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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 CO_2 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 CO_2 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 CO_2 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 m × 20 m) pada dua kedalaman iaitu 0 – 50 cm dan 50 – 100 cm. Sampel tersebut telah dikeringkan di dalam ketuhar pada suhu 55 ℃ 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 cm dan 50 – 100 cm) berbanding dengan kelembapan hutan gambut. Pertumbuhan batang pokok kelapa sawit menunjukkan korelasi positif dengan kelembapan tanah pada kedalaman 0 – 50 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 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 saliran 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_2O	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	*Sistem maklumat geografi*
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 CO_2, CH_4 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).