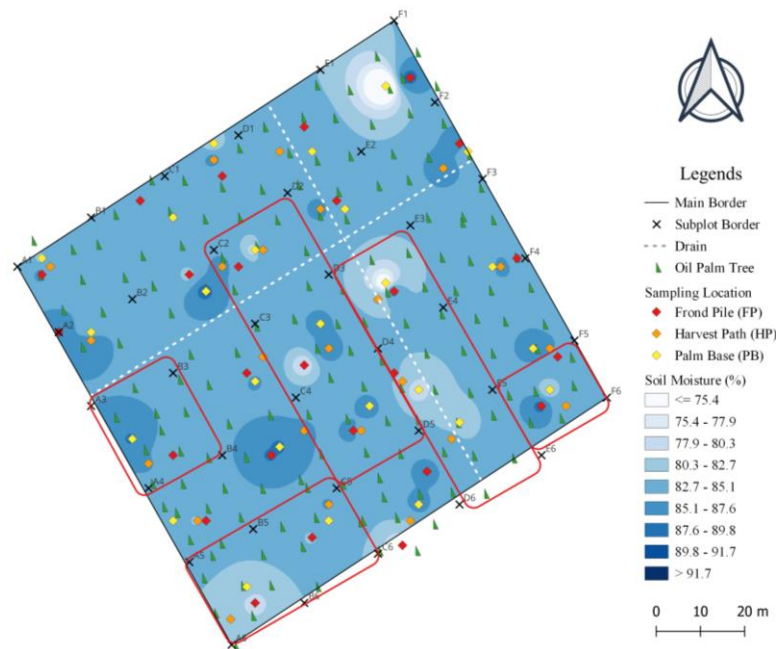


Figure 4.8: Map highlighting subplots with oil palm trees showing negative trunk diameter growth (indicated within red boxes) at 0 – 50 cm moisture profile.

Diurnal fluctuations of trunk diameter have been well documented in literature (Junjittakarn et al., 2011; Chan et al., 2016), however a continuous decrement of diameter has not been extensively researched in the case of oil palms. Negative trunk growths are

commonly associated with measurement errors in the early years of planting (Lesser & Kalsbeek, 1999; Pastur et al., 2007). However, consistent reverse annual growth is possibly due to a decrease in water content in the stem, which in return results in contraction of the trunk at different rates (Baronasa et al., 2001; Pastur et al., 2007; Itaka et al., 2014).

4.4 Humification Degree

Table 4.2 shows the C, H, N and O content in peat soil from Sebungan Estate and Sabaju Forest according to depth. The nitrogen content of forest peat was higher than that of plantation peat, supporting the findings of Muniandy et al (2009). The total carbon content of the surface peat in plantation and forest was statistically insignificant, however, the quality may differ as lowering of the water table would accelerate decomposition, leaving recalcitrant carbon predominating in the cultivated peat (Könönen et al., 2016; Könönen et al., 2018). The C content in Sebungan Estate at 0 – 50 cm (53.09 ± 3.09 %) was significantly lower than that at the deeper peat of 50 – 100 cm (57.95 ± 2.46 %). This trend was in the reverse order in the forest with the topsoil (52.49 ± 4.06 %) containing higher C than the deeper soil (50.86 ± 2.32 %) ($p = 0.003$). Changes in the H and O content by depth was likewise different in the plantation and forest. The H content in Sebungan Estate at 0 – 50 cm (5.42 ± 0.53 %) was lower than that at 50 – 100 cm (6.08 ± 0.41 %). Sabaju Forest on the other hand had higher H content in the topsoil. The O content in the plantation decreased with increasing depth and this trend was inverted in the secondary forest. Variations in elemental compositions indicate humification degree variability in the two ecosystems, which can be further evaluated using the atomic ratios of C/N, H/C, and O/C (Table 4.3; refer to Appendices 6–9).

Table 4.2: Average carbon, nitrogen, hydrogen and oxygen percentages in Sebungan Oil Palm Plantation and Sabaju Secondary Forest peat from the surface downwards.

Location	Depth (cm)	n	Mean $\pm$ STD			
			C (%)	N (%)	H (%)	O (%)
Sebungan	0 – 50	74	53.09 $\pm$ 3.09 ^a	1.10 $\pm$ 0.29 ^a	5.42 $\pm$ 0.53 ^a	40.30 $\pm$ 3.38 ^a
Oil Palm Plantation	50 – 100	72	57.95 $\pm$ 2.46 ^b	1.04 $\pm$ 0.19 ^a	6.08 $\pm$ 0.41 ^b	34.90 $\pm$ 2.72 ^b
Sabaju	0 – 50	74	52.49 $\pm$ 4.06 ^a	1.50 $\pm$ 0.27 ^a	5.38 $\pm$ 0.68 ^a	40.56 $\pm$ 4.79 ^a
Secondary Forest	50 – 100	73	50.86 $\pm$ 2.32 ^b	1.46 $\pm$ 0.16 ^a	4.82 $\pm$ 0.53 ^b	42.80 $\pm$ 2.66 ^b

Same superscript letters between depths in each location indicate no significant differences ($p > 0.05$)

At 0 – 50 cm, C content in the oil palm plantation was in the order of HP (54.18 $\pm$ 1.79) > FP (52.84 $\pm$ 2.67) > PB (52.25 $\pm$ 4.11). N content and H content at the three management zones were in the following order; N content: HP (1.15 $\pm$ 0.27) > PB (1.11 $\pm$ 0.35) > FP (1.04 $\pm$ 0.25), H content: HP (1.15 $\pm$ 0.27) > PB (1.11 $\pm$ 0.35) > FP (1.04 $\pm$ 0.25). For O content, it was in the order of PB (37.30 $\pm$ 3.38) > FP (36.59 $\pm$ 3.09) > HP (35.04 $\pm$ 2.17). Significant differences were only observed between PB and HP ($p = 0.049$) for the O content, whereas no significant differences ($p > 0.05$) were observed between the three management zones for C, N and H content. At 50 – 100 cm, C content was in the order of FP (58.20 $\pm$ 2.39) > HP (57.96 $\pm$ 2.36) > PB (57.64 $\pm$ 2.72), N content in the order of PB (1.09 $\pm$ 0.19) > FP (1.04 $\pm$ 0.21) > HP (1.00 $\pm$ 0.13), H content in the order of HP (6.10 $\pm$ 0.39) > FP (6.08 $\pm$ 0.43) > PB (6.03 $\pm$ 0.42) and O content in the order of PB (31.40 $\pm$ 2.73) > HP (30.82 $\pm$ 2.73) > FP (30.57 $\pm$ 2.73). Similarly, no significant differences were observed between the three management zones for C, N, H and O content at the lower peat depth.

The carbon-to-nitrogen, C/N ratio is widely used as an indicator for soil productivity where a lower C/N ratio is attributable to higher mobile N reserves. When peat soil is drained for agricultural activities, organic nitrogen is converted into ammonium; under aerobic condition, nitrification process takes place, oxidizing ammonium to nitrate ions which are subsequently reduced into nitrous oxide via microbial denitrification (Jauhiainen et al., 2012). The markedly higher C/N ratio in the oil palm plantation signifies escalated decomposition; under aerobic condition with reduced litter input, the soil will eventually deplete in N (Sari & Forro, 2008; Klavins & Purmalis, 2013; Könönen et al., 2016). It is evidenced that nitrification is enhanced upon lowering of water table in drained peat (Regina et al., 1996). Comparable results were registered in our previous studies comparing the secondary forest peat and cultivated peat for sago and oil palms (Sim et al., 2017; Sim et al., 2019). Ch'ng et al. (2009) reported significant decrease in N content of peat with increasing age of oil palm plantation; the longer the peat is subjected to plantation, the lower is the N content. This observation is likely associated with the alteration in N dynamics upon the land use conversion. The nitrification in peat cultivated with oil palm was accelerated with fertilisation and fluctuation in soil moisture. Fertilization was a more significant factor as this increased microbial activity, enhancing nitrogen mineralisation and escalating its loss to the environment (Ariffin et al., 2019).

By depth, the surface peat in Sebungun Estate exhibited significantly lower C/N (60.31 ± 8.83) than that at 50 – 100 cm (66.97 ± 7.78), ($p = 0.008$). Similar findings of higher C/N in the surface peat were reported in the previous studies (Raghunandan & Sriraam, 2017; Sim et al., 2019). Hypothetically, the C/N ratio is expected to decrease with increasing depth as the microbial activity intensifies, improving nitrogen availability. This contradictory trend suggests inconsistency in N mineralisation rate probably due to the

alternating dry and wet conditions in soil (Biester et al., 2014). The C/N ratio in Sabaju Forest is different from the results in the plantation; no significant difference was deduced in the mean C/N ratios of the two profiles. The N-cycling and N-transforming microbial community in the natural and drained peatland was found to be significantly dissimilar; denitrification and N₂ fixing potential were lower in the cultivated peatland whereas in the natural peat, denitrification and dissimilatory nitrate reduction to ammonium (DNRA) pathways are the controlling mechanisms (Espenberg et al., 2018).

Table 4.3: Average C/N, H/C and O/C ratio in Sebungan Oil Palm Plantation and Sabaju Secondary Forest peat from the surface downwards.

Location	Depth (cm)	n	Mean $\pm$ STD		
			C/N ratio	H/C ratio	O/C ratio
Sebungan Oil	0 – 50	74	60.31 $\pm$ 8.83 ^a	1.22 $\pm$ 0.07 ^a	0.52 $\pm$ 0.06 ^a
Palm Plantation	50 – 100	72	66.97 $\pm$ 7.78 ^b	1.26 $\pm$ 0.04 ^b	0.40 $\pm$ 0.03 ^b
Sabaju Secondary	0 – 50	74	41.88 $\pm$ 3.28 ^a	1.22 $\pm$ 0.06 ^a	0.53 $\pm$ 0.10 ^a
Forest	50 – 100	73	40.94 $\pm$ 2.81 ^a	1.13 $\pm$ 0.06 ^b	0.58 $\pm$ 0.05 ^b

Same superscript letters according to location in each column indicate no significant differences ($p > 0.05$)

The H/C and O/C ratios are used as indicators of structural changes in humic matter (Sim & Mohamed, 2007; Klavins & Purmalis, 2013; Moore et al., 2018). As humification advances, the humic matter is typically enriched with carboxylic and aromatic characteristics, indicative of more persistent lignin fraction over polysaccharides (Norden et al., 1986). The H/C is an index of aromaticity whilst the O/C indicates the quantity of oxygen-containing functional groups present. The average H/C and O/C in Sebungan Estate and Sabaju Forest fluctuated in the range of 1.13 – 1.26 and 0.4 – 0.58, respectively, with

significant difference between depths. The relationships between O/C, H/C and C/N are further illustrated using the van Krevelen diagram (Figure 4.9). The diagram is classically used to indicate the maturity of kerogen and petroleum; as the substrate decomposes from vegetation through organic matter into peat and coal, decreasing O/C and H/C ratios is anticipated (Large & Marshall, 2015). The O/C and H/C ratio typical to peat soil is $0.1 \leq \text{O/C} \leq 0.67$ and $0.7 \leq \text{H/C} \leq 1.5$ respectively which due to lignin/carboxylic-rich compounds with aromatic and aliphatic moieties (Ide et al., 2017).

The functional group characteristics of peat was examined using FTIR. The IR spectra profile showed major absorption signals in the regions of $3600 - 3000 \text{ cm}^{-1}$ (O-H), $3000 - 2800 \text{ cm}^{-1}$ (C-H), $1800 - 1500 \text{ cm}^{-1}$ (C=O and C=C) and $1300 - 1000 \text{ cm}^{-1}$ (C-O). The ratio signals at 1700 cm^{-1} (carbonyl and carboxylic C=O), 1600 cm^{-1} (aromatic C=C and COO⁻) and 1510 cm^{-1} (aromatic C=C and C=O of amides) against that at 1030 cm^{-1} (polysaccharides) are used as the humification indices (Holmgren & Norden, 1988; Niemeyer et al., 1992; Beer et al., 2008). Figure 4.10 illustrates the IR spectra of forest and plantation peat with the humification indices calculated based on selected wavelengths. The increasing ratio of A_{1700}/A_{1030} , A_{1605}/A_{1030} and A_{1510}/A_{1030} points to increasing decomposition as a result of polysaccharides degradation. The plantation peat demonstrated relatively higher A_{1700}/A_{1030} signifying pronounced carboxyl and carbonyl attributes. Overall, the atomic ratio depicts that forest peat contained higher level of nitrogen compared to oil palm plantation peat, nevertheless, the latter exhibits greater abundance of carboxyl groups.

Humification takes place through two stages; the initial process involves microbial degradation of labile plant-derived compounds forming products enriched with nitrogen,

followed by formation of humic substances with decreasing nitrogen and methoxyl groups but increasing carboxyl and carbonyl moieties. This postulates that forest peat is at the earlier stage of humification, less decomposed than the plantation peat; the lowering of water table for oil palm plantation would expose the upper peat profile to permanently increased aerobic decomposition.

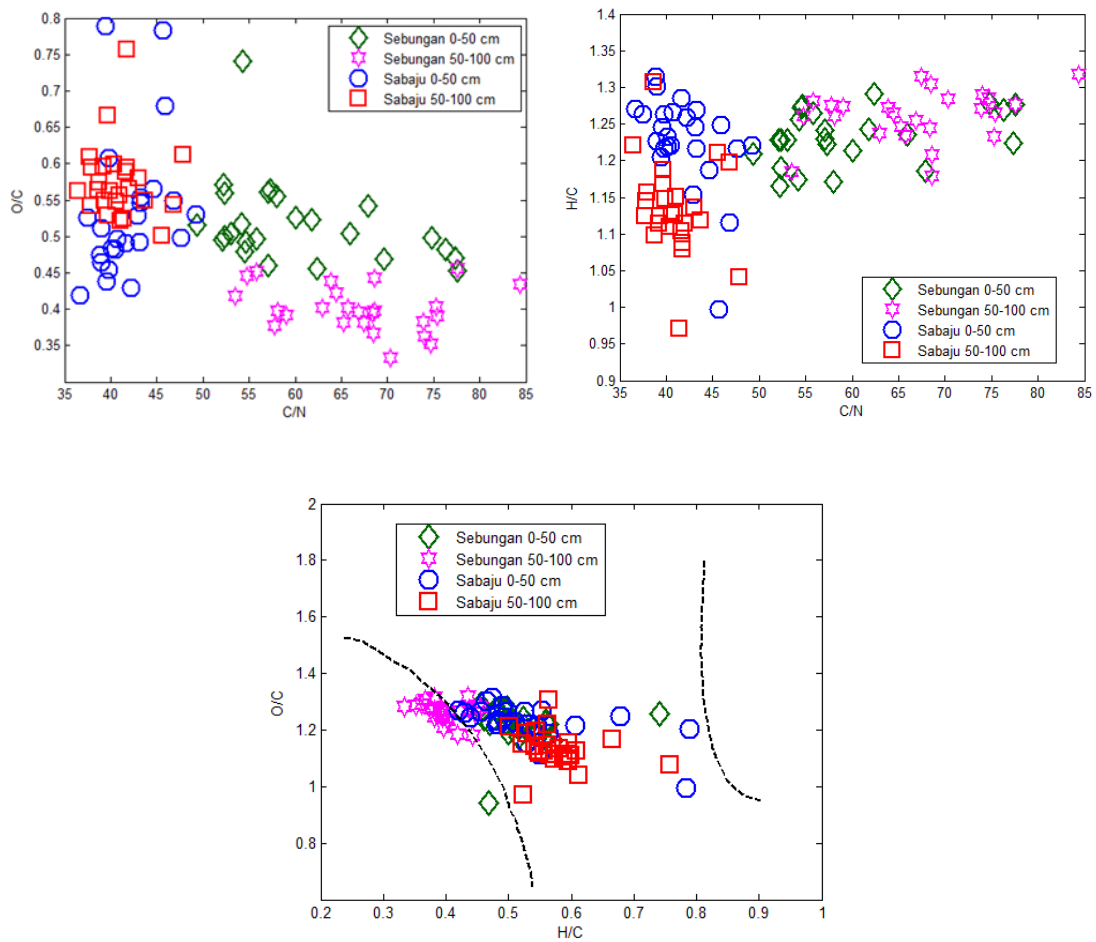


Figure 4.9: The relationships between O/C, H/C and C/N.

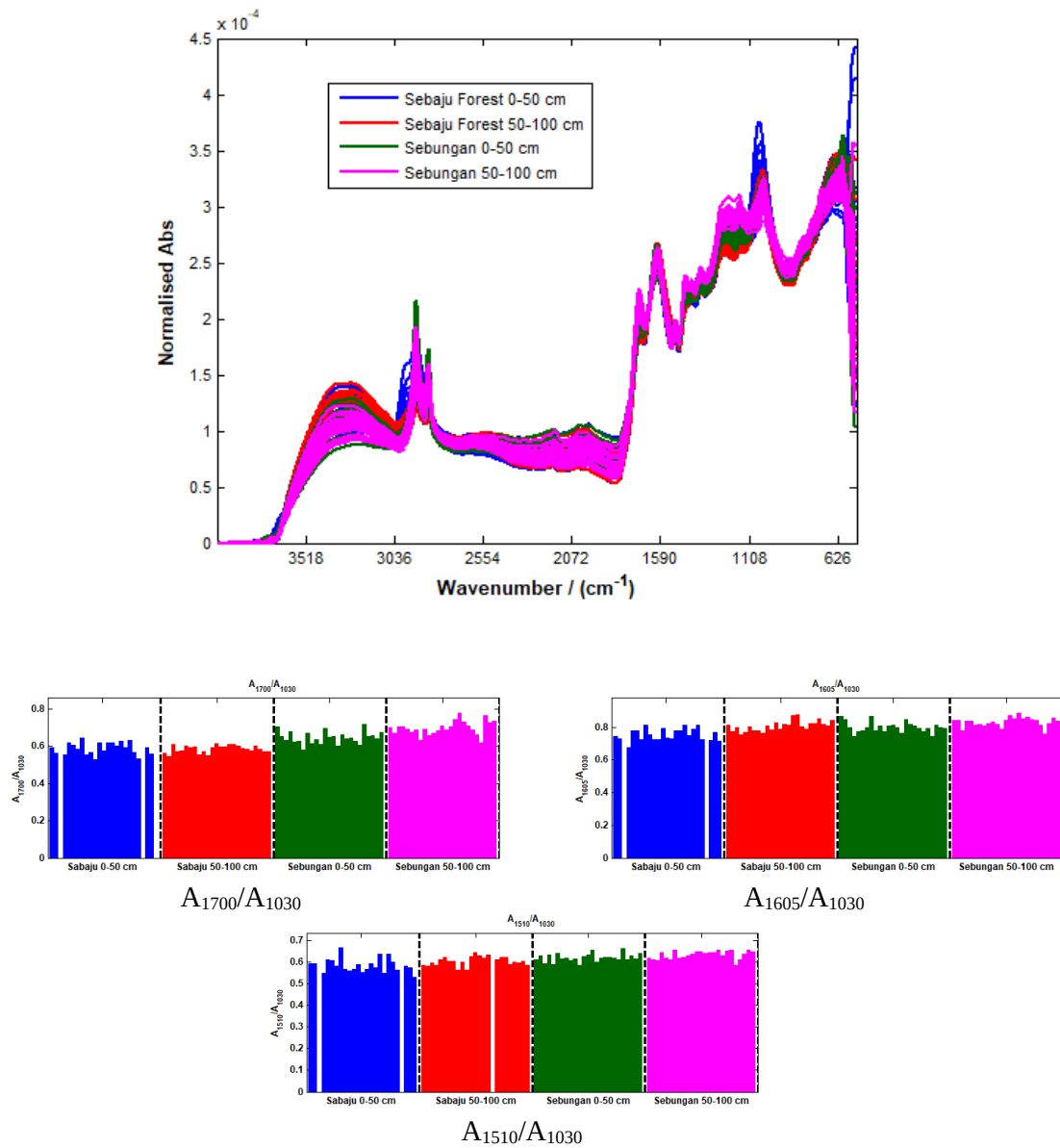


Figure 4.10: IR spectra profile of forest and plantation peat with the corresponding humification indices.

Figure 4.11 illustrates the relationship between the C/N ratio and the A_{1700}/A_{1030} humification index. The index demonstrates that plantation peat is more humified than forest peat, with the former having a higher C/N ratio. Classically, the C/N ratio is an indicator of the humification degree where a lower C/N implies more humified state. In the comparison between the two ecosystems (oil palm plantation against forest), the plantation peat which

was drained and subjected to permanent lowering of peat table demonstrated higher C/N which inferred a lower humification degree, contradicting with the index. This gives an indication that the C/N ratio of the two ecosystems cannot be compared directly due to their differences in N-cycling ecology; the plantation has a lower N-cycling rate but a greater potential of N-loss via nitrification process profoundly (conversion of NH_4^+ to NO_3^-) in which the losses can be boosted in manifolds upon fertilization (Silver et al., 2005) whereas in the forest, anaerobic denitrification and DNRA pathways involving conversion of NO_3^- to N_2O and NH_4^+ , respectively predominate. The land use changes would alter the N dynamics changing the soil C and N stoichiometry. Hence, the C/N ratio is used to compare the humification degree within a similar ecosystem.

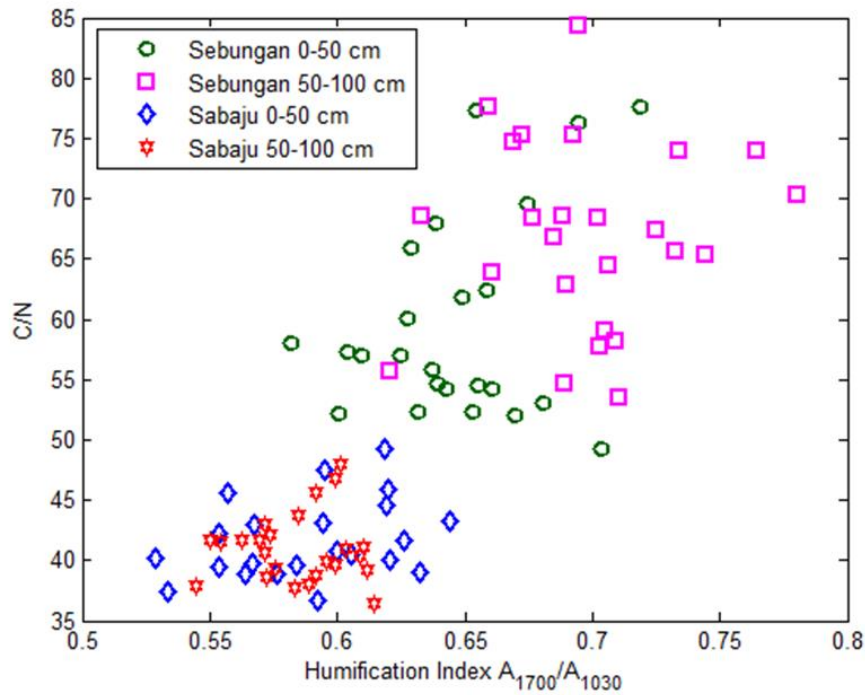
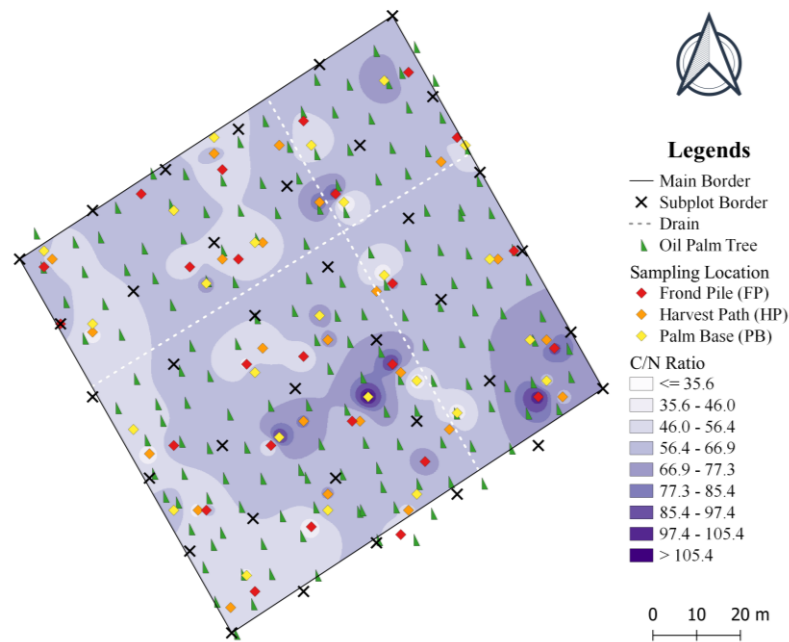


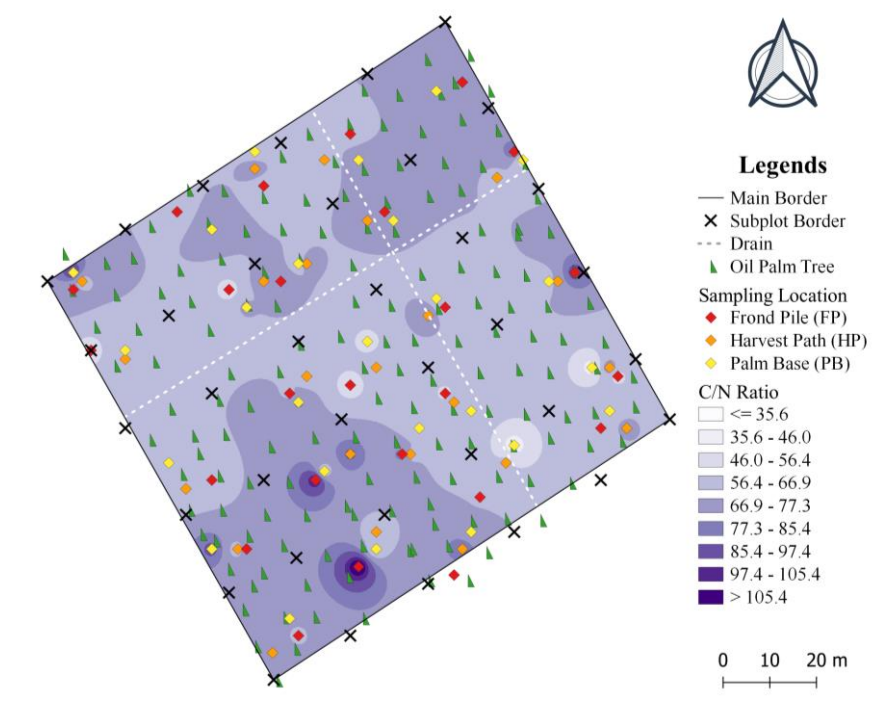
Figure 4.11: The C/N ratio against the humification index of A_{1700}/A_{1030} .

4.5 Spatial Variation of C/N Ratio

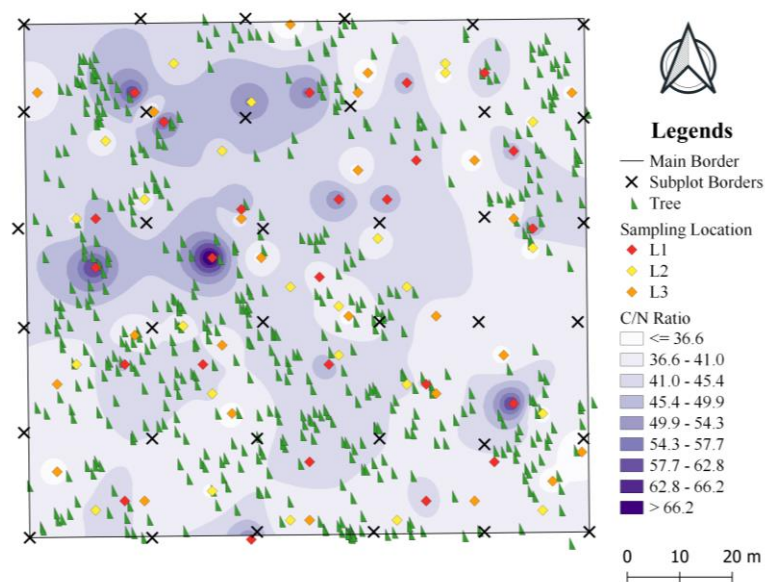
Figure 4.12 illustrates the spatial map of the C/N ratios. At 0 – 50 cm, the region towards the west of the plantation is seemingly more humified (lower C/N ratio: 35.6 – 46.0) than other areas within the profile (higher C/N ratio: 46.0 – 97.4). At 50 – 100 cm, the areas surrounding the drains are characterized with lower C/N ratio (46.0 – 56.4, more humified), comparable with the humification degree at the surface. In Sabaju Forest, topsoil peat in the north-west of the forest was less humified with C/N ratio greater than 45.4 at 0 – 50 cm depth with a similar C/N ratio pattern observed at 50 – 100 cm. The area towards the east of the forest appears to be more humified (lower C/N ratio) at both peat profiles. To determine the relationship between C/N ratio and the number of trees in subplots, a correlation analysis was performed. The C/N ratio was found to be inversely related to the number of trees ($r = -0.2$, $p = 0.338$, $n = 25$), supporting the relationship between soil humification and plant growth (refer to Section 4.6).



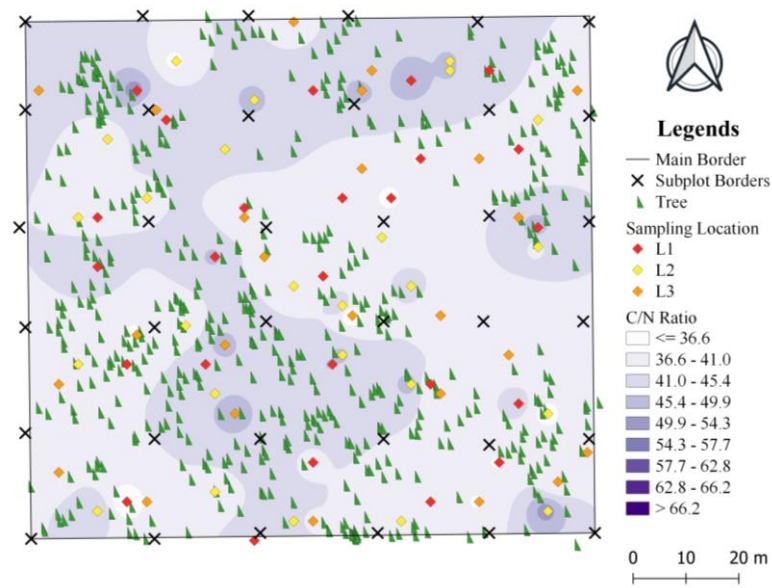
(a) 0 – 50 cm



(b) 50 – 100 cm



(c) 0 – 50 cm



(d) 50 – 100 cm

Figure 4.12: Maps of C/N ratio in (a, b) Sebungan Oil Palm Plantation (range: 35.6 – 105.4) and (c, d) Sabaju Secondary Forest (range: 36.6 – 66.2).

4.6 Correlation of Humification Degree with Oil Palm Growth

The C/N ratio was found to be related to palm growth, in which the 2014 to 2018 data was provided by MPOB. C/N ratio and palm growth based on the number of fronds ($n = 25$, $r = -0.400$, $p = 0.048$) and the diameter at breast height ($r = -0.283$, $p = 0.171$, $n = 25$) had inverse correlations. This observation (highlighted in Figure 4.13) suggests that oil palms which grow on peat with lower C/N ratio produce more fronds with greater diameter size. Some palms with lower number of fronds were found in subplots with relatively higher C/N ratio. The spatial analysis confirms the variability of humification degree in peat soil with higher degree of decomposition located near the drainage system.

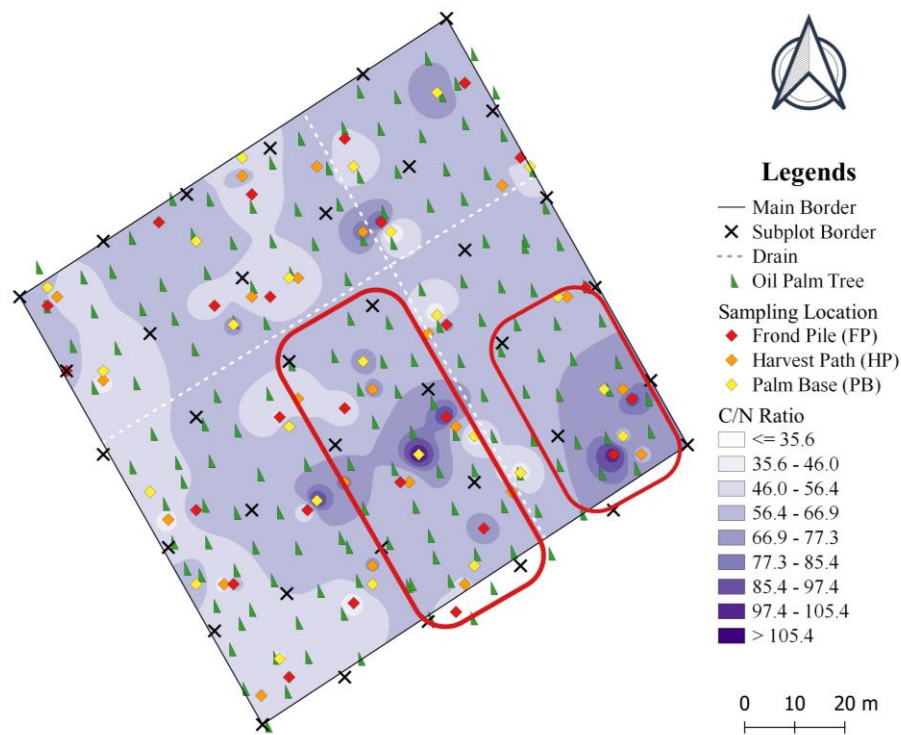


Figure 4.13: Map highlighting subplots with oil palm trees exhibiting lower number of fronds (indicated within red boxes) at 0 – 50 cm peat profile.

4.7 pH and Electrical Conductivity

The mean pH value at soil profiles 0 – 50 cm in both Sebungun Oil Palm Plantation (3.58 ± 0.26) and Sabaju Forest (3.98 ± 0.28) was significantly lower than at 50 – 100 cm (Table 4.4; refer to Appendices 10 – 11). The lower soil pH at 0 – 50 cm in the oil palm plantation compared to forest is likely a result of enhanced soil nitrification as reported in drained peat elsewhere (Lang et al., 1995; Hikmatullah & Sukarman, 2014). Additionally, higher topsoil pH in the forest compared to plantation postulates enhanced microbial activity in the former; forest peat decomposition is enhanced due to continuous inputs of labile C compounds (i.e., cellulose and hemicellulose) from various forest vegetations (Moilanen et al., 2012; Könönen et al., 2016).

Comparing the pH of 0 – 50 cm peat at the three management zones, the results were in decreasing order of PB (3.67 ± 0.27) > FP (3.56 ± 0.27) > HP (3.51 ± 0.22). A similar pattern was observed at the lower soil profile with higher pH; PB (4.01 ± 0.35) > FP (4.00 ± 0.31) > HP (3.94 ± 0.14). These findings contradict those of Tan et al. (2014), who discovered that the microsite surrounding the palm trees is the most acidic, followed by the harvest path and frond heaps. The continuous application of fertilisers surrounding palm trees has promoted soil nitrification escalating the release of H^+ whilst the higher pH at FP is attributed to the liming effect of frond decomposition. The pH pattern of PB > FP > HP attained in this study is in agreement with Formaglio et al. (2020) which observed significantly higher base saturation at palm circle and stacked-fronds management zones compared to that of inter-row. This was due to consistent input of fertiliser, lime and biomass litters at palm circle and stacked-frond zones (Formaglio et al., 2020).

Table 4.4: Average pH and electrical conductivity in Sebungun Oil Palm Plantation and Sabaju Secondary Forest peat from the surface downwards.

Location	<i>n</i>	Depth (cm)	pH	EC (μ S)
			Mean $\pm$ STD	Mean $\pm$ STD
Sebungun Oil Palm Plantation	75	0–50	3.58 ± 0.26^a	290.51 ± 316.78^a
	75	50–100	3.98 ± 0.28^b	215.14 ± 153.41^a
Sabaju Secondary Forest	75	0–50	3.68 ± 0.27^a	163.12 ± 24.92^a
	75	50–100	3.86 ± 0.32^b	189.44 ± 42.59^b

Same superscript letters between depths in each location indicate no significant differences ($p > 0.05$)

Electrical conductivity (EC) in the plantation ($290.51 \pm 316.78 \mu\text{S}$) is notably higher than the forest ($163.12 \pm 24.92 \mu\text{S}$). At the three plantation management zones, EC results were in decreasing order of FP ($322.47 \pm 513.95 \mu\text{S}$) > PB ($278.88 \pm 178.52 \mu\text{S}$) > HP ($270.17 \pm 108.39 \mu\text{S}$) at 0 – 50 cm whereas in deeper soil profile, EC results were in decreasing order of HP ($232.56 \pm 38.64 \mu\text{S}$) > FP ($216.0 \pm 255.81 \mu\text{S}$) > PB ($196 \pm 70.51 \mu\text{S}$).

Our result of higher EC in the plantation than forest was consistent with findings reported elsewhere; higher EC values were observed in degraded peatland (Walter et al., 2012) and more decomposed peatland (Asadi & Huat, 2009) compared to peatland in natural state and less decomposed peatland, respectively. Asadi & Huat (2009) further highlighted EC decreased as soil organic matter content increased; this correlation between EC and organic matter content is due to the soil cation exchange capacity (CEC), (Slater & Reeve, 2002; Walter et al., 2012). More decomposed peat has a higher CEC, holds a negative charge (i.e., peat has a net negative charge caused by the dissociation of H^+ ions from organic matter functional groups during decomposition process) and thus has more chargeable colloidal particles compared to less decomposed peat. This leads to higher EC in the former (Asadi et al., 2009; Asadi & Huat, 2009).

4.8 Momentary Peat Surface Carbon Dioxide Emission

Figure 4.14 summarizes the peat surface total CO_2 , $\text{CO}_{2\text{tot}}$ emissions from Sebungun Estate and Sabaju Forest at the time of sampling. The forest emitted an average of $0.8265 \pm 0.26 \text{ g CO}_2 \text{ m}^{-2} \text{ hr}^{-1}$, which was significantly higher than the oil palm plantation ($0.5397 \pm 0.27 \text{ g CO}_2 \text{ m}^{-2} \text{ hr}^{-1}$) throughout the 25 subplots (refer to Appendix 12). Statistical analysis was conducted to compare mean $\text{CO}_{2\text{tot}}$ emissions between management zones HP, FP and

PB; total emissions increased in ascending order of FP ($0.3614 \pm 0.11 \text{ g CO}_2 \text{ m}^{-2} \text{ hr}^{-1}$) < HP ($0.5865 \pm 0.21 \text{ g CO}_2 \text{ m}^{-2} \text{ hr}^{-1}$) < PB ($0.6878 \pm 0.18 \text{ g CO}_2 \text{ m}^{-2} \text{ hr}^{-1}$). $\text{CO}_{2\text{tot}}$ emission at FP was significantly lower than at HP ($p = 0.012$) and PB ($p < 0.05$) but there was no significant difference between HP and PB ($p = 0.362$).

In this study, the monitored $\text{CO}_{2\text{tot}}$ emissions in both study locations include emissions from various contributing conditions and sources including activity of live roots (autotrophic respiration) and organic matter decomposition (heterotrophic respiration), (Rustad et al., 2000; Chen et al., 2011; Melling et al., 2013; Girkin et al., 2018). The contribution of autotrophic root emissions to the total soil CO_2 emissions depends on vegetation type and the region in which peatlands are located (i.e., non-tropical or tropical); it varies between 10 – 90 % in non-tropical peatlands (Hanson et al., 2000) and 9 – 36 % in tropical peatlands (Jauhiainen et al., 2012). Theoretically, root respiration is expected to be less at cultivated peat than the forest due to denser network of tree roots in the latter (Hirano et al., 2009; Sundari et al., 2012), nonetheless the contribution of live roots respiration cannot be clearly determined from this study. However, it has been reported elsewhere that soil surface litter contributes greatly to total soil CO_2 emission through the enhancement of peat decomposition in drained sites (Hirano et al., 2009; Sundari et al., 2012).

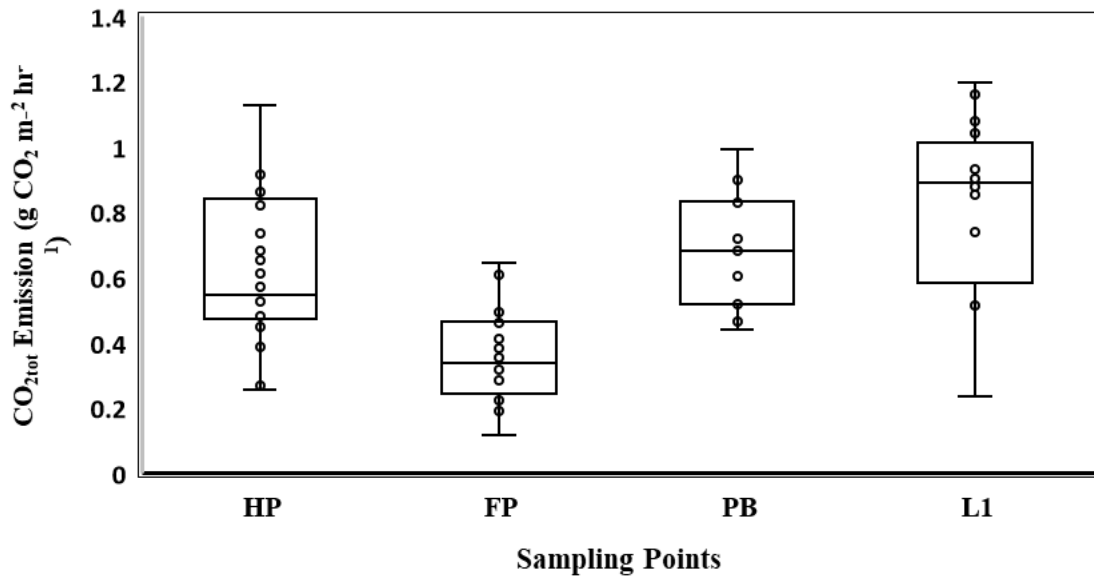


Figure 4.14: Momentary $\text{CO}_{2\text{tot}}$ emission at sampling points frond pile (FP), harvest path (HP) and palm base (PB) in Sebung Oil Palm Plantation and L1 in Sabaju Secondary Forest.

The differences in $\text{CO}_{2\text{tot}}$ emission in Sabaju Forest compared to Sebung Estate may be attributable to the presence of more recalcitrant C compounds in the latter; the lowering of water table level through drainage greatly modifies peat C compound composition by accelerating peat decomposition processes, leaving recalcitrant C compounds to accumulate in cultivated peat (Kumar & Sharma, 2014; Könönen et al., 2016; Miettinen et al., 2016; Könönen et al., 2018). Peat decomposability is determined by peat C compound composition which in return influences the rate of gaseous C emission release; in degraded peatlands such as the oil palm plantation, the progressive enrichment of recalcitrant C with time reduces peat decomposition rates and thus lowers CO_2 emission compared to that of peat forest (Jauhiainen et al., 2008; Hirano et al., 2014). Sabaju Forest peat is less decomposed (i.e., lower A_{1700}/A_{1030} humification index) and records higher $\text{CO}_{2\text{tot}}$ emission than the oil palm plantation; this could be due to consistent deposits of more labile C

compounds through leaves and woody debris onto the forest surface, providing favourable conditions for peat decomposition through high nutrient availability and presence of more easily-decomposable materials (Lampela et al., 2014; Jauhiainen et al., 2016). Hence, higher peat decomposability in the forest may cause CO₂ emission to be greater than at the oil palm plantation (Sundari et al., 2012; Hirano et al., 2014; Könönen et al., 2016).

CHAPTER 5

CONCLUSION AND RECOMMENDATION

In conclusion, this study confirms that changes on land use especially drainage and vegetation removal can modify both the soil-water dynamic and rate of humification in tropical peatlands, and that both factors affect the growth of oil palms which are planted on peatlands.

The oil palm plantation clearly showed lower moisture content at both peat profiles (0 – 50 cm and 50 – 100 cm) compared to the secondary forest. Moreover, it was observed that soil moisture of topsoil peat (0 – 50 cm) of the unregulated secondary forest was still higher than the soil moisture at 50 – 100 cm peat layer, confirming that the oil palm plantation fluctuates much lower than the expected range of 30 – 60 cm. The growth of oil palm trunks also showed a significant positive correlation with the topsoil moisture. Oil palms with negative trunk diameter growth were found in relatively drier subplots or close to the drain; this observation could be clearly identified from the soil moisture map. For these reasons, it is recommended that the water table in the oil plantation be measured and maintained consistently throughout the year at the recommended depth of 30 – 60 cm below the soil surface as one of the methods to enhance the growth of oil palms planted on peat soil. Besides that, it is also recommended that the growth of oil palm trees should be continuously monitored as this data would be required in correlating with the peat soil moisture content.

The overall C/N ratio (humification degree indicator) in the secondary forest was substantially lower than of the oil palm plantation as the former was characterized with a

higher N content. In contrast, the humification index calculated based on the functional group characteristics in FTIR indicated that the plantation peat was enriched with carboxyl and carbonyl groups suggesting that plantation peat was at the more advanced stage of humification. These results suggest that C/N ratio of the two ecosystems (cultivated peat under oil palm plantation and uncultivated peat) cannot be compared directly due to their differences in N-cycling ecology. Correlation analysis between C/N ratio of topsoil plantation peat and oil palm growth based on the number of fronds and breast height diameter showed inverse correlations. The C/N ratio map highlighted that oil palms which grow on peat lower C/N ratio (more humified) produced more fronds with greater diameter size, whereas palms producing lower number of fronds were in areas with relatively higher C/N ratio (less humified).

Overall, pH value in the topsoil profiles in both plantation and forest were significantly lower than that at 50 – 100 cm. Higher topsoil pH in the forest than the plantation postulates enhanced microbial activity in the former, attributable to enhanced peat decomposition due to continuous inputs of labile C compounds. On the other hand, electrical conductivity was observably higher in the oil palm plantation as a result of decreased organic matter inputs. Momentary peat surface total CO₂ emissions, CO_{2tot} in the secondary forest was significantly higher than the oil palm plantation, likely attributable to the higher concentrations of recalcitrant C compounds in the latter due to drainage, accelerating peat decomposition process.

The use of spatial maps to visualize peat characteristics (i.e., soil moisture and C/N ratio as humification degree indicator) has been helpful in highlighting the location of oil palm trees which exhibit either positive or negative growth. As Malaysia has enforced a

strict non-conversion of peatlands for oil palm plantation and enacted oil palm cultivation rules on existing peatlands, the visualization of various peat characteristics using GIS would be a helpful tool for oil palm plantation management to continue managing and utilizing existing peatlands which have been cultivated in a more effective and sustainable manner. Information provided by these peat characteristic maps could also be used to locate problematic peat areas within the plantation or to identify possible factors on why some oil palm trees within the area are not thriving as well as the others. Lastly, these maps have provided better insights into the spatial heterogeneity of peat characteristics at two different land uses, allowing comparison and highlighting the effects of land use conversion on tropical peat.

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APPENDICES

Appendix 1: Photographs of floor vegetation from Sebungan Oil Palm Plantation (above) and Sabaju Secondary Forest (below).



Appendix 2: Peat soil moisture (%) in Sebungan Oil Palm Plantation at 0 – 50 cm depth.

Subplot	Management Zone	Depth (cm)	Wet Mass (g)	Dried Mass (g)	Difference (g)	Soil Moisture (%)
1	HP	0-50	354.33	65.38	288.96	81.55
2	HP	0-50	420.96	75.10	345.86	82.16
3	HP	0-50	611.31	90.20	521.11	85.24
4	HP	0-50	480.08	61.60	418.48	87.17
5	HP	0-50	555.90	93.46	462.44	83.19
6	HP	0-50	396.80	59.07	337.73	85.11
7	HP	0-50	494.95	68.94	426.01	86.07
8	HP	0-50	410.81	64.56	346.25	84.29
9	HP	0-50	499.74	73.03	426.71	85.39
10	HP	0-50	511.33	75.05	436.28	85.32
11	HP	0-50	567.17	98.66	468.51	82.61
12	HP	0-50	303.61	47.02	256.59	84.51
13	HP	0-50	567.44	71.40	496.04	87.42
14	HP	0-50	542.73	74.58	468.15	86.26
15	HP	0-50	536.27	74.40	461.87	86.13
16	HP	0-50	472.51	71.56	400.95	84.86
17	HP	0-50	538.71	74.23	464.49	86.22
18	HP	0-50	561.75	96.08	465.68	82.90
19	HP	0-50	452.58	79.08	373.50	82.53
20	HP	0-50	796.22	131.73	664.50	83.46
21	HP	0-50	403.00	65.34	337.66	83.79
22	HP	0-50	706.23	100.45	605.79	85.78
23	HP	0-50	387.14	53.49	333.66	86.18
24	HP	0-50	528.11	71.35	456.77	86.49
25	HP	0-50	493.37	64.81	428.56	86.86

Appendix 2: continued

1	FP	0-50	244.30	51.33	192.97	78.99
2	FP	0-50	533.75	79.60	454.15	85.09
3	FP	0-50	329.10	53.96	275.14	83.60
4	FP	0-50	732.58	98.43	634.15	86.56
5	FP	0-50	563.30	80.45	482.85	85.72
6	FP	0-50	304.15	47.60	256.55	84.35
7	FP	0-50	447.80	80.79	367.01	81.96
8	FP	0-50	456.97	74.23	382.74	83.76
9	FP	0-50	431.84	52.39	379.45	87.87
10	FP	0-50	405.14	70.84	334.30	82.51
11	FP	0-50	507.70	118.79	388.91	76.60
12	FP	0-50	491.11	69.05	422.06	85.94
13	FP	0-50	367.77	82.78	285.00	77.49
14	FP	0-50	497.52	75.34	422.18	84.86
15	FP	0-50	326.56	55.55	271.02	82.99
16	FP	0-50	466.20	71.70	394.50	84.62
17	FP	0-50	481.35	77.12	404.23	83.98
18	FP	0-50	366.85	47.88	318.97	86.95
19	FP	0-50	457.98	78.42	379.57	82.88
20	FP	0-50	748.60	102.20	646.40	86.35
21	FP	0-50	424.95	48.92	376.03	88.49
22	FP	0-50	631.21	103.24	527.97	83.64
23	FP	0-50	389.73	59.78	329.96	84.66
24	FP	0-50	588.87	78.78	510.09	86.62
25	FP	0-50	719.53	73.07	646.46	89.85

Appendix 2: continued

1	PB	0-50	263.36	47.34	216.02	82.02
2	PB	0-50	560.77	86.05	474.72	84.65
3	PB	0-50	656.11	79.89	576.22	87.82
4	PB	0-50	711.30	118.69	592.61	83.31
5	PB	0-50	548.11	96.68	451.43	82.36
6	PB	0-50	444.55	72.44	372.11	83.71
7	PB	0-50	448.60	50.35	398.26	88.78
8	PB	0-50	455.01	64.94	390.07	85.73
9	PB	0-50	638.01	76.05	561.96	88.08
10	PB	0-50	467.50	73.22	394.28	84.34
11	PB	0-50	433.88	58.48	375.40	86.52
12	PB	0-50	569.97	77.65	492.32	86.38
13	PB	0-50	702.82	95.53	607.29	86.41
14	PB	0-50	361.42	78.54	282.88	78.27
15	PB	0-50	614.94	116.40	498.54	81.07
16	PB	0-50	769.17	117.68	651.49	84.70
17	PB	0-50	662.08	112.63	549.45	82.99
18	PB	0-50	372.61	112.04	260.57	69.93
19	PB	0-50	338.19	74.94	263.25	77.84
20	PB	0-50	429.29	83.87	345.42	80.46
21	PB	0-50	600.13	117.00	483.13	80.50
22	PB	0-50	549.28	74.56	474.72	86.43
23	PB	0-50	501.54	80.98	420.56	83.85
24	PB	0-50	566.63	92.47	474.17	83.68
25	PB	0-50	532.59	193.69	338.90	63.63

Appendix 3: Peat soil moisture (%) in Sebung Oil Palm Plantation at 50 – 100 cm depth.

Subplot	Management Zone	Depth (cm)	Wet Mass (g)	Dried Mass (g)	Difference (g)	Soil Moisture (%)
1	HP	50-100	393.57	52.72	340.85	86.60
2	HP	50-100	741.63	85.10	656.53	88.53
3	HP	50-100	583.48	78.29	505.20	86.58
4	HP	50-100	489.61	66.26	423.36	86.47
5	HP	50-100	825.80	103.75	722.05	87.44
6	HP	50-100	549.38	77.67	471.71	85.86
7	HP	50-100	398.55	53.70	344.85	86.53
8	HP	50-100	605.05	68.02	537.03	88.76
9	HP	50-100	624.09	87.18	536.91	86.03
10	HP	50-100	623.55	91.18	532.37	85.38
11	HP	50-100	526.75	74.89	451.86	85.78
12	HP	50-100	340.53	44.28	296.25	87.00
13	HP	50-100	491.22	56.34	434.88	88.53
14	HP	50-100	621.26	83.96	537.30	86.49
15	HP	50-100	584.26	80.45	503.81	86.23
16	HP	50-100	557.48	69.58	487.90	87.52
17	HP	50-100	608.57	75.86	532.71	87.54
18	HP	50-100	559.37	74.47	484.90	86.69
19	HP	50-100	557.60	79.67	477.93	85.71
20	HP	50-100	591.81	89.55	502.26	84.87
21	HP	50-100	549.54	57.69	491.85	89.50
22	HP	50-100	790.34	133.52	656.82	83.11
23	HP	50-100	499.32	69.88	429.44	86.00
24	HP	50-100	943.80	113.27	830.53	88.00
25	HP	50-100	636.57	83.26	553.31	86.92

Appendix 3: continued

1	FP	50-100	285.21	47.37	237.84	83.39
2	FP	50-100	500.08	63.58	436.50	87.29
3	FP	50-100	536.13	73.21	462.92	86.35
4	FP	50-100	519.16	63.04	456.13	87.86
5	FP	50-100	514.11	58.67	455.44	88.59
6	FP	50-100	441.44	50.33	391.11	88.60
7	FP	50-100	633.54	82.94	550.61	86.91
8	FP	50-100	435.51	46.03	389.48	89.43
9	FP	50-100	559.10	100.55	458.55	82.02
10	FP	50-100	576.21	70.85	505.36	87.70
11	FP	50-100	789.99	111.64	678.35	85.87
12	FP	50-100	373.28	35.33	337.95	90.54
13	FP	50-100	512.78	62.72	450.06	87.77
14	FP	50-100	377.51	39.84	337.67	89.45
15	FP	50-100	480.86	62.46	418.40	87.01
16	FP	50-100	329.64	38.49	291.15	88.32
17	FP	50-100	469.50	82.64	386.86	82.40
18	FP	50-100	521.24	66.25	454.99	87.29
19	FP	50-100	668.46	87.68	580.77	86.88
20	FP	50-100	395.96	45.91	350.05	88.41
21	FP	50-100	695.96	67.49	628.47	90.30
22	FP	50-100	435.13	64.35	370.78	85.21
23	FP	50-100	459.67	58.23	401.45	87.33
24	FP	50-100	591.20	82.90	508.30	85.98
25	FP	50-100	637.84	97.39	540.45	84.73

Appendix 3: continued

1	PB	50-100	362.69	75.00	287.69	79.32
2	PB	50-100	338.47	47.22	291.25	86.05
3	PB	50-100	464.55	56.27	408.28	87.89
4	PB	50-100	521.22	70.17	451.05	86.54
5	PB	50-100	765.44	82.25	683.19	89.25
6	PB	50-100	390.69	44.93	345.77	88.50
7	PB	50-100	627.63	86.55	541.08	86.21
8	PB	50-100	559.98	64.33	495.66	88.51
9	PB	50-100	390.83	41.78	349.05	89.31
10	PB	50-100	630.52	75.44	555.08	88.04
11	PB	50-100	440.68	41.97	398.71	90.48
12	PB	50-100	393.09	73.91	319.18	81.20
13	PB	50-100	514.22	68.23	445.99	86.73
14	PB	50-100	607.33	86.82	520.51	85.70
15	PB	50-100	595.26	63.25	532.01	89.37
16	PB	50-100	648.36	98.15	550.21	84.86
17	PB	50-100	313.56	50.69	262.87	83.83
18	PB	50-100	880.60	115.22	765.38	86.92
19	PB	50-100	526.51	85.94	440.57	83.68
20	PB	50-100	460.68	55.69	404.99	87.91
21	PB	50-100	579.91	69.67	510.24	87.99
22	PB	50-100	414.80	48.12	366.68	88.40
23	PB	50-100	608.80	65.80	543.00	89.19
24	PB	50-100	418.88	50.89	367.99	87.85
25	PB	50-100	519.41	67.24	452.17	87.05

Appendix 4: Peat soil moisture (%) in Sabaju Secondary Forest at 0 – 50 cm.

Subplot	Management Zone	Depth (cm)	Wet Mass (g)	Dried Mass (g)	Difference (g)	Soil Moisture (%)
1	L1	0-50	551.36	51.83	499.53	90.60
2	L1	0-50	627.07	48.42	578.65	92.28
3	L1	0-50	536.84	54.95	481.89	89.76
4	L1	0-50	426.02	38.62	387.40	90.93
5	L1	0-50	890.14	89.05	801.09	90.00
6	L1	0-50	602.65	50.76	551.89	91.58
7	L1	0-50	488.88	44.40	444.48	90.92
8	L1	0-50	581.73	50.15	531.58	91.38
9	L1	0-50	545.28	48.57	496.71	91.09
10	L1	0-50	407.11	41.15	365.96	89.89
11	L1	0-50	429.51	48.81	380.70	88.64
12	L1	0-50	600.10	52.15	547.95	91.31
13	L1	0-50	547.53	50.87	496.66	90.71
14	L1	0-50	544.42	74.10	470.32	86.39
15	L1	0-50	660.25	95.00	565.25	85.61
16	L1	0-50	445.00	59.42	385.58	86.65
17	L1	0-50	524.11	47.10	477.01	91.01
18	L1	0-50	416.20	46.41	369.79	88.85
19	L1	0-50	410.37	32.05	378.32	92.19
20	L1	0-50	568.91	55.21	513.70	90.29
21	L1	0-50	406.73	34.79	371.94	91.45
22	L1	0-50	402.78	48.04	354.74	88.07
23	L1	0-50	582.43	61.45	520.98	89.45
24	L1	0-50	455.60	70.04	385.56	84.63
25	L1	0-50	389.81	51.19	338.63	86.87

Appendix 4: continued

1	L2	0-50	452.95	58.76	394.19	87.03
2	L2	0-50	777.94	58.20	719.74	92.52
3	L2	0-50	456.03	96.43	359.60	78.85
4	L2	0-50	532.03	51.69	480.34	90.28
5	L2	0-50	438.53	49.32	389.21	88.75
6	L2	0-50	690.60	55.09	635.51	92.02
7	L2	0-50	499.77	50.21	449.56	89.95
8	L2	0-50	373.37	33.12	340.26	91.13
9	L2	0-50	516.72	58.70	458.02	88.64
10	L2	0-50	558.91	38.13	520.78	93.18
11	L2	0-50	363.69	37.34	326.35	89.73
12	L2	0-50	504.74	64.11	440.63	87.30
13	L2	0-50	632.07	69.32	562.75	89.03
14	L2	0-50	328.82	27.18	301.64	91.73
15	L2	0-50	619.81	54.87	564.94	91.15
16	L2	0-50	361.30	35.08	326.23	90.29
17	L2	0-50	399.82	33.77	366.05	91.55
18	L2	0-50	420.05	46.17	373.89	89.01
19	L2	0-50	634.53	55.09	579.44	91.32
20	L2	0-50	522.53	42.31	480.22	91.90
21	L2	0-50	423.90	51.78	372.12	87.79
22	L2	0-50	472.18	48.75	423.43	89.68
23	L2	0-50	606.77	67.63	539.14	88.85
24	L2	0-50	618.10	101.32	516.78	83.61
25	L2	0-50	347.38	34.89	312.49	89.96

Appendix 4: continued

1	L3	0-50	385.83	41.61	344.22	89.22
2	L3	0-50	592.26	45.52	546.74	92.31
3	L3	0-50	918.87	39.42	879.45	95.71
4	L3	0-50	372.32	31.19	341.14	91.62
5	L3	0-50	412.16	40.30	371.86	90.22
6	L3	0-50	452.01	42.29	409.72	90.64
7	L3	0-50	445.91	41.16	404.75	90.77
8	L3	0-50	431.88	44.78	387.10	89.63
9	L3	0-50	392.98	83.84	309.14	78.67
10	L3	0-50	544.03	59.25	484.78	89.11
11	L3	0-50	469.05	50.54	418.51	89.22
12	L3	0-50	427.06	36.44	390.62	91.47
13	L3	0-50	258.84	21.76	237.08	91.59
14	L3	0-50	462.33	71.94	390.40	84.44
15	L3	0-50	631.70	107.36	524.34	83.01
16	L3	0-50	338.13	34.17	303.96	89.89
17	L3	0-50	650.93	58.58	592.35	91.00
18	L3	0-50	442.78	44.14	398.64	90.03
19	L3	0-50	344.35	38.56	305.79	88.80
20	L3	0-50	483.97	33.47	450.50	93.09
21	L3	0-50	400.57	41.79	358.78	89.57
22	L3	0-50	516.53	57.41	459.12	88.89
23	L3	0-50	370.72	33.87	336.85	90.86
24	L3	0-50	330.29	27.35	302.94	91.72
25	L3	0-50	404.18	39.64	364.54	90.19

Appendix 5: Peat soil moisture (%) in Sabaju Secondary Forest at 50 – 100 cm.

Subplot	Management Zone	Depth (cm)	Wet Mass (g)	Dried Mass (g)	Difference (g)	Soil Moisture (%)
1	L1	50-100	535.29	34.30	501.00	93.59
2	L1	50-100	406.40	33.54	372.86	91.75
3	L1	50-100	750.50	57.23	693.27	92.37
4	L1	50-100	576.87	54.55	522.32	90.54
5	L1	50-100	467.30	36.49	430.81	92.19
6	L1	50-100	566.48	28.53	537.95	94.96
7	L1	50-100	559.37	42.61	516.76	92.38
8	L1	50-100	492.14	47.17	444.97	90.41
9	L1	50-100	617.54	45.36	572.18	92.65
10	L1	50-100	435.35	54.59	380.76	87.46
11	L1	50-100	482.33	48.87	433.46	89.87
12	L1	50-100	385.31	27.04	358.27	92.98
13	L1	50-100	454.56	37.62	416.94	91.72
14	L1	50-100	465.91	41.94	423.97	91.00
15	L1	50-100	385.32	31.98	353.34	91.70
16	L1	50-100	488.18	39.87	448.31	91.83
17	L1	50-100	420.86	35.02	385.84	91.68
18	L1	50-100	486.20	41.84	444.36	91.39
19	L1	50-100	309.21	23.58	285.63	92.37
20	L1	50-100	481.54	40.43	441.11	91.60
21	L1	50-100	494.30	42.59	451.71	91.38
22	L1	50-100	476.46	51.55	424.91	89.18
23	L1	50-100	426.06	38.05	388.01	91.07
24	L1	50-100	597.07	57.61	539.46	90.35
25	L1	50-100	469.92	53.90	416.02	88.53

Appendix 5: continued

1	L2	50-100	503.33	51.24	452.09	89.82
2	L2	50-100	561.80	39.03	522.77	93.05
3	L2	50-100	679.23	49.04	630.20	92.78
4	L2	50-100	561.50	36.24	525.26	93.55
5	L2	50-100	475.75	36.46	439.29	92.34
6	L2	50-100	635.55	55.87	579.68	91.21
7	L2	50-100	421.89	33.35	388.54	92.10
8	L2	50-100	480.63	35.51	445.12	92.61
9	L2	50-100	473.00	44.13	428.87	90.67
10	L2	50-100	597.60	46.60	551.00	92.20
11	L2	50-100	565.04	82.80	482.25	85.35
12	L2	50-100	599.49	48.61	550.88	91.89
13	L2	50-100	279.82	42.52	237.30	84.81
14	L2	50-100	393.00	52.73	340.27	86.58
15	L2	50-100	376.19	44.12	332.07	88.27
16	L2	50-100	281.29	25.59	255.70	90.90
17	L2	50-100	331.56	27.64	303.92	91.66
18	L2	50-100	425.16	37.28	387.88	91.23
19	L2	50-100	635.67	51.53	584.14	91.89
20	L2	50-100	387.48	29.95	357.53	92.27
21	L2	50-100	710.05	68.09	641.96	90.41
22	L2	50-100	531.57	61.82	469.75	88.37
23	L2	50-100	570.68	58.36	512.32	89.77
24	L2	50-100	540.11	51.55	488.56	90.45
25	L2	50-100	483.59	34.98	448.61	92.77

Appendix 5: continued

1	L3	50-100	434.19	50.55	383.64	88.36
2	L3	50-100	441.49	30.82	410.67	93.02
3	L3	50-100	583.93	53.34	530.59	90.87
4	L3	50-100	665.10	50.86	614.24	92.35
5	L3	50-100	640.18	45.70	594.48	92.86
6	L3	50-100	576.04	49.74	526.30	91.36
7	L3	50-100	869.66	40.80	828.86	95.31
8	L3	50-100	530.98	47.24	483.74	91.10
9	L3	50-100	582.90	41.34	541.56	92.91
10	L3	50-100	438.70	35.28	403.42	91.96
11	L3	50-100	394.25	32.32	361.94	91.80
12	L3	50-100	495.05	39.91	455.14	91.94
13	L3	50-100	488.71	35.60	453.11	92.72
14	L3	50-100	383.09	31.63	351.46	91.74
15	L3	50-100	419.27	35.46	383.81	91.54
16	L3	50-100	379.68	32.55	347.13	91.43
17	L3	50-100	355.25	32.27	322.98	90.92
18	L3	50-100	424.15	37.11	387.04	91.25
19	L3	50-100	555.69	52.79	502.90	90.50
20	L3	50-100	589.31	45.38	543.93	92.30
21	L3	50-100	377.60	33.25	344.35	91.19
22	L3	50-100	503.92	54.61	449.31	89.16
23	L3	50-100	349.87	31.70	318.17	90.94
24	L3	50-100	501.52	44.80	456.72	91.07
25	L3	50-100	532.01	48.03	483.98	90.97

Appendix 6: Elemental composition and atomic ratio of peat in Sebungun Oil Palm Plantation at 0 – 50 cm.

Subplot	Management Zone	Depth (cm)	C	H	N	S	O	C/N	H/C	O/C
1	HP	0-50	57.02	5.50	1.38	0.10	36.00	48.33	1.16	0.47
2	HP	0-50	56.74	5.94	1.70	0.09	35.53	38.94	1.26	0.47
3	HP	0-50	54.15	5.22	1.53	0.10	39.01	41.32	1.16	0.54
4	HP	0-50	56.10	5.58	1.70	0.11	36.51	38.41	1.19	0.49
5	HP	0-50	56.62	5.60	1.54	0.10	36.15	42.91	1.19	0.48
6	HP	0-50	57.08	5.60	1.46	0.08	35.77	45.69	1.18	0.47
7	HP	0-50	54.70	5.27	1.26	0.08	38.69	50.79	1.16	0.53
8	HP	0-50	52.90	5.47	1.31	0.13	40.19	47.11	1.24	0.57
9	HP	0-50	50.43	5.15	0.74	0.10	43.59	79.45	1.22	0.65
10	HP	0-50	54.75	5.48	0.92	0.11	38.74	69.08	1.20	0.53
11	HP	0-50	51.82	5.38	1.11	0.13	41.55	54.29	1.25	0.60
12	HP	0-50	53.42	5.66	1.04	0.13	39.74	59.74	1.27	0.56
13	HP	0-50	56.12	6.21	0.95	0.12	36.60	68.72	1.33	0.49
14	HP	0-50	52.82	5.74	1.19	0.13	40.13	51.88	1.30	0.57
15	HP	0-50	52.98	5.08	1.00	0.20	40.75	61.82	1.15	0.58
16	HP	0-50	53.72	5.13	1.04	0.13	39.98	60.39	1.15	0.56
17	HP	0-50	54.17	5.30	0.75	0.12	39.66	84.18	1.17	0.55
18	HP	0-50	52.56	5.29	1.04	0.11	41.00	58.85	1.21	0.59
19	HP	0-50	53.08	5.32	1.05	0.12	40.43	59.18	1.20	0.57
20	HP	0-50	51.68	5.13	1.01	0.11	42.08	59.92	1.19	0.61
21	HP	0-50	53.07	5.33	0.96	0.11	40.53	64.23	1.20	0.57
22	HP	0-50	53.48	5.20	0.87	0.11	40.34	71.57	1.17	0.57
23	HP	0-50	55.59	6.57	1.04	0.08	36.70	62.13	1.42	0.50
24	HP	0-50	54.67	5.95	1.10	0.15	38.13	57.84	1.31	0.52

Appendix 6: continued

25	HP	0-50	54.91	5.67	1.03	0.11	38.28	62.16	1.24	0.52
1	FP	0-50	53.54	5.31	1.13	0.12	39.91	55.14	1.19	0.56
2	FP	0-50	52.60	5.40	1.01	0.10	40.88	60.63	1.23	0.58
3	FP	0-50	54.24	5.60	1.04	0.11	39.01	60.59	1.24	0.54
4	FP	0-50	53.81	5.68	1.00	0.10	39.41	62.59	1.27	0.55
5	FP	0-50	55.01	5.69	0.96	0.11	38.23	67.07	1.24	0.52
6	FP	0-50	49.98	4.97	0.99	0.12	43.94	59.07	1.19	0.66
7	FP	0-50	48.23	4.55	1.11	0.11	45.99	50.81	1.13	0.72
8	FP	0-50	54.67	5.39	1.53	0.09	38.32	41.62	1.18	0.53
9	FP	0-50	55.18	6.25	1.47	0.07	37.01	43.66	1.36	0.50
10	FP	0-50	51.48	5.47	1.51	0.09	41.45	39.76	1.28	0.60
11	FP	0-50	49.70	5.02	1.11	0.08	44.10	52.16	1.21	0.67
12	FP	0-50	51.92	5.24	1.08	0.09	41.67	55.98	1.21	0.60
13	FP	0-50	48.73	4.86	1.24	0.08	45.08	45.92	1.20	0.69
14	FP	0-50	49.35	4.95	1.07	0.10	44.53	53.71	1.20	0.68
15	FP	0-50	51.01	5.09	1.20	0.09	42.60	49.58	1.20	0.63
16	FP	0-50	52.19	5.06	1.08	0.07	41.59	56.28	1.16	0.60
17	FP	0-50	53.01	5.09	0.65	0.06	41.19	94.52	1.15	0.58
18	FP	0-50	51.15	5.09	0.82	0.09	42.85	72.37	1.19	0.63
19	FP	0-50	55.98	5.95	0.64	0.06	37.37	101.38	1.28	0.50
20	FP	0-50	52.27	5.34	0.84	0.08	41.47	72.29	1.23	0.60
21	FP	0-50	59.25	6.92	0.65	0.08	33.10	105.83	1.40	0.42
22	FP	0-50	56.47	6.24	0.73	0.08	36.48	90.48	1.33	0.48
23	FP	0-50	55.10	5.62	1.04	0.03	38.20	61.69	1.22	0.52
24	FP	0-50	53.21	5.82	1.05	0.11	39.82	59.28	1.31	0.56
25	FP	0-50	NA	6.13	NA	0.06	NA	NA	NA	NA

Appendix 6: continued

1	PB	0-50	48.85	5.21	1.28	0.10	44.55	44.40	1.28	0.68
2	PB	0-50	53.64	5.92	0.98	0.07	39.39	64.17	1.33	0.55
3	PB	0-50	52.59	5.16	1.12	0.10	41.04	55.00	1.18	0.59
4	PB	0-50	50.41	5.14	1.01	0.06	43.37	57.97	1.22	0.65
5	PB	0-50	53.91	5.83	1.03	0.07	39.16	61.09	1.30	0.54
6	PB	0-50	51.40	5.44	0.79	0.08	42.28	75.50	1.27	0.62
7	PB	0-50	52.27	5.34	0.84	0.08	41.47	72.29	1.23	0.60
8	PB	0-50	53.53	5.62	0.92	0.08	39.85	67.58	1.26	0.56
9	PB	0-50	55.57	5.79	0.64	0.13	37.88	101.34	1.25	0.51
10	PB	0-50	54.72	6.00	1.09	0.09	38.10	58.70	1.32	0.52
11	PB	0-50	52.33	5.36	0.94	0.07	41.29	64.62	1.23	0.59
12	PB	0-50	57.92	6.40	0.60	0.02	35.06	113.14	1.33	0.45
13	PB	0-50	53.71	5.38	0.89	0.04	39.98	70.77	1.20	0.56
14	PB	0-50	51.81	5.08	1.18	0.03	41.90	51.36	1.18	0.61
15	PB	0-50	49.12	4.69	1.27	0.00	44.92	45.16	1.15	0.69
16	PB	0-50	53.20	5.37	1.35	0.04	40.04	45.88	1.21	0.56
17	PB	0-50	48.96	5.03	2.27	0.19	43.55	25.12	1.23	0.67
18	PB	0-50	36.17	4.11	1.34	0.05	58.33	31.58	1.36	1.21
19	PB	0-50	51.41	5.25	1.61	0.07	41.66	37.37	1.23	0.61
20	PB	0-50	49.56	5.15	1.46	0.08	43.75	39.68	1.25	0.66
21	PB	0-50	54.73	5.59	1.02	0.00	38.67	62.66	1.23	0.53
22	PB	0-50	55.06	5.40	0.92	0.00	38.62	69.99	1.18	0.53
23	PB	0-50	55.34	5.68	1.02	0.00	37.96	63.39	1.23	0.51
24	PB	0-50	53.42	5.36	1.33	0.09	39.79	46.73	1.21	0.56
25	PB	0-50	56.69	3.03	0.86	0.00	39.42	77.06	0.64	0.52

Appendix 7: Elemental composition and atomic ratio of peat in Sebungan Oil Palm Plantation at 50 – 100 cm.

Subplot	Management Zone	Depth (cm)	C	H	N	S	O	C/N	H/C	O/C
1	HP	50-100	61.06	6.97	1.01	0.11	30.85	70.80	1.37	0.38
2	HP	50-100	59.51	6.42	1.11	0.10	32.86	62.40	1.29	0.41
3	HP	50-100	59.04	6.23	1.17	0.11	33.44	58.91	1.27	0.42
4	HP	50-100	57.64	6.09	1.14	0.09	35.04	58.97	1.27	0.46
5	HP	50-100	53.07	5.40	1.04	0.14	40.34	59.43	1.22	0.57
6	HP	50-100	58.67	6.06	0.93	0.12	34.23	73.93	1.24	0.44
7	HP	50-100	58.42	6.15	0.97	0.11	34.35	70.43	1.26	0.44
8	HP	50-100	58.52	5.90	1.12	0.11	34.35	60.99	1.21	0.44
9	HP	50-100	56.86	5.99	0.76	0.09	36.30	87.38	1.26	0.48
10	HP	50-100	56.47	5.76	1.13	0.13	36.51	58.23	1.22	0.48
11	HP	50-100	61.11	6.64	0.83	0.10	31.32	86.12	1.30	0.38
12	HP	50-100	57.79	6.14	1.08	0.15	34.83	62.33	1.28	0.45
13	HP	50-100	58.34	5.70	1.11	0.12	34.73	61.49	1.17	0.45
14	HP	50-100	54.81	5.31	0.93	0.16	38.79	68.64	1.16	0.53
15	HP	50-100	58.48	5.89	0.94	0.12	34.57	72.68	1.21	0.44
16	HP	50-100	60.11	6.55	1.16	0.11	32.07	60.30	1.31	0.40
17	HP	50-100	60.14	6.33	1.05	0.10	32.38	66.80	1.26	0.40
18	HP	50-100	61.50	6.59	0.91	0.09	30.91	78.52	1.29	0.38
19	HP	50-100	58.70	6.11	1.10	0.14	33.94	62.33	1.25	0.43
20	HP	50-100	59.22	6.14	1.19	0.10	33.35	57.87	1.24	0.42
21	HP	50-100	57.58	6.27	0.96	0.12	35.07	70.00	1.31	0.46
22	HP	50-100	51.44	5.44	0.82	0.11	42.20	73.40	1.27	0.62
23	HP	50-100	57.08	6.27	0.85	0.10	35.70	78.62	1.32	0.47
24	HP	50-100	57.59	6.17	1.02	0.12	35.10	65.56	1.29	0.46

Appendix 7: continued

25	HP	50-100	55.91	5.92	0.81	0.10	37.27	80.60	1.27	0.50
1	FP	50-100	57.83	5.97	1.02	0.09	35.09	66.06	1.24	0.46
2	FP	50-100	61.32	6.64	0.98	0.07	31.00	73.24	1.30	0.38
3	FP	50-100	58.69	6.28	1.21	0.10	33.72	56.57	1.28	0.43
4	FP	50-100	58.37	6.28	1.35	0.09	33.91	50.46	1.29	0.44
5	FP	50-100	61.15	6.21	1.03	0.13	31.48	69.45	1.22	0.39
6	FP	50-100	57.34	6.02	1.18	0.11	35.35	56.61	1.26	0.46
7	FP	50-100	54.59	5.29	1.27	0.12	38.74	50.32	1.16	0.53
8	FP	50-100	58.70	5.97	1.06	0.13	34.14	64.72	1.22	0.44
9	FP	50-100	55.25	6.27	0.60	0.07	37.80	106.99	1.36	0.51
10	FP	50-100	55.37	6.33	0.56	0.07	37.68	115.48	1.37	0.51
11	FP	50-100	56.39	5.65	0.92	0.09	36.94	71.56	1.20	0.49
12	FP	50-100	59.01	6.44	0.84	0.11	33.61	82.44	1.31	0.43
13	FP	50-100	56.77	5.63	1.40	0.11	36.09	47.43	1.19	0.48
14	FP	50-100	56.29	5.25	0.90	0.13	37.44	73.30	1.12	0.50
15	FP	50-100	57.17	5.74	1.10	0.11	35.88	60.67	1.21	0.47
16	FP	50-100	59.19	6.12	1.12	0.09	33.47	61.42	1.24	0.42
17	FP	50-100	62.29	6.77	0.99	0.06	29.89	73.75	1.30	0.36
18	FP	50-100	55.29	5.31	1.19	0.13	38.07	54.22	1.15	0.52
19	FP	50-100	58.30	6.29	1.26	0.10	34.06	53.99	1.29	0.44
20	FP	50-100	59.65	6.41	1.05	0.09	32.81	66.56	1.29	0.41
21	FP	50-100	56.27	6.03	1.12	0.13	36.46	58.83	1.29	0.49
22	FP	50-100	55.88	5.79	1.23	0.16	36.95	53.14	1.24	0.50
23	FP	50-100	63.19	6.70	0.82	0.11	29.19	90.02	1.27	0.35
24	FP	50-100	58.81	6.24	0.79	0.16	34.00	86.63	1.27	0.43
25	FP	50-100	61.94	6.56	0.99	0.08	30.42	72.69	1.27	0.37

Appendix 7: continued

1	PB	50-100	NA	6.53	NA	0.07	NA	NA	NA	NA
2	PB	50-100	59.89	6.30	0.79	0.08	32.94	88.32	1.26	0.41
3	PB	50-100	NA	6.88	NA	0.06	NA	NA	NA	NA
4	PB	50-100	58.54	6.15	1.01	0.08	34.22	67.60	1.26	0.44
5	PB	50-100	60.03	6.29	0.72	0.08	32.87	96.81	1.26	0.41
6	PB	50-100	58.68	6.04	0.92	0.10	34.26	74.65	1.24	0.44
7	PB	50-100	60.86	6.52	1.05	0.10	31.47	67.93	1.29	0.39
8	PB	50-100	57.41	5.71	0.84	0.22	35.82	79.99	1.19	0.47
9	PB	50-100	56.79	6.27	1.13	0.13	35.68	58.79	1.33	0.47
10	PB	50-100	54.42	5.59	1.07	0.14	38.77	59.08	1.23	0.53
11	PB	50-100	58.01	6.23	0.99	0.10	34.66	68.31	1.29	0.45
12	PB	50-100	57.60	5.65	1.21	0.10	35.44	55.67	1.18	0.46
13	PB	50-100	56.39	5.58	1.28	0.10	36.65	51.44	1.19	0.49
14	PB	50-100	57.62	6.02	1.05	0.08	35.23	63.74	1.25	0.46
15	PB	50-100	55.12	6.35	1.07	0.07	37.38	59.98	1.38	0.51
16	PB	50-100	57.20	5.66	0.90	0.09	36.14	74.18	1.19	0.47
17	PB	50-100	NA	6.14	NA	0.06	NA	NA	NA	NA
18	PB	50-100	57.21	6.03	1.04	0.09	35.64	64.34	1.26	0.47
19	PB	50-100	56.86	5.87	1.14	0.11	36.02	58.12	1.24	0.48
20	PB	50-100	49.56	5.15	1.46	0.08	43.75	39.68	1.25	0.66
21	PB	50-100	54.73	5.59	1.02	0.00	38.67	62.66	1.23	0.53
22	PB	50-100	59.52	6.61	1.71	0.11	32.05	40.68	1.33	0.40
23	PB	50-100	59.16	6.30	1.30	0.14	33.11	53.19	1.28	0.42
24	PB	50-100	59.50	6.88	1.38	0.03	32.21	50.12	1.39	0.41
25	PB	50-100	63.03	NA	1.07	NA	NA	68.48	NA	NA

Appendix 8: Elemental composition and atomic ratio of peat in Sabaju Secondary Forest at 0 – 50 cm.

Subplot	Management Zone	Depth (cm)	C	H	N	S	O	C/N	H/C	O/C
1	L1	0-50	NA	2.88	NA	0.00	NA	NA	NA	NA
2	L1	0-50	53.76	6.42	1.47	0.00	38.35	42.57	1.43	0.53
3	L1	0-50	57.95	6.12	1.55	0.05	34.33	43.61	1.27	0.44
4	L1	0-50	60.08	6.32	1.34	0.06	32.20	52.19	1.26	0.40
5	L1	0-50	51.88	5.06	1.38	0.07	41.62	43.97	1.17	0.60
6	L1	0-50	53.26	5.24	1.35	0.07	40.09	46.19	1.18	0.56
7	L1	0-50	57.18	5.96	1.53	0.06	35.28	43.71	1.25	0.46
8	L1	0-50	45.48	4.70	1.08	0.05	48.70	49.19	1.24	0.80
9	L1	0-50	51.01	5.27	1.44	0.08	42.19	41.38	1.24	0.62
10	L1	0-50	50.79	4.31	0.97	0.04	43.89	60.85	1.02	0.65
11	L1	0-50	57.04	5.66	1.29	0.08	35.93	51.47	1.19	0.47
12	L1	0-50	46.47	4.50	1.11	0.07	47.85	48.96	1.16	0.77
13	L1	0-50	53.17	6.12	1.57	0.00	39.14	39.57	1.38	0.55
14	L1	0-50	54.68	5.74	0.90	0.00	38.67	70.50	1.26	0.53
15	L1	0-50	45.74	4.97	0.87	0.00	48.42	61.23	1.30	0.79
16	L1	0-50	54.00	5.81	1.27	0.05	38.86	49.49	1.29	0.54
17	L1	0-50	53.69	5.55	1.25	0.06	39.45	50.20	1.24	0.55
18	L1	0-50	53.17	5.42	1.17	0.06	40.18	52.94	1.22	0.57
19	L1	0-50	52.40	5.41	1.38	0.08	40.73	44.42	1.24	0.58
20	L1	0-50	49.98	4.96	1.24	0.07	43.74	47.12	1.19	0.66
21	L1	0-50	51.52	5.69	1.40	0.09	41.31	43.01	1.32	0.60
22	L1	0-50	51.07	5.55	1.24	0.07	42.08	48.16	1.30	0.62
23	L1	0-50	53.70	5.94	1.13	0.06	39.17	55.24	1.33	0.55
24	L1	0-50	40.91	1.97	0.81	0.03	56.27	58.82	0.58	1.03

Appendix 8: continued

25	L1	0-50	50.27	4.07	0.98	0.03	44.65	59.97	0.97	0.67
1	L2	0-50	59.04	6.33	1.84	0.09	32.69	37.45	1.29	0.42
2	L2	0-50	53.96	5.75	1.68	0.09	38.52	37.49	1.28	0.54
3	L2	0-50	52.35	5.18	1.68	0.11	40.69	36.34	1.19	0.58
4	L2	0-50	54.09	5.77	1.75	0.10	38.29	36.06	1.28	0.53
5	L2	0-50	56.97	5.65	1.62	0.09	35.67	41.11	1.19	0.47
6	L2	0-50	53.98	5.50	1.64	0.10	38.79	38.34	1.22	0.54
7	L2	0-50	56.19	5.83	1.58	0.08	36.32	41.46	1.24	0.48
8	L2	0-50	54.46	5.55	1.50	0.09	38.40	42.32	1.22	0.53
9	L2	0-50	52.75	5.28	1.48	0.08	40.41	41.58	1.20	0.57
10	L2	0-50	52.29	5.17	1.75	0.10	40.69	34.90	1.19	0.58
11	L2	0-50	52.26	5.76	1.82	0.11	40.05	33.57	1.32	0.57
12	L2	0-50	54.48	5.40	1.41	0.08	38.63	44.94	1.19	0.53
13	L2	0-50	56.07	5.90	1.52	0.08	36.43	43.15	1.26	0.49
14	L2	0-50	54.29	5.53	1.60	0.09	38.48	39.47	1.22	0.53
15	L2	0-50	54.16	5.59	1.57	0.08	38.60	40.33	1.24	0.53
16	L2	0-50	54.98	5.89	1.66	0.07	37.39	38.54	1.29	0.51
17	L2	0-50	53.00	5.74	1.58	0.07	39.61	39.12	1.30	0.56
18	L2	0-50	54.51	5.86	1.56	0.08	37.99	40.81	1.29	0.52
19	L2	0-50	52.54	5.38	1.60	0.10	40.39	38.29	1.23	0.58
20	L2	0-50	47.13	4.89	1.52	0.08	46.37	36.18	1.25	0.74
21	L2	0-50	51.65	5.38	1.82	0.09	41.05	33.13	1.25	0.60
22	L2	0-50	51.62	5.07	1.44	0.07	41.80	41.76	1.18	0.61
23	L2	0-50	53.55	4.79	1.14	0.07	40.45	54.71	1.07	0.57
24	L2	0-50	42.24	4.33	1.10	0.07	52.26	44.95	1.23	0.93
25	L2	0-50	52.97	5.14	1.44	0.08	40.38	42.89	1.16	0.57

Appendix 8: continued

1	L3	0-50	54.19	5.67	1.77	0.10	38.27	35.77	1.25	0.53
2	L3	0-50	54.70	5.62	1.75	0.09	37.84	36.49	1.23	0.52
3	L3	0-50	55.24	6.14	1.64	0.08	36.89	39.27	1.33	0.50
4	L3	0-50	54.82	5.64	1.67	0.08	37.79	38.30	1.23	0.52
5	L3	0-50	53.44	5.78	1.77	0.08	38.92	35.20	1.30	0.55
6	L3	0-50	55.10	5.77	1.75	0.06	37.32	36.80	1.26	0.51
7	L3	0-50	54.19	5.61	1.88	0.09	38.22	33.59	1.24	0.53
8	L3	0-50	55.07	6.18	1.68	0.07	37.01	38.27	1.35	0.50
9	L3	0-50	33.69	3.29	1.11	0.05	61.85	35.50	1.17	1.38
10	L3	0-50	54.25	5.67	1.91	0.08	38.08	33.06	1.25	0.53
11	L3	0-50	52.79	5.22	1.74	0.09	40.17	35.33	1.19	0.57
12	L3	0-50	52.98	5.35	1.55	0.07	40.05	39.99	1.21	0.57
13	L3	0-50	54.63	5.74	1.87	0.08	37.68	34.03	1.26	0.52
14	L3	0-50	48.38	4.75	1.49	0.06	45.31	37.80	1.18	0.70
15	L3	0-50	42.85	4.30	1.38	0.06	51.42	36.15	1.20	0.90
16	L3	0-50	51.24	5.21	1.75	0.07	41.73	34.18	1.22	0.61
17	L3	0-50	54.09	5.93	1.77	0.06	38.15	35.61	1.32	0.53
18	L3	0-50	53.21	5.43	1.75	0.08	39.54	35.45	1.22	0.56
19	L3	0-50	53.70	5.44	1.82	0.09	38.96	34.35	1.22	0.54
20	L3	0-50	51.34	5.18	1.66	0.09	41.73	36.13	1.21	0.61
21	L3	0-50	53.49	5.41	1.72	0.09	39.29	36.30	1.21	0.55
22	L3	0-50	52.37	5.10	1.53	0.08	40.92	39.88	1.17	0.59
23	L3	0-50	53.43	5.57	1.90	0.09	39.01	32.75	1.25	0.55
24	L3	0-50	51.96	5.11	1.83	0.09	41.01	33.10	1.18	0.59
25	L3	0-50	52.24	5.27	1.62	0.08	40.79	37.66	1.21	0.59

Appendix 9: Elemental composition and atomic ratio of peat in Sabaju Secondary Forest at 50 – 100 cm.

Subplot	Management Zone	Depth (cm)	C	H	N	S	O	C/N	H/C	O/C
1	L1	50-100	51.98	4.70	1.67	0.06	41.59	36.28	1.09	0.60
2	L1	50-100	50.86	4.60	1.62	0.05	42.87	36.63	1.09	0.63
3	L1	50-100	52.66	4.77	1.51	0.00	41.06	40.69	1.09	0.58
4	L1	50-100	52.08	4.62	1.45	0.00	41.86	42.01	1.06	0.60
5	L1	50-100	51.87	4.73	1.83	0.00	41.57	33.04	1.09	0.60
6	L1	50-100	52.33	5.00	1.50	0.07	41.11	40.69	1.15	0.59
7	L1	50-100	53.46	5.61	1.48	0.06	39.39	42.00	1.26	0.55
8	L1	50-100	52.25	5.07	1.34	0.06	41.28	45.66	1.16	0.59
9	L1	50-100	52.54	2.56	1.57	0.04	43.28	38.95	0.59	0.62
10	L1	50-100	50.73	7.07	1.36	0.10	40.74	43.45	1.67	0.60
11	L1	50-100	46.47	4.20	1.13	0.07	48.13	47.86	1.08	0.78
12	L1	50-100	49.49	4.52	1.65	0.10	44.24	35.03	1.10	0.67
13	L1	50-100	49.73	4.70	1.55	0.09	43.93	37.42	1.13	0.66
14	L1	50-100	51.14	4.77	1.28	0.07	42.74	46.52	1.12	0.63
15	L1	50-100	51.34	5.00	1.38	0.07	42.21	43.46	1.17	0.62
16	L1	50-100	50.37	4.73	1.47	0.08	43.35	40.07	1.13	0.65
17	L1	50-100	48.90	4.70	1.37	0.08	44.95	41.55	1.15	0.69
18	L1	50-100	49.67	4.49	1.43	0.08	44.33	40.61	1.08	0.67
19	L1	50-100	49.13	4.58	1.58	0.09	44.61	36.27	1.12	0.68
20	L1	50-100	49.42	4.45	1.58	0.09	44.46	36.38	1.08	0.67
21	L1	50-100	50.86	4.72	1.37	0.07	42.99	43.40	1.11	0.63
22	L1	50-100	49.12	4.20	1.14	0.07	45.46	50.06	1.03	0.69
23	L1	50-100	49.68	4.95	1.38	0.07	43.93	42.00	1.19	0.66
24	L1	50-100	50.43	4.55	1.29	0.08	43.65	45.55	1.08	0.65

Appendix 9: continued

25	L1	50-100	50.37	5.11	1.12	0.06	43.34	52.41	1.22	0.65
1	L2	50-100	50.25	4.54	1.13	0.08	44.01	51.94	1.08	0.66
2	L2	50-100	52.29	5.17	1.51	0.10	40.94	40.52	1.19	0.59
3	L2	50-100	51.83	5.09	1.45	0.09	41.54	41.79	1.18	0.60
4	L2	50-100	51.49	5.10	1.54	0.10	41.78	39.13	1.19	0.61
5	L2	50-100	51.23	4.81	1.33	0.08	42.55	45.10	1.13	0.62
6	L2	50-100	51.62	4.97	1.55	0.09	41.78	38.89	1.15	0.61
7	L2	50-100	52.62	5.00	1.35	0.08	40.95	45.35	1.14	0.58
8	L2	50-100	50.05	5.02	1.26	0.06	43.61	46.39	1.20	0.65
9	L2	50-100	52.39	4.84	1.27	0.07	41.43	48.28	1.11	0.59
10	L2	50-100	48.70	4.56	1.62	0.09	45.02	35.10	1.12	0.69
11	L2	50-100	39.74	3.61	1.15	0.06	55.43	40.22	1.09	1.05
12	L2	50-100	51.03	4.55	1.41	0.08	42.93	42.10	1.07	0.63
13	L2	50-100	52.07	5.80	1.53	0.06	40.54	39.72	1.34	0.58
14	L2	50-100	41.10	4.24	1.34	0.07	53.26	35.87	1.24	0.97
15	L2	50-100	50.17	4.67	1.43	0.07	43.66	40.91	1.12	0.65
16	L2	50-100	48.72	4.45	1.50	0.08	45.25	37.92	1.10	0.70
17	L2	50-100	50.08	4.59	1.45	0.08	43.80	40.30	1.10	0.66
18	L2	50-100	53.93	5.40	1.41	0.06	39.20	44.69	1.20	0.55
19	L2	50-100	50.55	4.64	1.47	0.09	43.24	40.20	1.10	0.64
20	L2	50-100	49.66	4.83	1.48	0.09	43.93	39.03	1.17	0.66
21	L2	50-100	50.97	4.74	1.30	0.07	42.92	45.86	1.12	0.63
22	L2	50-100	48.83	4.10	1.24	0.07	45.75	45.85	1.01	0.70
23	L2	50-100	53.62	4.67	1.32	0.07	40.32	47.33	1.04	0.56
24	L2	50-100	50.20	4.48	1.42	0.08	43.82	41.21	1.07	0.65
25	L2	50-100	50.12	4.69	1.65	0.09	43.45	35.52	1.12	0.65

Appendix 9: continued

1	L3	50-100	48.91	4.66	1.56	0.08	44.79	36.60	1.14	0.69
2	L3	50-100	52.55	5.09	1.69	0.08	40.59	36.27	1.16	0.58
3	L3	50-100	53.69	5.30	1.53	0.08	39.39	40.82	1.19	0.55
4	L3	50-100	NA	5.44	NA	0.06	NA	NA	NA	NA
5	L3	50-100	52.01	4.99	1.53	0.07	41.39	39.70	1.15	0.60
6	L3	50-100	53.03	5.58	1.57	0.10	39.73	39.38	1.26	0.56
7	L3	50-100	54.32	5.59	1.28	0.09	38.72	49.37	1.23	0.53
8	L3	50-100	53.38	5.45	1.29	0.07	39.82	48.23	1.22	0.56
9	L3	50-100	54.25	5.51	1.71	0.09	38.45	37.12	1.22	0.53
10	L3	50-100	52.85	4.95	1.65	0.08	40.47	37.33	1.12	0.57
11	L3	50-100	50.35	4.45	1.59	0.08	43.52	37.06	1.06	0.65
12	L3	50-100	52.06	4.89	1.56	0.08	41.41	38.94	1.13	0.60
13	L3	50-100	50.98	5.07	1.85	0.09	42.02	32.15	1.19	0.62
14	L3	50-100	52.29	5.00	1.67	0.08	40.96	36.51	1.15	0.59
15	L3	50-100	52.03	5.02	1.72	0.08	41.14	35.29	1.16	0.59
16	L3	50-100	51.10	4.77	1.51	0.07	42.56	39.61	1.12	0.62
17	L3	50-100	50.89	4.55	1.51	0.07	42.98	39.35	1.07	0.63
18	L3	50-100	50.95	4.65	1.58	0.08	42.73	37.59	1.10	0.63
19	L3	50-100	50.17	5.22	1.57	0.06	42.99	37.38	1.25	0.64
20	L3	50-100	NA	4.73	NA	0.08	NA	NA	NA	NA
21	L3	50-100	51.68	4.80	1.64	0.08	41.81	36.81	1.12	0.61
22	L3	50-100	51.52	4.67	1.26	0.05	42.50	47.75	1.09	0.62
23	L3	50-100	52.17	4.86	1.46	0.06	41.46	41.78	1.12	0.60
24	L3	50-100	49.90	4.63	1.52	0.07	43.89	38.39	1.11	0.66
25	L3	50-100	51.34	4.57	1.45	0.06	42.58	41.18	1.07	0.62

Appendix 10: pH and electrical conductivity in Sebungan Oil Palm Plantation and Sabaju Secondary Forest at 0 – 50 cm.

Sebungan Oil Palm Plantation					Sabaju Secondary Forest				
Subplot	Management Zone	Depth (cm)	pH	EC	Subplot	Management Zone	Depth (cm)	pH	EC (μS)
1	HP	0-50	3.30	336.33	1	L1	0-50	3.70	147.57
2	HP	0-50	3.91	188.67	2	L1	0-50	3.60	178.10
3	HP	0-50	3.35	326.00	3	L1	0-50	3.51	161.33
4	HP	0-50	3.54	289.33	4	L1	0-50	3.52	181.27
5	HP	0-50	3.58	280.67	5	L1	0-50	3.42	168.90
6	HP	0-50	3.65	229.00	6	L1	0-50	3.46	173.30
7	HP	0-50	3.40	298.33	7	L1	0-50	3.40	202.50
8	HP	0-50	3.26	366.67	8	L1	0-50	3.45	190.97
9	HP	0-50	3.53	202.83	9	L1	0-50	3.59	166.83
10	HP	0-50	3.71	203.33	10	L1	0-50	3.36	150.20
11	HP	0-50	4.06	206.03	11	L1	0-50	3.64	139.80
12	HP	0-50	3.50	245.67	12	L1	0-50	3.72	139.17
13	HP	0-50	3.54	196.30	13	L1	0-50	3.74	141.23
14	HP	0-50	3.77	244.00	14	L1	0-50	3.73	127.13
15	HP	0-50	3.43	614.67	15	L1	0-50	3.78	125.03
16	HP	0-50	3.33	207.00	16	L1	0-50	3.84	159.03
17	HP	0-50	3.40	392.00	17	L1	0-50	3.99	143.47
18	HP	0-50	3.88	188.30	18	L1	0-50	3.71	152.17
19	HP	0-50	3.32	234.67	19	L1	0-50	3.74	139.50
20	HP	0-50	3.60	217.67	20	L1	0-50	3.93	152.30
21	HP	0-50	3.34	236.00	21	L1	0-50	3.80	158.27
22	HP	0-50	3.39	169.23	22	L1	0-50	3.91	152.60
23	HP	0-50	3.26	169.53	23	L1	0-50	3.57	156.80

Appendix 10: continued

24	HP	0-50	3.31	516.00	24	L1	0-50	3.87	129.00
25	HP	0-50	3.46	195.90	25	L1	0-50	3.44	164.57
1	FP	0-50	3.28	199.30	1	L2	0-50	3.18	168.87
2	FP	0-50	3.60	151.50	2	L2	0-50	3.33	160.53
3	FP	0-50	3.38	169.57	3	L2	0-50	3.80	132.63
4	FP	0-50	4.03	179.17	4	L2	0-50	3.25	162.37
5	FP	0-50	3.41	238.00	5	L2	0-50	3.18	164.93
6	FP	0-50	3.52	554.33	6	L2	0-50	3.26	171.33
7	FP	0-50	3.18	2734.67	7	L2	0-50	3.33	150.20
8	FP	0-50	4.27	261.00	8	L2	0-50	3.72	123.17
9	FP	0-50	3.73	146.40	9	L2	0-50	3.46	139.13
10	FP	0-50	3.99	185.50	10	L2	0-50	3.05	212.67
11	FP	0-50	3.54	123.90	11	L2	0-50	3.59	164.87
12	FP	0-50	3.60	150.13	12	L2	0-50	3.42	146.50
13	FP	0-50	3.81	155.77	13	L2	0-50	3.71	122.47
14	FP	0-50	3.44	253.67	14	L2	0-50	3.72	140.90
15	FP	0-50	3.28	494.00	15	L2	0-50	3.65	154.43
16	FP	0-50	3.36	174.23	16	L2	0-50	3.75	132.37
17	FP	0-50	3.25	358.33	17	L2	0-50	3.89	118.30
18	FP	0-50	3.47	189.10	18	L2	0-50	3.82	142.27
19	FP	0-50	3.68	92.57	19	L2	0-50	3.68	146.33
20	FP	0-50	3.56	188.23	20	L2	0-50	3.87	134.77
21	FP	0-50	3.90	117.03	21	L2	0-50	3.79	157.43
22	FP	0-50	3.33	215.67	22	L2	0-50	3.59	133.60
23	FP	0-50	3.39	201.97	23	L2	0-50	3.12	161.53
24	FP	0-50	3.35	256.67	24	L2	0-50	3.39	124.97
25	FP	0-50	3.54	271.00	25	L2	0-50	3.51	140.90

Appendix 10: continued

1	PB	0-50	3.92	214.77	1	L3	0-50	3.54	185.87
2	PB	0-50	3.44	181.80	2	L3	0-50	3.65	170.03
3	PB	0-50	3.34	215.00	3	L3	0-50	3.48	206.33
4	PB	0-50	4.09	243.33	4	L3	0-50	3.52	163.10
5	PB	0-50	3.20	432.67	5	L3	0-50	4.00	189.80
6	PB	0-50	3.76	268.67	6	L3	0-50	3.48	170.90
7	PB	0-50	3.60	250.00	7	L3	0-50	3.65	198.80
8	PB	0-50	3.53	197.07	8	L3	0-50	3.98	192.47
9	PB	0-50	3.54	131.40	9	L3	0-50	3.76	151.40
10	PB	0-50	3.43	287.00	10	L3	0-50	3.35	230.67
11	PB	0-50	3.92	170.57	11	L3	0-50	3.86	190.23
12	PB	0-50	4.08	103.33	12	L3	0-50	3.92	169.37
13	PB	0-50	3.92	163.40	13	L3	0-50	4.08	184.60
14	PB	0-50	3.49	315.67	14	L3	0-50	3.90	178.07
15	PB	0-50	3.39	512.67	15	L3	0-50	3.86	170.20
16	PB	0-50	3.65	316.67	16	L3	0-50	4.25	191.07
17	PB	0-50	3.53	782.33	17	L3	0-50	4.08	176.67
18	PB	0-50	3.44	166.47	18	L3	0-50	3.96	172.77
19	PB	0-50	3.79	255.67	19	L3	0-50	3.93	171.97
20	PB	0-50	3.75	185.10	20	L3	0-50	3.93	179.90
21	PB	0-50	3.58	178.87	21	L3	0-50	3.93	175.13
22	PB	0-50	3.37	156.00	22	L3	0-50	4.03	203.97
23	PB	0-50	3.91	192.67	23	L3	0-50	4.21	187.00
24	PB	0-50	3.65	799.33	24	L3	0-50	3.98	225.67
25	PB	0-50	4.28	251.67	25	L3	0-50	4.13	189.70

Appendix 11: pH and electrical conductivity in Sebungan Oil Palm Plantation and Sabaju Secondary Forest at 50 – 100 cm.

Sebungan Oil Palm Plantation					Sabaju Secondary Forest				
Subplot	Management Zone	Depth (cm)	pH	EC	Subplot	Management Zone	Depth (cm)	pH	EC (μS)
1	HP	50-100	3.81	177.27	1	L1	50-100	3.57	218.53
2	HP	50-100	4.05	141.93	2	L1	50-100	3.73	177.83
3	HP	50-100	3.85	161.17	3	L1	50-100	3.55	203.77
4	HP	50-100	4.05	216.67	4	L1	50-100	3.46	200.00
5	HP	50-100	3.84	229.67	5	L1	50-100	3.58	226.67
6	HP	50-100	3.59	252.00	6	L1	50-100	3.59	205.33
7	HP	50-100	3.98	226.33	7	L1	50-100	3.66	203.00
8	HP	50-100	3.86	246.00	8	L1	50-100	3.61	210.00
9	HP	50-100	3.82	236.67	9	L1	50-100	3.66	237.00
10	HP	50-100	3.99	228.00	10	L1	50-100	3.46	226.00
11	HP	50-100	3.87	213.00	11	L1	50-100	3.54	241.33
12	HP	50-100	3.94	249.67	12	L1	50-100	4.18	135.33
13	HP	50-100	3.85	209.27	13	L1	50-100	4.32	122.50
14	HP	50-100	3.79	254.33	14	L1	50-100	4.30	121.97
15	HP	50-100	4.05	252.67	15	L1	50-100	4.24	126.07
16	HP	50-100	3.83	260.00	16	L1	50-100	4.31	127.97
17	HP	50-100	4.09	218.27	17	L1	50-100	4.64	101.47
18	HP	50-100	4.12	206.67	18	L1	50-100	3.94	153.73
19	HP	50-100	3.94	243.00	19	L1	50-100	4.12	142.40
20	HP	50-100	3.93	260.00	20	L1	50-100	3.96	157.60
21	HP	50-100	3.87	252.33	21	L1	50-100	3.99	152.43
22	HP	50-100	4.10	233.00	22	L1	50-100	3.63	194.00
23	HP	50-100	4.24	229.67	23	L1	50-100	3.60	225.67

Appendix 11: continued

24	HP	50-100	4.03	341.00	24	L1	50-100	3.75	211.67
25	HP	50-100	3.97	275.33	25	L1	50-100	3.74	199.53
1	FP	50-100	3.58	339.33	1	L2	50-100	3.36	196.53
2	FP	50-100	4.25	81.93	2	L2	50-100	3.48	186.87
3	FP	50-100	3.75	135.73	3	L2	50-100	3.58	233.67
4	FP	50-100	4.74	194.30	4	L2	50-100	3.60	241.00
5	FP	50-100	3.96	167.13	5	L2	50-100	3.54	259.33
6	FP	50-100	3.89	181.10	6	L2	50-100	3.60	208.33
7	FP	50-100	3.32	1412.67	7	L2	50-100	3.68	213.33
8	FP	50-100	4.34	125.07	8	L2	50-100	3.67	222.33
9	FP	50-100	4.08	99.57	9	L2	50-100	3.82	246.00
10	FP	50-100	3.93	165.20	10	L2	50-100	3.78	244.00
11	FP	50-100	3.61	200.57	11	L2	50-100	3.90	237.67
12	FP	50-100	4.08	119.20	12	L2	50-100	4.13	136.17
13	FP	50-100	3.83	144.57	13	L2	50-100	4.15	128.30
14	FP	50-100	3.76	216.67	14	L2	50-100	4.51	130.63
15	FP	50-100	3.83	301.00	15	L2	50-100	4.10	127.17
16	FP	50-100	4.10	149.73	16	L2	50-100	4.33	127.83
17	FP	50-100	4.27	128.30	17	L2	50-100	4.10	105.13
18	FP	50-100	3.95	155.27	18	L2	50-100	3.93	158.57
19	FP	50-100	3.89	135.07	19	L2	50-100	4.53	161.93
20	FP	50-100	4.04	143.83	20	L2	50-100	4.08	137.87
21	FP	50-100	4.16	130.10	21	L2	50-100	4.04	160.67
22	FP	50-100	3.75	203.53	22	L2	50-100	3.68	197.03
23	FP	50-100	4.24	112.97	23	L2	50-100	3.83	222.67
24	FP	50-100	4.53	176.53	24	L2	50-100	3.41	208.83
25	FP	50-100	4.16	180.70	25	L2	50-100	3.26	201.83

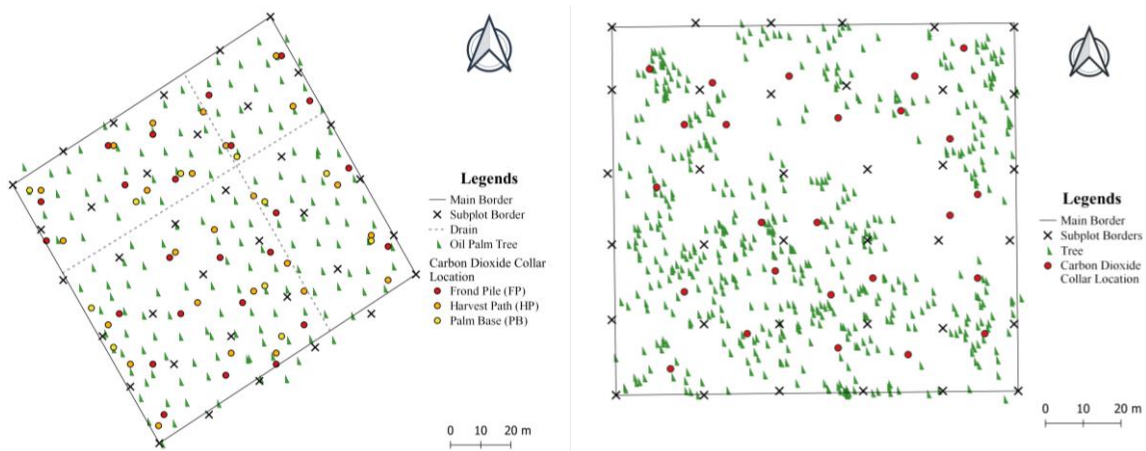
Appendix 11: continued

1	PB	50-100	4.07	247.33	1	L3	50-100	3.45	199.53
2	PB	50-100	3.99	134.13	2	L3	50-100	3.48	187.50
3	PB	50-100	3.90	111.83	3	L3	50-100	3.59	235.00
4	PB	50-100	5.31	185.27	4	L3	50-100	3.54	242.33
5	PB	50-100	3.56	288.33	5	L3	50-100	3.65	257.67
6	PB	50-100	3.59	292.33	6	L3	50-100	3.61	207.00
7	PB	50-100	3.78	233.00	7	L3	50-100	3.63	223.00
8	PB	50-100	3.86	175.00	8	L3	50-100	3.71	248.00
9	PB	50-100	3.83	175.63	9	L3	50-100	3.70	264.33
10	PB	50-100	4.22	129.93	10	L3	50-100	3.83	257.33
11	PB	50-100	4.08	199.03	11	L3	50-100	3.71	211.00
12	PB	50-100	4.12	148.57	12	L3	50-100	4.05	209.00
13	PB	50-100	3.96	153.63	13	L3	50-100	4.23	157.53
14	PB	50-100	3.59	373.00	14	L3	50-100	4.56	159.93
15	PB	50-100	4.64	110.83	15	L3	50-100	4.38	129.23
16	PB	50-100	4.06	159.10	16	L3	50-100	4.16	149.63
17	PB	50-100	3.87	251.33	17	L3	50-100	3.99	158.13
18	PB	50-100	3.82	142.70	18	L3	50-100	3.89	166.00
19	PB	50-100	4.04	302.67	19	L3	50-100	4.07	158.80
20	PB	50-100	3.87	224.00	20	L3	50-100	4.16	192.60
21	PB	50-100	3.82	141.23	21	L3	50-100	4.19	165.77
22	PB	50-100	3.88	138.50	22	L3	50-100	4.24	195.57
23	PB	50-100	4.23	133.97	23	L3	50-100	3.95	223.33
24	PB	50-100	4.09	290.00	24	L3	50-100	3.99	209.67
25	PB	50-100	3.98	180.37	25	L3	50-100	3.55	184.73

Appendix 12: Momentary peat surface carbon dioxide emissions in Sebungan Oil Palm Plantation and Sabaju Secondary Forest.

Sebungan Oil Palm Plantation				Sabaju Secondary Forest	
Subplot	<i>n</i>	Carbon Dioxide Emission (g CO ₂ m ⁻² hr ⁻¹)	Standard Deviation	Subplot	Carbon Dioxide Emission (g CO ₂ m ⁻² hr ⁻¹)
1	2	0.4708	0.26	1	0.5194
2	3	0.5946	0.23	2	1.0384
3	3	0.5253	0.13	3	0.7355
4	2	0.3424	0.21	4	0.5098
5	3	0.4643	0.26	5	0.9114
6	2	0.4528	0.10	6	NA
7	3	0.5045	0.10	7	0.9014
8	2	0.6768	0.64	8	0.5326
9	2	0.7035	0.30	9	NA
10	2	0.2910	0.04	10	1.0754
11	3	0.6761	0.32	11	NA
12	3	0.7025	0.26	12	NA
13	2	0.5517	0.13	13	0.8748
14	3	0.4178	0.25	14	1.1582
15	2	0.3934	0.25	15	0.9286
16	2	0.5519	0.08	16	0.2321
17	3	0.4883	0.07	17	NA
18	3	0.5564	0.27	18	0.8502
19	2	1.0573	0.77	19	0.8501
20	2	0.6354	0.40	20	NA
21	1	0.4479	NA	21	NA
22	3	0.4977	0.19	22	NA
23	3	0.5697	0.38	23	NA
24	2	0.5184	0.30	24	1.1957
25	2	0.3248	0.30	25	0.9096

Appendix 13: Maps of Carbon Dioxide Collar Locations in Sebungan Oil Palm Plantation and Sabaju Secondary Forest.



Appendix 14: Publication

Ngau, L. D., Sim, S. F., Kho, L. K., Rumpang, E., Vasander, H., Jauhiainen, J., Yrjälä, K., & Silvennoinen, H. (2022). Mapping peat soil moisture under oil palm plantation and tropical forest in Sarawak. *Mires and Peat*, 28(13).
<http://dx.doi.org/10.19189/MaP.2022.OMB.StA.2370>