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MAPPING THE CHARACTERISTICS OF TROPICAL FOREST PEAT AND CULTIVATED PEAT UNDER OIL PALM PLANTATION IN SARAWAK, BORNEO

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ABSTRACT

This study attempts to establish and map the characteristics of peat soil under oil palm plantation and forest ecosystem. Peat soil from oil palm plantation and forest was collected for analysis at the depths of 0-15 cm, 100 cm, 200 cm and 300 cm. The plantation peat was found richer with exchangeable calcium and potassium likely due to the fertilisation and liming practices at the estate. The carbon dioxide (CO_2) flux was detected higher at the plantation with elevated emission recorded near the drainage canal. As the depth increased, moisture was evidenced to surge with declining bulk density, indicative of less decomposed underlying peat. The E_4/E_6 values, however, did not reveal any statistical difference in peat soil from different land use and depths. The carbon-to-nitrogen (C/N) ratio was found lower in the cultivated peat suggesting reduced nitrogen stores. This was likely associated with the plantation management practices, resulting in enhanced mineralisation of nitrogen. The C/N ratio was evidenced to increase with increasing depths in both plantation and forest, indicative of lower humification degree for the horizon peat. It was concluded that the soil characteristics differed between land use and depths with spatial variations within each land use.

Keywords: humification degree, E_4/E_6, carbon-to-nitrogen ratio, CO_2 emission, characteristics maps.

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INTRODUCTION

A total of 1.6 million hectares of peatland is found in Sarawak, accounting for 66% of the total peatland in Malaysia. It is largely used for agriculture purposes including oil palm and sago palm plantations. One of the challenges of planting on peat is that their yield is generally lower. According to Melling (2000), the degree of humification is an imperative factor governing the productivity of agriculture development on peat. It has profound effects on the bulk density, moisture holding capacity and nutrient availability of the soil. Veloo *et al.* (2015) similarly inferred that peat maturity has the most significant effect on the yield; the presence of undecomposed wood in the tropical peat profile was reported to relate to poor rooting and inadequate nutrient uptake in oil palm leading to pre-mature dehydration of

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fronds. In the experience of sago plantation on the other hand, the palms are unable to produce trunk upon maturity (Sim *et al.*, 2017).

Peat is formed from the partially decomposed organic materials. During the decomposition process, a stabilised organic substance (referred to as humic substances) consisting of hydrophobic and hydrophilic functional groups is produced (Maryganova *et al.*, 2010). These humified materials serve to agglutinate soil (Clapp *et al.*, 1999), improving aeration and water retention capacity which ultimately lead to increased crop production (Piccolo, 2002). As reported by Venegas-Gonzàlez *et al.* (2013), blackberry planted in better humified compost demonstrates improved nutrient uptake.

Peat maturity is a crucial factor determining the productivity of the organic soil. However, limited information is available for agricultural development on peatland. Typically, the land suitability is mainly assessed based on the soil depth and its drainability (Veloo *et al.*, 2014; Paramanathan and Omar, 2015). In this study, we attempt to establish the characteristics of forest and cultivated peat where the characteristics were latter mapped to depict the spatial variability in humification degree. The variation in chemical and physical properties can be used to describe the degree of decomposition; for example, undecomposed peat characteristically demonstrates low bulk density with high fibre content. These maps are simple representations of bulk soil data that can be used for planning, utilisation and management of peatland. Essentially, peat is highly vulnerable to decomposition upon drainage and compression. With understanding on the spatial variability of humification degree, it is possible to zone the peat according to their suitability and readiness for agriculture purposes, *i.e.* mature peat can be utilised while young peat is conserved.

MATERIALS AND METHODS

Study Sites

Peat soil samples were collected from a 1 ha plot in Sebungan Oil Palm Estate (N 03º 09' 58.32" E 113º 21' 15.43") and Sebaju 4 Forest (N 03º 09' 58.32" E 113º 24' 21.32"), respectively in Sarawak, Malaysia as shown in *Figure 1*.

The 1 ha plot consisted of 25 subplots, each with dimensions of 20 m × 20 m, labelled and represented schematically in *Figure 2*. The peat soil of Sebungan Estate has a depth of 1 m to more than 3 m whilst at the secondary forest, the depth is uncharacterised. The water table was maintained at 30-40 cm below the surface in Sebungan Estate whilst the water table in Sebaju Forest was unregulated.

Sampling

Three soil samples were randomly collected at the area under the vegetation canopies within a subplot. The samples were taken from the surface at 0-15 cm and at the depth of 100 cm, 200 cm and 300 cm using an Eijkelkamp gouge auger with extension rod (core diameter 52 mm, length 0.5 m). The samples were removed from the auger, placed in ziplock bags and labelled according to subplots.

Sample Preparation and Analyses

The soil samples were air-dried, ground into fine particles and sieved through 2 mm sieve. The samples were subjected to analyses in triplicates that included moisture content, bulk density, pH, electrical conductivity, ash content, exchangeable bases, cation exchange capacity (CEC) and humification degree. Note that for the underlying peat at 100, 200 and 300 cm, the samples were only

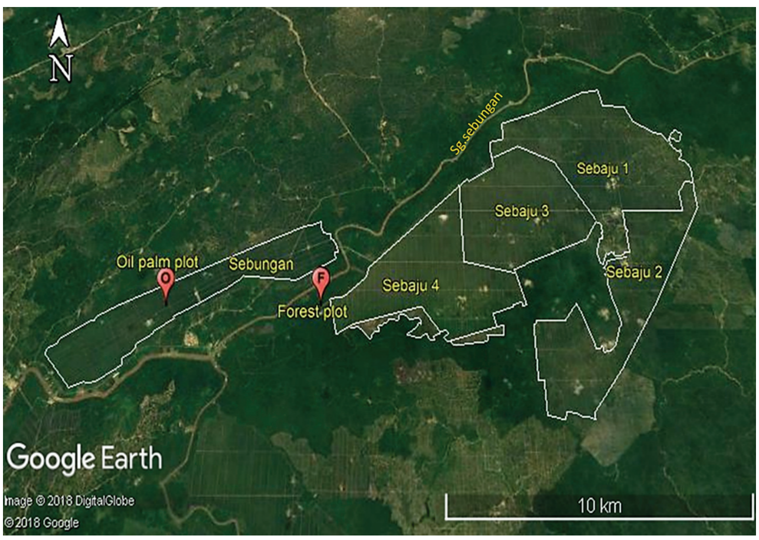

Figure 1. The sampling plot in Sebungan Estate and Sebaju Forest.

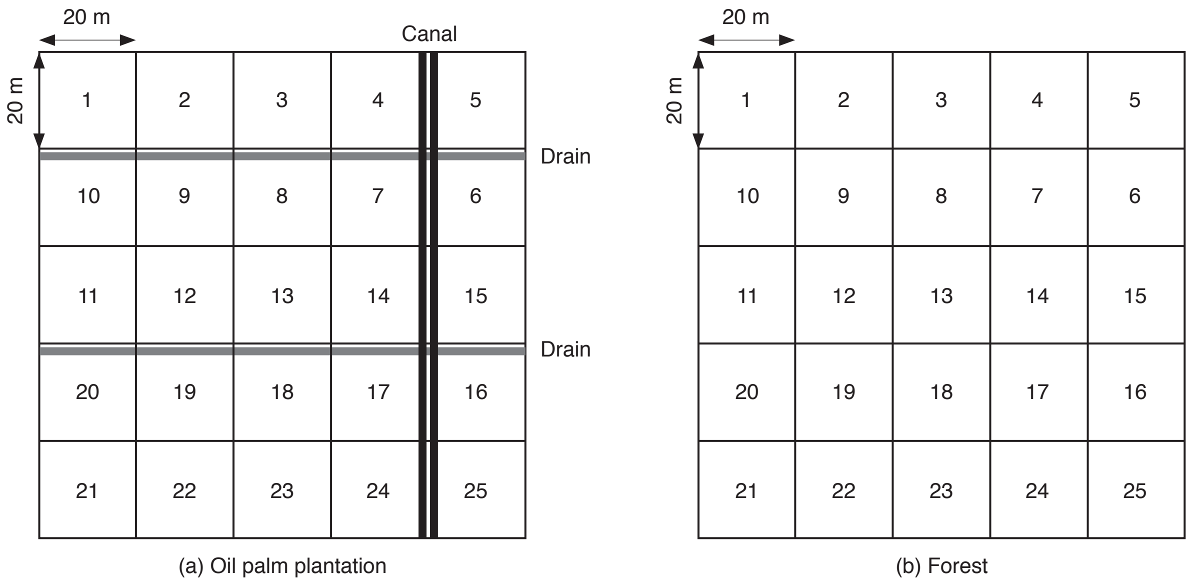

Figure 2. Schematic representation of subplots in (a) oil palm plantation and (b) forest.

analysed for moisture, pH, electrical conductivity and humification degree. Carbon dioxide (CO_2) emission from 25 subplots in oil palm plantation and forest was also measured using EGM-4 Infra-Red Gas Analyser (IRGA) system according to Marthews *et al.* (2014).

The pH and electrical conductivity were measured using a pH/conductivity meter (EXTECH ExStik II) in a soil to water suspension of 1:5 (McLean, 1982). The moisture was measured based on loss on drying whilst the ash content was determined according to the loss-on-ignition method (ASTM, 1987). For ash content, the soil sample was dried in an oven at 100°C overnight. One gram of the dried soil was then weighed into a crucible and combusted in a furnace at 550°C for 6 hr. Bulk density was the ratio of oven dried mass of the soil to its volume where the soil was dried until constant weight was attained (Blake, 1965).

For exchangeable bases, 2 g of soil (≤ 2 mm) were weighed in a 100 ml Erlenmeyer flask and added with 40 ml of 1 M ammonium acetate (NH_4OAc), prepared from glacial acetic acid and concentrated ammonium hydoxide. The sample was left overnight and filtered through a 0.45 μm membrane filter. This process was repeated four times with 25 ml of 1 M NH_4OAc. The leachate was transferred into a 250 ml volumetric flask and made up to mark with deionised water. The filtrate was analysed for exchangeable bases (Ca, Mg, Na and K) using the Inductively Coupled Plasma Optical Emission Spectrophotometer (Perkin Elmer, Optima 800) (Li *et al.*, 2016).

For determination of CEC, excess NH_4OAc in soil was leached with 150 ml ethanol to wash away all the electrolytes and the leachate was discarded. The soil sample was then leached with 250 ml of 10% acidified NaCl. The leachate was transferred to 800 ml Kjeldahl flask and added with 25 ml of 1 M NaOH. A 60 ml volume of the solution was then distilled into 50 ml of 2% boric acid. The solution was titrated with 0.1 M HCl to determine the adsorbed NH_4^+ in the presence of bromocresol green – methyl red as the indicator. At the end point, the colour changed from bluish green to pink. Blank samples were analysed on each run. The CEC was calculated in the unit of $cmol_c\,kg^{-1}$. The exchangeable bases and CEC were according to the US EPA Method 9080 (1986) and calculated according to the following equations.

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

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

$$\text{Exchangeable cations } (cmol_c.\ kg^{-1}) = \frac{s \times v}{m \times j \times 10^3} \times 100$$

where:

s = Concentration of cation (mg litre^{-1})

V = Volume of leachate samples (ml)

m = Weight of soil sample (g)

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

The humification index was determined using the UV-Vis spectrophotometer. A 0.5 g of peat soil was added with 60 ml of 0.5% NaOH and centrifuged at 3600 rpm for 15 min. The supernatant was transferred into a 50 ml beaker and acidified with 0.6 M of concentrated HCl until pH 1. The solution was left to stand for 1 hr for the humic acid fraction to precipitate. The solution was then centrifuged at 4000 rpm for 15 min. The supernatant was discarded; the precipitate was washed with distilled water and centrifuged for 5 min. The humic acid fraction was dissolved in 5 ml of 0.1 M NaOH and the solution was brought to mark in a 100 ml volumetric flask (Khan *et al.*, 2006). The absorbance at E_{465} and E_{665} nm was recorded using a UV-Vis spectrophotometer (Shimadzu, UV-1800). The humification index was measured based on absorbance at 465 and 665 nm, often referred to as E_4/E_6. The carbon and nitrogen content of composite soils from 25 subplots at each profile were measured using a carbon and nitrogen analyser (LECO) in triplicates. The samples were heated at 60°C for 24 hr prior to analysis.

CO_2 Emission

Two PVC collars of approximately 10 cm in length were installed at each subplot in Sebungan Estate and Sebaju Forest yielding a total of 100 collars. The PVC collar was gently hammered into the soil at each subplot. Before the collar insertion, the vegetation and litter were removed to minimise the influence of litter decomposition and root respiration on the measurement (Hergoualc'h and Verchot, 2013). The collar was labelled and left for a week. The CO_2 emission was measured after one week. At each measurement, the height of the collar as well as the soil moisture, soil temperature and air temperature were recorded. The carbon dioxide emission was calculated according to the following equations.

Raw carbon dioxide measurement:

$$R_{uc} = \frac{C_f - C_i}{t_f - t_i} \times \frac{p}{(T_a + 273.15)} \times \frac{V_d}{A} \times \frac{44.01 \times 0.36}{R_u} \text{ g } CO_2 \text{ m}^{-2} \text{hr}^{-1}$$

Corrected carbon dioxide measurement:

$$R_c = R_{uc} \times \frac{V_d + V_{added}}{V} \text{ g } CO_2 \text{ m}^{-2} \text{hr}^{-1}$$

Volume of collar:

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

where,

R_{uc} is uncorrected CO_2 efflux (g CO_2 m^{-2} hr^{-1})

R_c is corrected CO_2 efflux (g CO_2 m^{-2} hr^{-1})

t_f and t_i are the final and initial times (s)

C_f and C_i are the final and initial CO_2 concentrations (ppmv)

P is ambient pressure at time t_i

T_a is air temperature at t_f (°C)

V_d is the SRC-1 chamber volume which is 0.0012287 m^3.

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

R_u is the universal gas constant which is 8.31432 J mol^{-1}K^{-1}

Data Analysis

The average measurements attained for each subplot were arranged into a matrix with rows representing subplots and columns denoting variables. The dimensions of the matrix were 25×12 for surface soil and 25×5 for the lower peat layers. The measurements of each variable (25×1) were organised into a matrix of 5×5 according to the subplot in *Figure 2* and illustrated on colour maps. Two sample t-test with equal mean was used to compare the mean between two sample groups at 95% significant difference. Analysis of variance (ANOVA) was employed to compare the mean of more than two sample groups with Tukey's test applied for multiple comparisons at 95% significant difference.

RESULTS AND DISCUSSION

Figure 3 illustrates the characteristics maps of surface peat from the oil palm plantation and forest. Statistically, there was a significant different in conductivity, exchangeable cations (Mg, Na, K and Ca) and CO_2 emission ($p < 0.05$).

The conductivity of forest peat was higher than that from the plantation, with richer exchangeable Na and Mg in the former whilst Ca and K predominated the latter. This concurs with the findings of Sulistiyanto *et al.* (2007) who reported higher Mg and Na in peat water at the forest sites whilst K was more prominent in the deforested area. Peat soil is naturally susceptible to leaching of K due to low level of clay content and absence of mineral matter (Ahmed *et al*., 2005). In agricultural practices, fertilisers are used to improve the retention of K in peat (Ahmed *et al.*, 2015). It is hence believed that the more pronounced K and Ca in the plantation is a result of liming and fertiliser applications at the estate. The lower Mg and Na in the reclaimed ecosystem is possibly due to leaching; Suharjo and Nurhayati (2005) revealed that the nutrients are susceptible to loss, especially after burning. For CO_2 emission, oil palm plantation was found to release significantly higher CO_2 than that from the forest with cumulative flux of 1.61 and 1.04 kg CO_2 m^{-2} yr^{-1}, respectively. The emission recorded at the plantation is comparable with the measurement reported by Melling *et al.* (2007) at 1.54 kg CO_2 m^{-2} yr^{-1}. For the emission from forest, however, the measurement recorded is lower than the findings of Melling *et al.* (2007) at 2.13 kg CO_2 m^{-2} yr^{-1}. The controlling factor of CO_2 emission is the drainage (Ishikura *et al.*, 2018). In the process of reclamation, drainage may foster mineralisation of organic matter leading to increase in CO_2 flux (Grønlund *et al.*, 2008) hence it is important to manage the water table for sustainable development of peat. The characteristic maps further suggest that CO_2 emission from the estate is generally more heterogeneous than that occurring in the forest. A higher CO_2 flux was identified at subplots near the access road (subplots

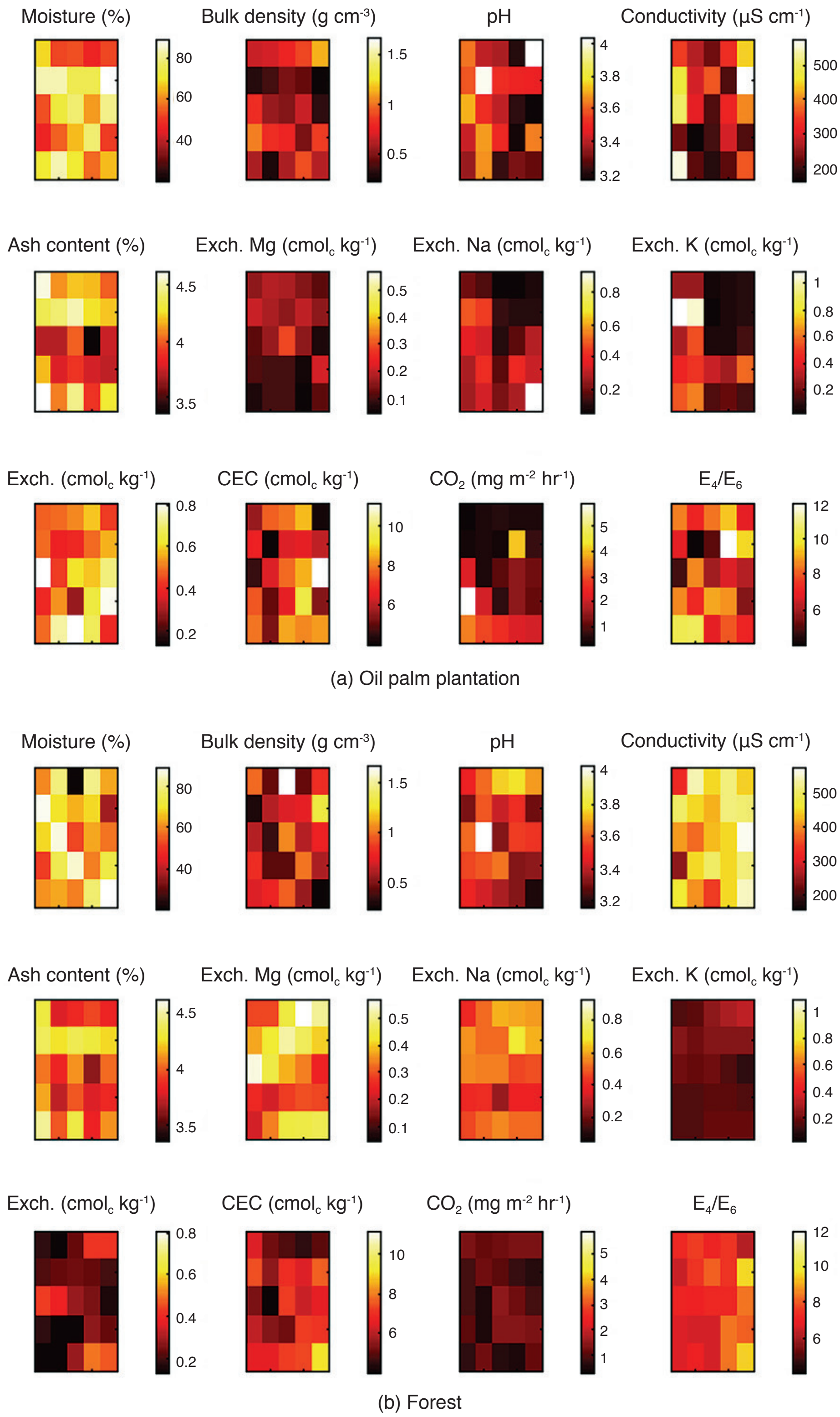

Figure 3. Characteristics maps of surface peat from oil palm plantation and forest.

11 and 20) and drainage canal (subplots 7, 14 and 17) in the plantation. This suggests that the conversion and drainage of peatland has an effect on the CO_2 emission. Spatial variability in methane flux was similarly reported in drained peatland as a result of vegetation heterogeneity and ditches (Minkinnen and Laine, 2006). Premke *et al.* (2016) further corroborated the variation in carbon fluxes from five different landscapes, associating with the landscape heterogeneity and diversity. The profile maps of moisture, pH, bulk density, conductivity and humification degree are shown in *Figure 4* with

the average characteristics summarised in *Table 1*.

The profile maps confirm that the soil was completely submerged at 100 cm, 200 cm and 300 cm for both plantation and forest peat. The soil pH and conductivity were found to decline with increasing depths ($p < 0.05$). The bulk density of the surface peat was also notably higher than the underlying peat for both sites with statistical difference ($p < 0.05$); this opposes the findings reported on the temperate peat where the bulk density was found to increase with depths (Ott and Chimner, 2016). Bulk density is an indicator of decomposition; the bulk density

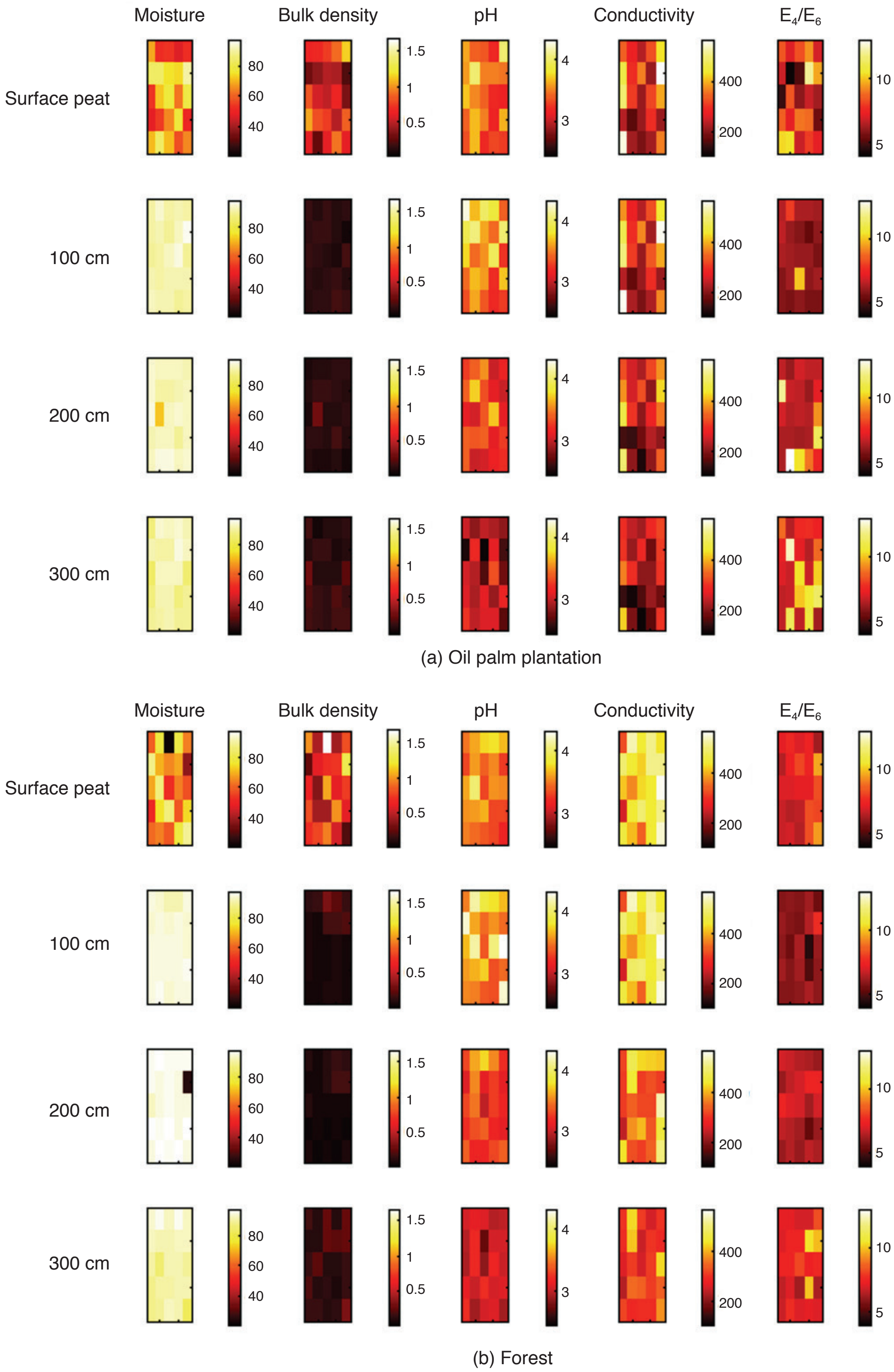

Figure 4. The profile characteristics maps of peat soil from (a) oil palm plantation and (b) forest.

TABLE 1. AVERAGE PEAT SOIL CHARACTERISTICS FROM (A) OIL PALM PLANTATION AND (B) FOREST ACCORDING TO PROFILE

(A) Oil palm plantation

Profile	Moisture (%)	Bulk density (g cm^{-3})	pH	Conductivity (μS cm^{-1})	E4/E6
Surface	66.67±12.78^{a}	0.64±0.24^{b}	3.48±0.23^{c}	317.61±118.85a^{b}	7.67±1.88^{b}
100 cm	90.45±1.69^{b}	0.16±0.03^{a}	3.63±0.29^{c}	322.09±119.30^{b}	6.27±0.93^{a}
200 cm	90.70±4.32^{b}	0.15±0.04^{a}	3.28±0.20^{b}	279.65±102.10a^{b}	7.62±1.99^{b}
300 cm	89.42±2.78^{b}	0.17±0.05^{a}	2.96±0.22^{a}	240.74±82.18^{b}	8.33±1.91^{b}

Note: Same letters in a column indicate no significant difference ($p > 0.05$).

(B) Forest

Profile	Moisture (%)	Bulk density (g cm^{-3})	pH	Conductivity (μS cm^{-1})	E4/E6
Surface	66.09±15.58^{a}	0.72±0.32^{b}	3.51±0.19^{c}	451.87±73.50^{c}	7.44±0.87^{c}
100 cm	93.60±1.18^{b}	0.13±0.07^{a}	3.70±0.30^{d}	456.31±75.03^{c}	5.94±0.56^{a}
200 cm	92.11±13.84^{b}	0.10±0.04^{a}	3.31±0.18^{b}	375.97±75.77^{b}	6.59±0.52^{b}
300 cm	90.08±2.97^{b}	0.19±0.06^{a}	3.05±0.12^{a}	316.37±53.65^{a}	7.577±1.06^{c}

Note: Same letters in a column indicate no significant difference ($p > 0.05$).

may range from 0.05 g cm^{-3} for poorly decomposed peat to 0.5 g cm^{-3} for well decomposed materials (Andriesse, 1988). The low bulk density of deeper peat agrees with the findings of Veloo *et al.* (2014) suggesting presence of undecomposed materials within the soil profiles. At the surface, the bulk density was noticeably higher than the underlying soil, which is not unexpected for reclaimed peat including secondary forest, due to drainage.

The E_4/E_6 is an index of humification; a lower E_4/E_6 suggests greater condensation structure, indicative of higher humification degree and vice versa (Sim *et al.*, 2017). The E_4/E_6 values for plantation and forest peat (from varying depths) range between 6.37 – 8.33 and 5.94 – 7.44, respectively, with the former exhibiting slightly higher value suggesting predominant presence of aliphatic compounds. This observation is in good agreement with the findings of Ywih *et al*. (2009). Statistically, there was no significant different for samples from varying depths and no observable pattern was deduced suggesting that E_4/E_6 is lacking in sensitivity to distinguish the humification degree. The humification degree was further estimated based on C/N ratio of composite subplot samples at different depths; soil with higher humification is expected with a lower C/N as a result of greater mobile nitrogen reserve (Sari and Forro, 2008). *Figure 5* illustrates the C/N profile for peat soil from plantation (34 - 95) and forest sites (21 - 60). The ratio determined for the surface peat (plantation: 34 and forest: 21) is within the range of 16-41 reported by Yonebayashi *et al.* (1994). The forest peat consistently demonstrated lower C/N ratio ($p < 0.05$) than the plantation peat inferring higher nitrogen reserve for the former. This higher stores of nitrogen in peat soil of the secondary forest over oil palm plantation is likewise reported by Muniandy *et al.* (2009). This variation is associated with the origin of parent materials, land clearance, water table management, fertiliser application and liming which lead to increase in soil pH enhancing microbial activity and mineralisation of nitrogen (Muniandy *et al.*, 2009). Wang *et al.* (2018) concludes that the soil C/N is closely related to the land use types with cultivated land demonstrating lower ratio than woodland and orchard. As the depth increased, the peat soil from both cultivated and forest system exhibited increasing C/N ratio, indicative of reduction in humification degree. This observation agrees with the findings of Tonk *et al.* (2017) signifying the undecomposed nature of the underlying tropical peat. This is in opposite to the characteristics of temperate peat where a decline in C/N ratio was observed with increasing depths (Vejre *et al.,* 2003; Callesen *et al.,* 2007; Gundersen *et al.*, 2009; Marty *et al.*, 2017). Comparatively, C/N ratio is a more sensitive index of humification over E_4/E_6.

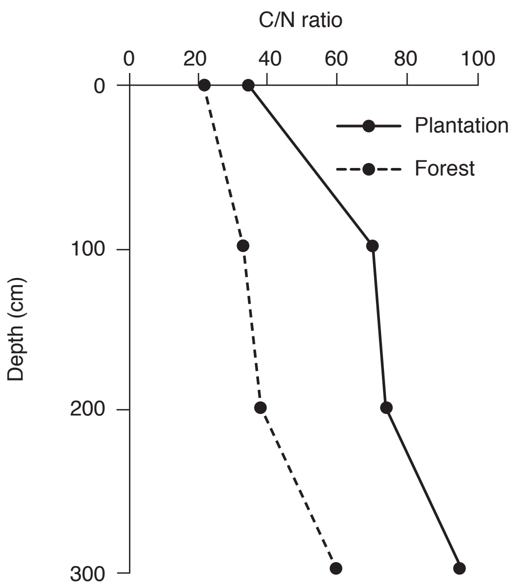

Figure 5. The carbon-to-nitrogen (C/N) profile of plantation and forest peat.

CONCLUSION

The cultivated peat exhibited higher exchangeable Ca, K and CO_2 flux than the forest peat, attributable to the fertilisation and drainage activities. As the depth increased, the soil pH, conductivity and bulk density were found to reduce in both plantation and forest. The declining bulk density suggested less decomposed nature of the lower layer peat, however, no substantial corroboration was drawn from the humification index of E_4/E_6. The C/N ratio offered a conclusive indication that the underlying tropical peat is less decomposed with plantation peat showing lower nitrogen reserve. The cultivated and forest peat differed mainly in nutrient availability and CO_2 emission with the former demonstrating a lower C/N ratio indicative of more pronounced nitrogen mineralisation.

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