

# Spatial Variability of Humification Degree in Tropical Peat of Oil Palm Plantations and Forests

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## ABSTRACT

The productivity of crops largely depends on the peat's degree of humification and the amount of fertilizer applied. Significant variability in oil palm growth within plantations suggests potential heterogeneity in peat humification at the local scale. However, the spatial variability of peat humification has not been previously demonstrated. This study aimed to compare the degree of peat humification between oil palm plantations and forests in East and West Malaysia, and to map its spatial distribution across the two ecosystems. The research was conducted in one-hectare plots divided into 20 m × 20 m subplots at Sebungun Oil Palm Plantation and Sabaju Secondary Forest in East Malaysia, and Amanah Saham Pahang Oil Palm Plantation and Pekan Forest Reserve in West Malaysia. The findings revealed that forest peat had a significantly lower C/N ratio than plantation peat, suggesting higher nitrogen accumulation relative to carbon. However, the C/N ratio did not correlate with spectroscopic humification indices, which indicated a higher degree of humification in plantation peat. This suggests that direct comparison of C/N ratios between forest and plantation peat may be inappropriate due to differences in nitrogen cycling. Mapping of the humification degree demonstrated some degree of spatial variability. The weak correlation between humification degree and soil moisture indicates that other factors, particularly those related to plantation management, may also influence peat humification.

Keywords: atomic ratio, elemental compositions, functional group characteristics, van Krevelen diagram

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## INTRODUCTION

Peat soil comprises of complex aromatic macromolecules constituting up to 60% of organic matter (Trevisan *et al.*, 2010; Verbeke *et al.*, 2021). The conversion of labile organic matter into humic substances *via* physical, chemical and microbiological processes is known as humification (Goel & Dhingra, 2021). The process results in the formation of compounds with aromatic structures, wherein carboxyl and carbonyl groups gradually replace phenolic, alcoholic, and methoxyl moieties.

The assessment of the humification process typically involves indirect measurements that

describe the structural changes of humic matters. As humification progresses, the extent to which organic matter has decomposed and transformed can be expressed as the degree of humification. Various chemical and physical properties of peat have been used to determine the degree of humification. Some commonly employed methods include: (1) the von Post humification (decomposition) scale, a field test on fresh peat samples, which grades humification into 10 degrees (H1-H10), based on the colour and turbidity of peat pore water and the remaining solid materials (von Post, 1924; Lourenco *et al.*, 2023), (2) the pyrophosphate test, a colorimetric method on air dry and ground peat samples, which determines the colour (optical density or

absorbance) of the extract (Kaila, 1956), (3) morphological characterisation and determination of the amount of fibre present (fibric, mesic and sapric) on field fresh material (Farnham & Finney, 1965), (4) atomic ratio analysis of carbon-to-nitrogen (C/N), oxygen-to-carbon (O/C) and hydrogen-to-carbon (H/C) ratios (5) spectroscopic approaches such as Fourier Transform Infrared (FTIR) spectroscopy, molecular fluorescence, nuclear magnetic resonance (NMR) spectroscopy, ultraviolet-visible (UV-Vis) spectroscopy and isotope ratio mass spectroscopy (IRMS) (Zaccone *et al.*, 2007; Biester *et al.*, 2014; Philben *et al.*, 2015).

Veloo *et al.* (2015) suggests that the degree of peat humification is the most influential factor determining the oil palm yield. The degree of humification defines the compositions and chemical characteristics of humic matter, ultimately affecting soil and plant productivity as well as their functions. The quality of humic substances influences soil properties such as soil available water content, pH and nitrogen content (Putra *et al.*, 2016). In peat soils the relationship between humification (or decomposition) and water-holding is complex: on the one hand, accumulation of highly humified humic substances may enhance water retention (via increased polymerisation and hydrophilic functional groups) (Szajdak *et al.*, 2020; Yang *et al.*, 2021). On the other hand, some studies (Campos *et al.*, 2011) find that less-decomposed peat materials demonstrate higher maximum water-holding capacity than more decomposed layers. Jakusné Sáři and Forró (2008) demonstrated the positive effects of peat with varying degree of humification on pepper yield. In their study, mixing peat materials at different stages of decomposition created a more balanced growing medium, which enhanced the physical and chemical properties of the substrate and consequently resulted in higher pepper yields. Furthermore, oil palm planted on more decomposed peat (sapric) exhibited higher yields (19.48 – 22.92 mt/ha) compared to those cultivated on less decomposed peat (hemic) (9.47 – 13.37 mt/ha) (Veloo *et al.*, 2015). The term of 'humification' and 'decomposition' are often used inter-changeably. It is hypothesized, that more decomposed matter comprises greater condensation structures that stimulate the activity of plasma membrane  $H^+$ -ATPase (Canellas & Façanha, 2004). On the other hand,

the carboxyl groups of humic matter function to form complexes with metal ions, enhancing their bioavailability (Kuhn & Maurice, 2014). Additionally, the microbial decomposition process further promotes N assimilation, enriching humic matter with amines ( $NH_2$ ) and ammonium ( $NH_4^+$ ) (Kulikova & Perminova, 2021).

In tropical used peatlands, persistent challenges of poor growth of oil palms have been observed in plantations. Large-scale sago palms planted on deep peat in Mukah, Sarawak, have demonstrated retarded growth with only 20% of the palms developing trunks, none of which reaching maturity even after 10 – 15 years (Purwanto *et al.*, 2002; Jong *et al.*, 2006). Similarly, oil palms planted on deep peat have shown relatively lower yields (Veloo *et al.*, 2015; Woittiez *et al.*, 2017; Rauf *et al.*, 2019; Awang *et al.*, 2021) with the highest reported yield of 23 – 25 t fruit bunches  $ha^{-1} year^{-1}$ , compared to 30 – 35 t  $ha^{-1} year^{-1}$  on mineral soil (Tohiruddin *et al.*, 2006; Othman *et al.*, 2011). Oil palms planted on peat soil exhibit significant variability in growth among individual palms and across plantation blocks. For instance, one palm increased in diameter at breast height from 55.3 cm in 2014 to 72 cm in 2018, while another palm on the same plot showed a decrease of breast diameter from 55.5 cm to 44 cm (Ngau *et al.*, 2022). In our previous study (Ngau *et al.*, 2022), considerable heterogeneity in soil moisture was found in Sebungan Oil Palm Plantation, with palm growth being compromised on drier soils. Similar inter-palm and inter-block variability in aboveground biomass across oil palm plantations was documented by Lewis *et al.* (2020).

We hypothesized, that the variability in soil moisture within oil palm plantations contributes to differences in the humification degree of peat. However, to date, no study has reported on the variation in humification degree at the local scale. This information is crucial for supporting effective local policies and plantation practices aimed at sustainable management and utilization of peat resources. Hence, this study aims to: 1) assess the humification degree of peat in oil palm plantations and forests and 2) map the humification degree using Geographical Information System (GIS). Visualizing this information would facilitate effective dissemination and lead to improved planning

and decision-making process regarding peat management. This aligns with the guidelines established by the European Commission (EU) for sustainable management of peatlands (European Commission, 2021). The EU advocates for the use of digital mapping techniques to provide essential information necessary for the sustainable management of peat including the degree of peat humification, stoichiometric ratio, proximal sensing, peat thickness, hotspots of greenhouse gas emissions, peat subsidence, water table and peat moisture, at scales ranging from field sites to the global level (Minasny *et al.*, 2023).

## MATERIALS AND METHODS

### Study Area

Peat soil samples were collected from oil palm plantations and forests in East and West Malaysia. In East Malaysia, the study sites were in the Sebungan Oil Palm Estate (3°9'58.32"N, 113°21'15.43"E) and the Sabaju Secondary Forest (3°09'58.32"N, 113°24'21.32"E), located in the Sebauh district, Bintulu, Sarawak (Figure 1). Peat soil in Sebungan Oil Palm Estate (hereafter referred as Sebungan Estate) was drained prior to oil palm planting in 2007 with a peat soil depth between 1 m to more than 3 m (Malaysian Palm Oil Board [MPOB], 2006). The Sabaju Secondary Forest (hereafter named as Sabaju Forest) is a closed-canopy secondary forest which has undergone up to two cycles of selective logging in the past. Sebungan Estate and Sabaju Forest are within the same vicinity. The peat depth reported is 4.0 m with a maximum of 5.6 m (MPOB, 2006; Cook *et al.*,

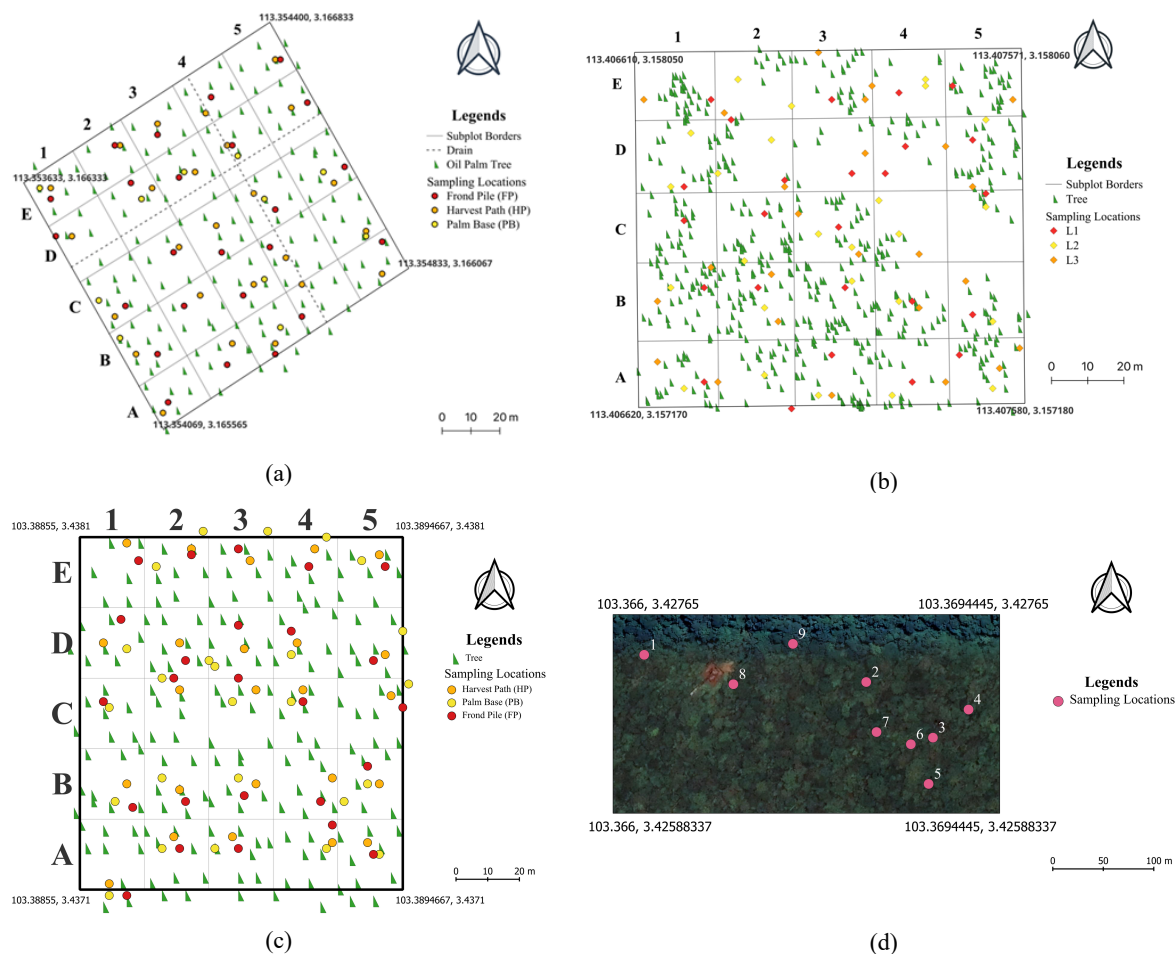
2018; Manning *et al.*, 2019). The area is an elliptical peat dome, formed over coastal or riverine alluvium during the Quaternary period. These areas are underlain by the Nyalau formation consisting mainly of sandstones, shale, mudstone, lignite with some marlstone, siltstone, and calcareous sandstones (MPOB, 2006).

In West Malaysia, the sites were located in the Pekan district, Pahang, which were the oil palm plantation of Ladang Amanah Saham Pahang (hereafter referred as ASPA Estate) (3°26'15.23"N, 103°23'20.43"E) and Pekan Forest Reserve (hereafter referred as Pekan Forest) (3°25'38.64"N, 103°21'59.28"E) (Figure 1). The parent materials of ASPA Estate and Pekan Forest consist mainly of marine and estuarine deposits including beach ridges, swales and organic deposits over sulfidic marine clay. ASPA Estate was previously drained and consists of mature oil palms, which were planted in 2006 to 2007. The peat depth in the estate was reported to be a maximum of 3.0 m (MPOB, 2016). The size of the overall Pekan Forest Reserve is about 7600 ha. However, this forest reserve has been divided into over 200 compartments of various sizes.

Sebungan Estate, Sabaju Forest and ASPA Estate were one-hectare plots consisting of 25 subplots of 20 m × 20 m, respectively as shown in Figure 2(a), 2(b) and 2(c). In Pekan Forest, our study site was located in compartment 75 and was an undisturbed primary forest with varying peat depths of maximum 4.3 m (MPOB, 2016). Sampling points location in Pekan Forest was as shown in Figure 2(d).



**Figure 1.** Locations of oil palm plantations and forests in East and West Malaysia



**Figure 2.** Arrangement of 25 subplots within 100 m × 100 m area in (a) Sebungan Oil Palm Estate, (b) Sabaju Forest and (c) Ladang Amanah Saham Pahang (ASPA) Estate. Each subplot is identified by a letter-number coding (e.g., A1, B2, C3 and so on). Figure 1 (d) shows the sampling points location in Pekan Forest Reserve

### Peat Sampling and Sample Preparation

Peat samples were taken at two depths: 0 – 50 cm and 50 – 100 cm from Sebungan Estate, Sabaju Forest, and ASPA Estate using a peat auger (Eijkelpamp, core diameter 5.2 cm, length 50 cm) equipped with an extension rod of 50 cm. Samples in oil palm estates were collected from each of the 25 subplots at three management zones namely the harvest path (HP), frond pile (FP) and palm base (PB). For Sabaju Forest, samples were taken from three random points, labelled as L1, L2 and L3 of each subplot. Soil sampling in Sabaju Forest was preferentially conducted on flat and open surfaces rather than immediately adjacent to or between forest trees, to minimise the chance of the corer contacting impenetrable woody materials. In the Pekan Forest, soil samples were collected from nine locations along a walking trail of approximately 500 m, with one sample taken from each location

at a depth of 0 – 50 cm using a similar peat auger. In total, 300 peat samples (2 depths × 3 sampling points × 25 subplots × 2 study sites) were collected from Sebungan Estate and Sabaju Forest (i.e., 75 peat samples from each depth in each site). The sampling plots are identical to those reported in our previous study (Ngau *et al.*, 2022). For ASPA Estate, a total of 150 samples were obtained (2 depths × 3 sampling points × 25 subplots), whereas for Pekan Forest, nine samples were obtained. At all sites, mineral soil was not reached during sampling.

Surface litter was removed prior to sampling. Each cored sample, representing the 50 cm soil layer obtained from borehole cuttings, was removed from the auger, sealed tightly in a zip-lock bag, and stored at temperatures below 4 °C until laboratory analysis. Samples were carefully examined, and only those with minimal root materials and no visible mineral contamination

were collected. Peat samples were then dried in an 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 2974-20. Dried samples were ground into fine particles using a pestle and mortar. Loose roots and surface litter were removed before the samples were sieved through a 2 mm sieve. The fine peat particles were mixed thoroughly before laboratory analyses. Coarse fragments (> 2 mm), primarily consisting of undecomposed plant fibres and roots, were excluded from the analytical subsample because they do not represent the fine, humified matrix of the peat. This procedure is consistent with standard soil and peat sample preparation for chemical and spectroscopic analyses. Across all study sites, the surface peat (0 – 50 cm) was more decomposed whereas at the deeper layer, the peat was woody and less decomposed.

### Elemental Analysis

Total C, H, N and S 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 similar weight of vanadium pentoxide (V<sub>2</sub>O<sub>5</sub>), an oxidizer, were transferred into designated tin boxes. Each sample was combusted in a reactor of 1000 °C and analysed in duplicates. The molar ratio of C/N, H/C and O/C were computed to determine the humification degree. 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). The van Krevelen diagram was used to visualise changes in the chemical composition of peat organic matter based on atomic ratios of hydrogen to carbon (H/C) and oxygen to carbon (O/C). The elemental ratio was calculated based on the atomic ratio of the respective elements, for example, the C/N ratio, Eq. (1).

$$\frac{C}{N} = \frac{\frac{C \text{ percentage}}{C \text{ atomic mass}}}{\frac{N \text{ percentage}}{N \text{ atomic mass}}} \quad \text{Eq. (1)}$$

### Peat Functional Group Analysis using Fourier Transform Infrared (FTIR) Spectroscopy

Samples from Sebungan Estate and Sabaju Forest were analysed using Fourier Transform Infrared (FTIR) spectroscopy for the peat functional group characterisation. A composite sample was created by combining samples from the three management zones within each subplot at Sebungan Estate and Sabaju Forest, totalling 100 samples (2 sites × 25 subplots × 2 depths). Within each subplot, peat samples were collected from three management zones at the 0 – 50 cm depth. The three subsamples from each zone were then merged to create a single composite sample per subplot for analysis. To receive spectra of the functional groups in the peat, the samples were scanned using an attenuated total reflection (ATR)-FTIR spectrometer (Nicolet, Thermo Fisher Scientific, Madison, WI) at spectral resolution of 0.4821 cm<sup>-1</sup> in the spectral range of 4000 – 525 cm<sup>-1</sup>. However, detailed interpretation focused on the 1700–600 cm<sup>-1</sup> region, where the most diagnostic absorption bands for peat components - such as carbonyl (C=O), aromatic (C=C), and polysaccharide (C–O) vibrations - occur. Each spectrum was calibrated against the background spectrum of the ATR crystal built-in as a reflector for the IR light penetrating the sample. The spectra in .csv format (comma-separated values) were saved and processed with the automated peak detection and matching algorithm to produce a peak table of rows and columns representing samples and variables (cm<sup>-1</sup>), respectively (Sim & Ting, 2012). For brevity, the algorithm detects the peaks in each spectrum based on the first derivative and computes the area of each peak. The peaks identified across all samples are then matched according to a pre-defined wavelength window of ± 9.6 cm<sup>-1</sup>.

### Vegetation Measures

The geographical coordinates of subplot borders, locations of oil palm and forest tree as well as the sampling points in Sebungan Estate, ASPA Estate and Sabaju Forest were recorded using a GPS (Garmin GPSMAP 64s, Olathe, KS) during sampling. In Sabaju Forest, only trees with diameter more than 10 cm were mapped; tree diameter and tree height ranged between 10.0 – 63.7 cm and 7.8 – 31.4 m, respectively. In Pekan

Forest, only geographical coordinates of sampling locations were recorded.

### Data Analysis

Statistical analyses on peat elemental analysis, soil properties and palm growth 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  $p < 0.05$ . Pearson correlation analysis was performed to evaluate the relationship between the C/N ratio and soil moisture. ANOVA was applied to assess the significance of differences in soil moisture, elemental composition, and elemental ratios among samples from different locations and depths. The coefficient of variation (CV) was used to determine the heterogeneity of the spatial maps. The CV is calculated as the ratio of the standard deviation to the mean. A  $CV < 0.1$  indicates low variability, while a CV between 0.1 and 0.2 suggests moderate variability. A CV greater than 0.2 implies high heterogeneity.

### Spatial Interpolation

The geographical coordinates of the study site, such as subplot boundaries, peat humification degree i.e., C/N, trees, sampling locations, moisture were allocated as attribute features in comma-separated values (CSV) files. The study sites and sampling points were represented as point layers in the Quantum Geographic Information System (QGIS) 3.20 program by importing the corresponding CSV files. Peat soil

moisture and C/N ratio were spatially interpolated using a built-in tool in QGIS known as the inverse distance weighted (IDW) interpolation. IDW interpolation estimates the values of unmeasured points by using points with known values. According to Liu *et al.* (2021), the influence is greater at places of known values that are closer to the estimate locations than it is at points that are more distant. The influence of known values is measured by the distance coefficient,  $p$ , which was kept at  $p = 2$  for all the maps in this study.

## RESULTS

### Peat Elemental Content and Atomic Ratios

Table 1 shows the soil moisture together with the C, H, N and O content in peat soil from oil palm plantations and forests according to the peat depth. The sulphur content is not included in the table, as its measured value is on average less than 0.1%. In comparison, peat soil in Sebungan Estate and Sabaju Forest were wetter than those in ASPA Estate and Pekan Forest. Both the ASPA Estate and Pekan Forest peat demonstrated significantly higher N-content than the Sabaju Forest and the Sebungan plantation peat. Statistically, no significant difference was found in the C content of the upper peat layer in the plantations and forests. The C content in Sebungan Estate at 0 – 50 cm ( $53.09 \pm 3.09\%$ ) was significantly lower than the deeper peat of 50–100 cm ( $57.95 \pm 2.46\%$ ). This trend was reversed in the Sabaju Forest with the topsoil ( $52.49 \pm 4.06\%$ ) containing higher C than the deeper soil ( $50.86 \pm 2.32\%$ ) ( $p = 0.003$ ).

**Table 1.** Average carbon, nitrogen, hydrogen and oxygen percentages in oil palm plantations and forest peat from the surface downwards

| Location                 | Depth (cm) | n  | Moisture (%)       | C (%)              | N (%)             | H (%)             | O (%)              |
|--------------------------|------------|----|--------------------|--------------------|-------------------|-------------------|--------------------|
|                          |            |    | Mean $\pm$ STD     | Mean $\pm$ STD     | Mean $\pm$ STD    | Mean $\pm$ STD    | Mean $\pm$ STD     |
| Sebungan Oil Palm Estate | 0 – 50     | 74 | $83.88 \pm 3.91^a$ | $53.09 \pm 3.09^a$ | $1.10 \pm 0.29^a$ | $5.42 \pm 0.53^a$ | $40.30 \pm 3.38^a$ |
| Sabaju Secondary Forest  | 50 – 100   | 72 | $86.86 \pm 2.10^b$ | $57.95 \pm 2.46^b$ | $1.04 \pm 0.19^a$ | $6.08 \pm 0.41^b$ | $34.90 \pm 2.72^b$ |
| Sabaju                   | 0 – 50     | 74 | $89.57 \pm 2.85^a$ | $52.49 \pm 4.06^a$ | $1.50 \pm 0.27^b$ | $5.38 \pm 0.68^a$ | $40.56 \pm 4.79^a$ |
| Secondary Forest         | 50 – 100   | 73 | $91.24 \pm 1.84^b$ | $50.86 \pm 2.32^b$ | $1.46 \pm 0.16^b$ | $4.82 \pm 0.53^b$ | $42.80 \pm 2.66^b$ |
| ASPA Oil Palm Estate     | 0 – 50     | 75 | $80.70 \pm 4.38^a$ | $49.50 \pm 1.43^a$ | $1.81 \pm 0.22^a$ | $5.17 \pm 0.44^a$ | $43.52 \pm 1.54^a$ |
| Estate                   | 50 – 100   | 75 | $85.57 \pm 8.36^a$ | $49.78 \pm 2.64^a$ | $1.54 \pm 0.20^a$ | $5.10 \pm 0.59^a$ | $43.57 \pm 3.02^a$ |
| Pekan Forest Reserve     | 0 – 50     | 9  | $88.57 \pm 1.11^b$ | $49.06 \pm 0.88^a$ | $2.98 \pm 0.79^b$ | $5.25 \pm 0.22^a$ | $42.71 \pm 1.23^a$ |

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

This variability was not evidenced in the ASPA Estate; no significant difference was deduced in the C content between depths and sites. Changes in the H and O content by depth was likewise different in Sebungan Estate and Sabaju Forest. The H content at 0 – 50 cm ( $5.42 \pm 0.53\%$ ) was lower than that at 50 – 100 cm ( $6.08 \pm 0.41\%$ ) in the plantation. Sabaju Forest on the other hand had higher H content in the upper peat layer. The O content in the plantation decreased with increasing depth and this trend

was inverted in the secondary forest of Sabaju. In ASPA Estate and Pekan Forest, both H and O content in peat were comparable between depths and sites. For N, there was a significant difference between plantations and forests with the latter demonstrating higher N content. This was evidenced in both study areas in East and West Malaysia suggesting variability in the humification degree of oil palm plantation and forest peat.

**Table 2.** Average C/N, H/C and O/C ratio in oil palm plantations and forest peat from the surface downwards

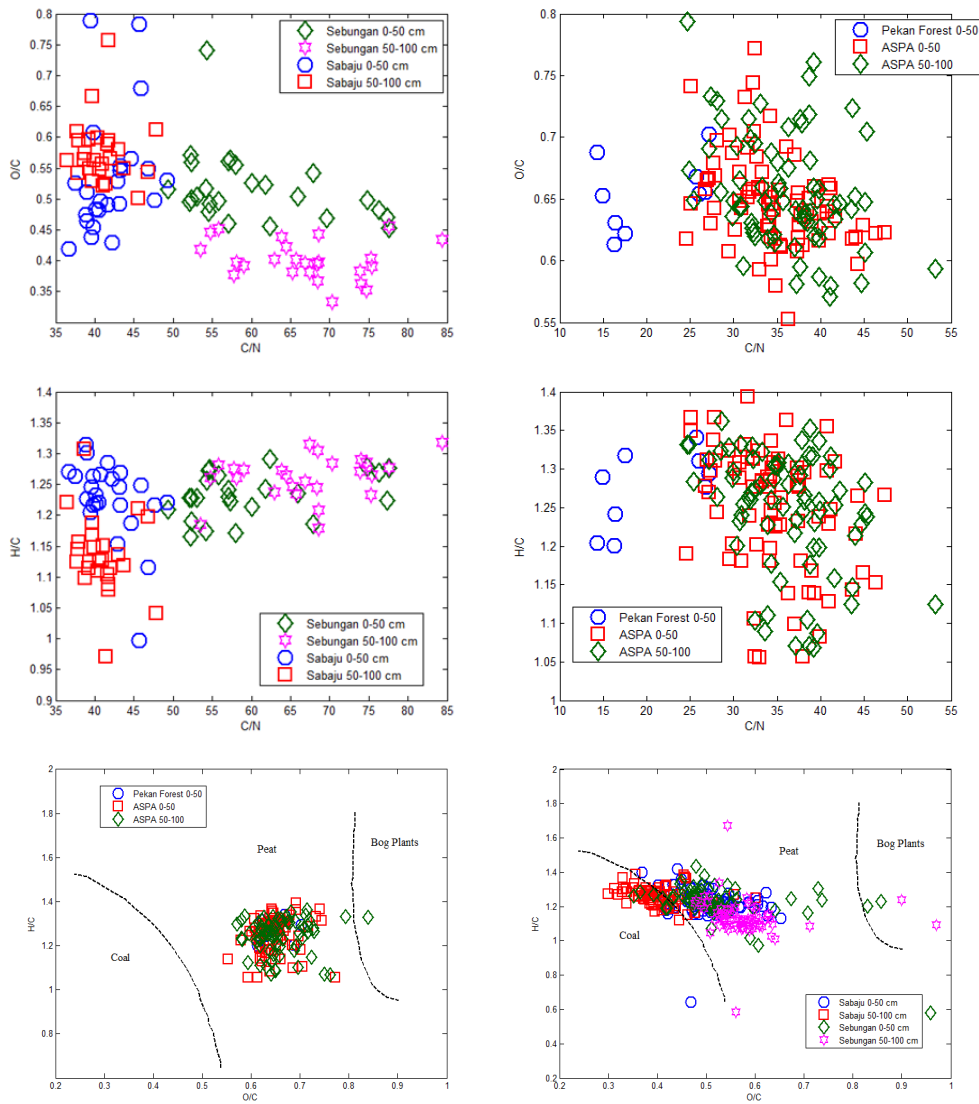
| Location                 | Depth (cm) | n  | C/N ratio                     | H/C ratio                    | O/C ratio                    |
|--------------------------|------------|----|-------------------------------|------------------------------|------------------------------|
|                          |            |    | Mean $\pm$ STD                | Mean $\pm$ STD               | Mean $\pm$ STD               |
| Sebungan Oil Palm Estate | 0 – 50     | 74 | 60.31 $\pm$ 8.83 <sup>a</sup> | 1.22 $\pm$ 0.07 <sup>a</sup> | 0.52 $\pm$ 0.06 <sup>a</sup> |
|                          | 50 – 100   | 72 | 66.97 $\pm$ 7.78 <sup>b</sup> | 1.26 $\pm$ 0.04 <sup>b</sup> | 0.40 $\pm$ 0.03 <sup>b</sup> |
| Sabaju Secondary Forest  | 0 – 50     | 74 | 41.88 $\pm$ 3.28 <sup>a</sup> | 1.22 $\pm$ 0.06 <sup>a</sup> | 0.53 $\pm$ 0.10 <sup>a</sup> |
|                          | 50 – 100   | 73 | 40.94 $\pm$ 2.81 <sup>a</sup> | 1.13 $\pm$ 0.06 <sup>b</sup> | 0.58 $\pm$ 0.05 <sup>b</sup> |
| ASPA Oil Palm Estate     | 0 – 50     | 75 | 34.62 $\pm$ 5.27 <sup>a</sup> | 1.24 $\pm$ 0.12 <sup>a</sup> | 0.65 $\pm$ 0.05 <sup>a</sup> |
|                          | 50 – 100   | 75 | 36.00 $\pm$ 5.48 <sup>a</sup> | 1.23 $\pm$ 0.11 <sup>a</sup> | 0.67 $\pm$ 0.09 <sup>a</sup> |
| Pekan Forest Reserve     | 0 – 50     | 9  | 20.55 $\pm$ 5.64 <sup>a</sup> | 1.27 $\pm$ 0.05 <sup>a</sup> | 0.65 $\pm$ 0.03 <sup>a</sup> |

Same superscript letters according to location in each column indicate no significant differences ( $p > 0.05$ ). The elemental ratio represents the average value of the designated ratio across all sampling points.

The atomic ratios of C/N, H/C and O/C for oil palm plantation and forest peat are summarised in Table 2. The upper peat layer in Sebungan Estate exhibited a significantly lower C/N ratio ( $60.31 \pm 8.83$ ) compared to the 50 – 100 cm depth ( $66.97 \pm 7.78$ ) ( $p = 0.008$ ). In Sabaju Forest, the C/N ratio was much lower than in the oil palm plantation, with no significant difference between the two forest profiles. The average H/C and O/C ratios in Sebungan Estate and Sabaju Forest ranged from 1.13 to 1.26 and 0.40 to 0.58, respectively, with significant differences between depths. In contrast, the C/N ratio in ASPA Estate showed no significant difference between depths. However, the C/N ratio of peat soil at 0 – 50 cm in ASPA Estate and Pekan Forest differed significantly ( $p = 0.00$ ). The H/C and O/C ratios in ASPA plantation and Pekan Forest ranged from 1.23 to 1.27 and 0.65 to 0.67, respectively. While the H/C ratio in ASPA plantation and Pekan Forest was comparable to that in Sebungan Estate and Sabaju Forest, the O/C ratio was noticeably higher in the former. The relationships between O/C, H/C, and C/N ratios are illustrated using the van Krevelen diagram (Figure 3).

### Peat Functional Group Analysis using FTIR

The IR spectra of the functional group characteristics in the composite peat samples revealed 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). Figure 4 illustrates the IR spectra of Sabaju Forest and Sebungan Estate peat, with humification indices calculated based on selected wavelengths. The ratio signals at  $1700 \text{ cm}^{-1}$  (carbonyl and carboxylic C=O),  $1600 \text{ cm}^{-1}$  (aromatic C=C and  $\text{COO}^-$ ), and  $1510 \text{ cm}^{-1}$  (aromatic C=C and C=O of amides) against that at  $1030 \text{ cm}^{-1}$  (polysaccharides) are used as humification indices (Holmgren & Norden, 1988; Niemeyer *et al.*, 1992; Beer *et al.*, 2008). The higher ratios of  $A_{1700}/A_{1030}$ ,  $A_{1605}/A_{1030}$ , and  $A_{1510}/A_{1030}$  in plantation peat compared to forest peat indicate increased decomposition in the former due to polysaccharides degradation. The relatively higher  $A_{1700}/A_{1030}$  also suggests more pronounced carboxyl and carbonyl attributes in plantation peat. This inference contrasts with the results of the C/N ratio, where forest peat exhibited a lower C/N ratio, indicative of a higher degree of decomposition. The relationship between the C/N ratio and the humification index of  $A_{1700}/A_{1030}$  is illustrated in Figure 5.



**Figure 3.** The relationships between O/C, H/C and C/N at Sebungun Estate, Sabaju Forest, ASPA Estate and Pekan Forest

**Spatial Variation of C/N Ratio**

The C/N ratio is compared between Sebungun Estate and Sabaju Forest. Figure 6 illustrates the spatial map of the C/N ratios between these study sites while Table 3 and Table 4 tabulate the C/N ratios according to subplots and peat depths. At 0 – 50 cm, the region towards the west of the plantation is (subplots A1-E1) seemingly more humified (lower C/N ratio: 30.6 – 39.5) than other areas within the profile (higher C/N ratio: 48.4 – 83.5). At 50 – 100 cm, the areas surrounding the drains are characterised with lower C/N ratio (30.6 – 57.4, more humified), comparable with the humification degree at the surface. In Sabaju Forest, topsoil peat in the

north-west of the forest (subplots C1-C3, D1-D3, E1-E3) was less humified with C/N ratio higher than 43.6.

The spatial variability of C/N ratio for the ASPA Plantation and Pekan Forest is shown in Figure 7. In ASPA Plantation, lower C/N ratios were registered in peat soil at 0 – 50 cm in subplots to the South (subplots B1-B5, A1-A2). At the deeper horizon of 50 – 100 cm, similar profile was recorded with subplots towards the North (E2-E5, D1-D5, C1-C3) exhibiting increased C/N values whilst subplots B1-B5 and A1 remained relatively lower in the C/N ratio values.

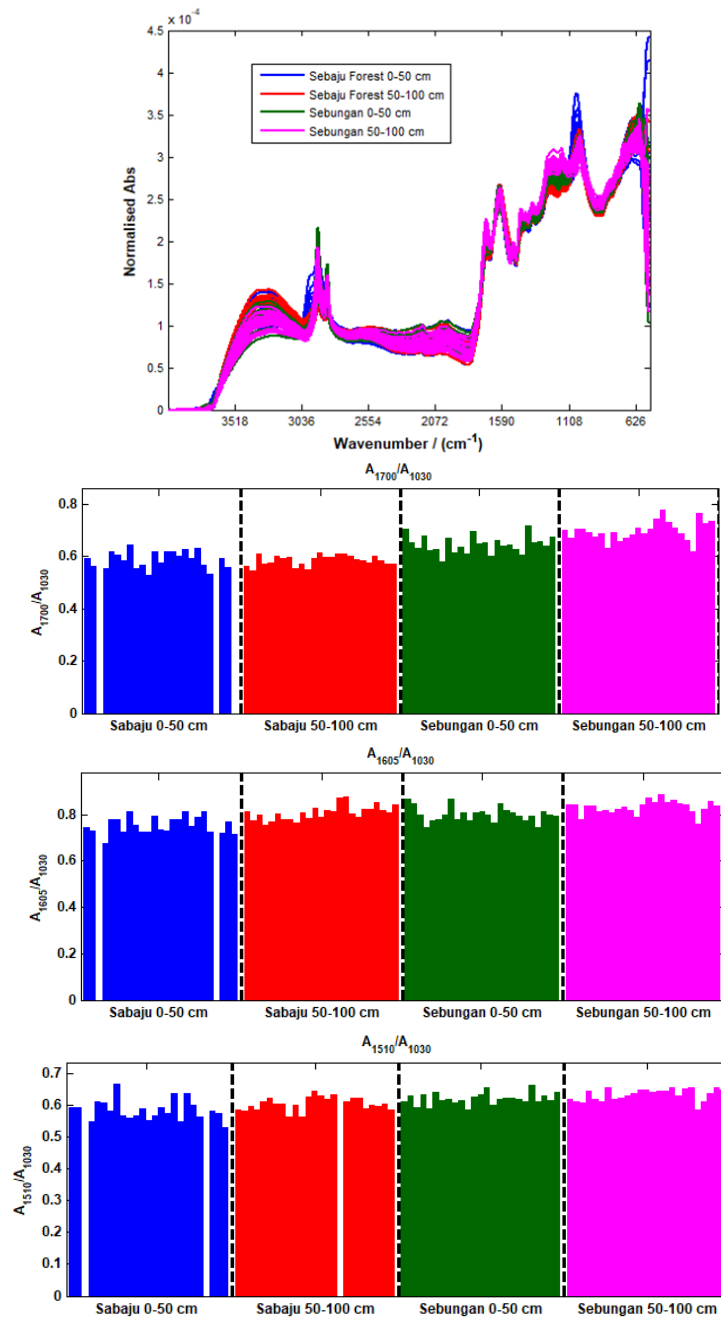


Figure 4. IR spectra profile of Sebugan Oil Palm Plantation and Sabaju Forest with the corresponding humification indices

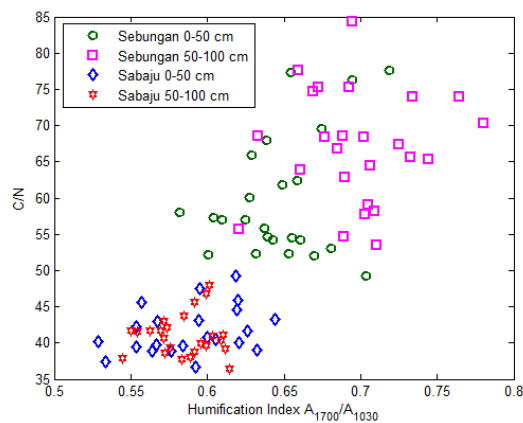
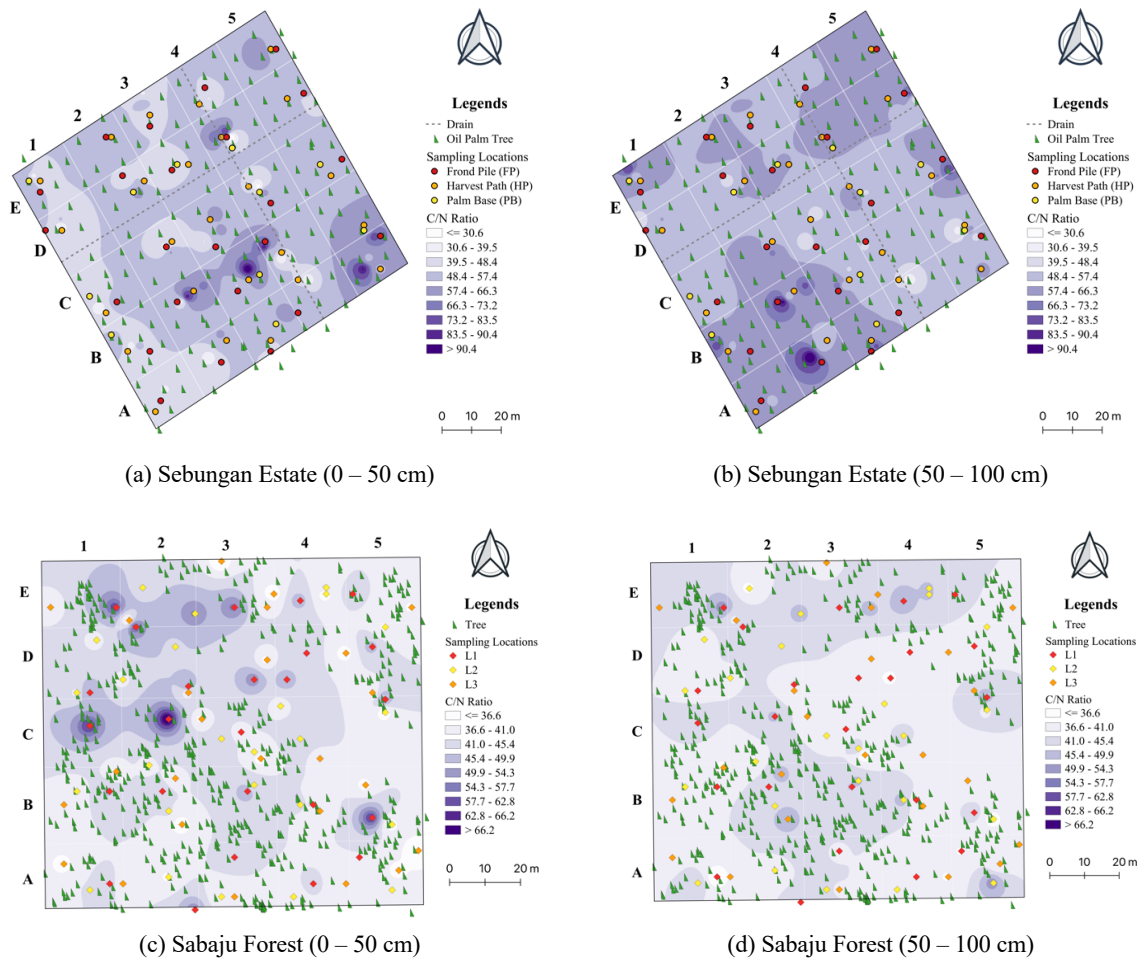


Figure 5. The C/N ratio against the humification index of  $A_{1700}/A_{1030}$



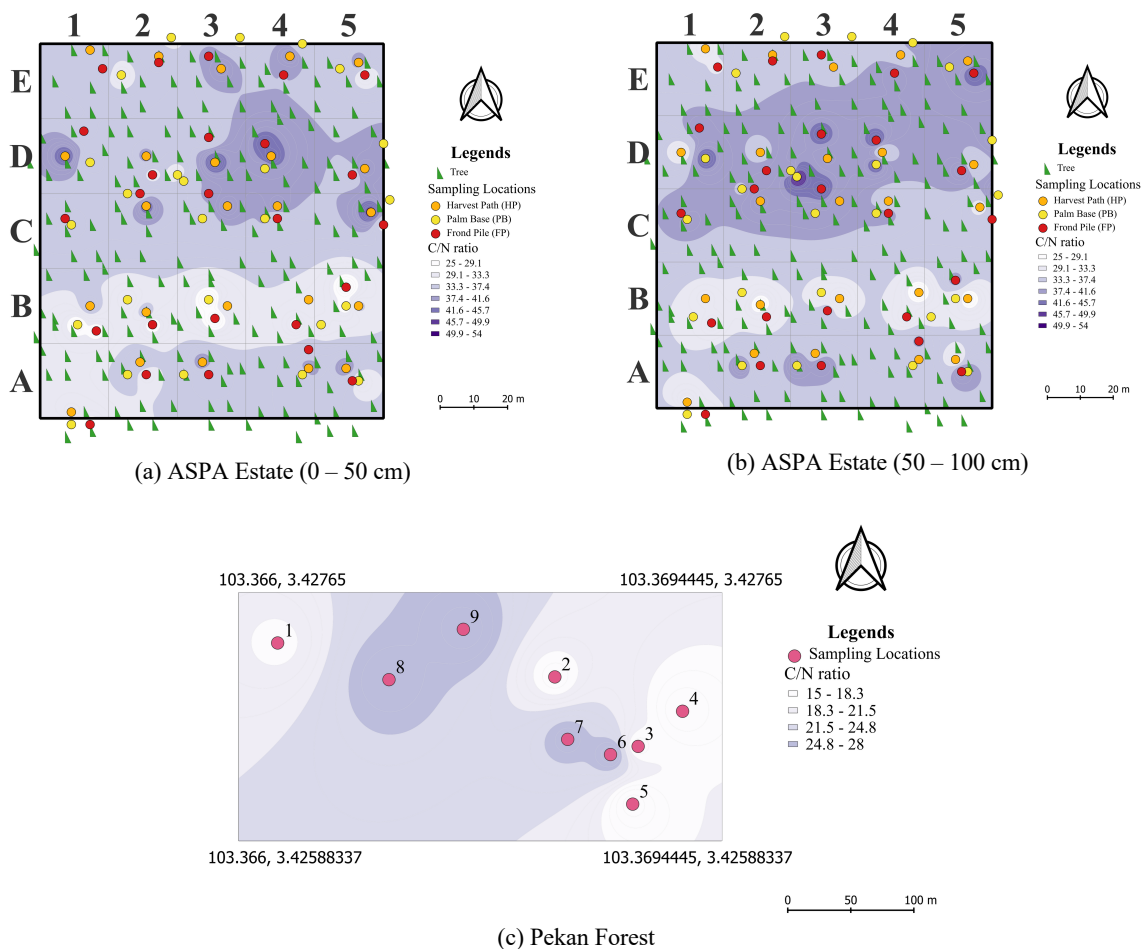
**Figure 6.** Maps of carbon/nitrogen, C/N ratio in Sebungan Oil Palm Estate (range: 30.6 – 90.4) and Sabaju Secondary Forest (range: 31.6 – 66.2) at different depths

**Table 3.** C/N ratios according to subplots and peat depths in Sebungan Oil Palm Estate and Sabaju Secondary Forest

| Sebungan Oil Palm Estate |         |           |          |         | Sabaju Secondary Forest |          |       |                             |          |         |           |                             |
|--------------------------|---------|-----------|----------|---------|-------------------------|----------|-------|-----------------------------|----------|---------|-----------|-----------------------------|
| Sub plot                 | C/N     |           | Sub plot | C/N     |                         | Sub plot | C/N   | Tree density within subplot | Sub plot | C/N     |           | Tree density within subplot |
|                          | 0-50 cm | 50-100 cm |          | 0-50 cm | 50-100 cm               |          |       |                             |          | 0-50 cm | 50-100 cm |                             |
| A1                       | 42.30   | 58.71     | D3       | 44.97   | 58.82                   | A1       | 31.47 | 35.70                       | D3       | 42.83   | 33.98     | 6                           |
| B1                       | 46.81   | 63.99     | E3       | 44.78   | 55.26                   | B1       | 33.31 | 32.41                       | E3       | 39.85   | 34.21     | 19                          |
| C1                       | 44.83   | 49.51     | E4       | 46.46   | 55.99                   | C1       | 34.07 | 35.24                       | E4       | 34.92   | 33.61     | 7                           |
| D1                       | 45.44   | 50.62     | D4       | 58.68   | 60.26                   | D1       | 36.84 | 34.80                       | D4       | 35.73   | 34.63     | 12                          |
| E1                       | 48.95   | 64.49     | C4       | 46.56   | 56.37                   | E1       | 34.37 | 33.68                       | C4       | 36.93   | 35.12     | 7                           |
| E2                       | 51.51   | 58.78     | B4       | 56.57   | 49.89                   | E2       | 34.68 | 34.08                       | B4       | 33.46   | 32.51     | 20                          |
| D2                       | 49.72   | 53.94     | A4       | 49.12   | 46.90                   | D2       | 33.95 | 39.19                       | A4       | 34.16   | 32.42     | 14                          |
| C2                       | 44.74   | 58.97     | A5       | 66.60   | 55.11                   | C2       | 37.12 | 40.22                       | A5       | 32.13   | 36.06     | 23                          |
| B2                       | 64.20   | 72.37     | B5       | 66.52   | 47.86                   | B2       | 33.85 | 35.55                       | B5       | 37.09   | 41.06     | 17                          |
| A2                       | 47.88   | 66.58     | C5       | 54.05   | 63.59                   | A2       | 36.82 | 33.11                       | C5       | 40.78   | 37.47     | 8                           |
| A3                       | 48.91   | 64.87     | D5       | 46.85   | 57.98                   | A3       | 34.42 | 35.76                       | D5       | 39.12   | 35.77     | 25                          |
| B3                       | 65.62   | 57.39     | E5       | 59.67   | 63.39                   | B3       | 38.31 | 33.17                       | E5       | 40.23   | 36.89     | 25                          |
| C3                       | 52.98   | 45.82     |          |         |                         | C3       | 33.36 | 31.23                       |          |         |           |                             |

**Table 4.** C/N ratios according to subplots and peat depths in ASPA Oil Palm Estate and Pekan Forest Reserve

| ASPA Oil Palm Estate |         |           |         |         |           | Pekan Forest Reserve |       |
|----------------------|---------|-----------|---------|---------|-----------|----------------------|-------|
| Subplot              | C/N     |           | Subplot | C/N     |           | Sampling locations   | C/N   |
|                      | 0-50 cm | 50-100 cm |         | 0-50 cm | 50-100 cm |                      |       |
| A1                   | 30.2    | 32.35     | D3      | 38.8    | 45.06     | 1                    | 17.54 |
| B1                   | 29.99   | 30.20     | E3      | 36.29   | 35.57     | 2                    | 16.33 |
| C1                   | 36.32   | 38.02     | E4      | 36.79   | 37.14     | 3                    | 16.30 |
| D1                   | 37.44   | 37.50     | D4      | 42.50   | 39.88     | 4                    | 14.89 |
| E1                   | 33.01   | 33.34     | C4      | 36.92   | 36.19     | 5                    | 14.31 |
| E2                   | 33.03   | 36.16     | B4      | 29.99   | 28.74     | 6                    | 27.17 |
| D2                   | 32.60   | 36.09     | A4      | 35.99   | 36.50     | 7                    | 25.73 |
| C2                   | 36.79   | 38.70     | A5      | 34.67   | 35.72     | 8                    | 25.98 |
| B2                   | 30.32   | 29.56     | B5      | 28.54   | 31.93     | 9                    | 26.74 |
| A2                   | 34.18   | 35.78     | C5      | 38.24   | 36.94     |                      |       |
| A3                   | 35.73   | 38.54     | D5      | 38.00   | 37.85     |                      |       |
| B3                   | 27.45   | 30.92     | E5      | 33.81   | 40.54     |                      |       |
| C3                   | 37.88   | 40.69     |         |         |           |                      |       |



**Figure 7.** Maps of carbon/nitrogen, C/N ratio in ASPA Oil Palm Estate (range: 24.66 – 53.17) at different depths and Pekan Forest (range: 14.31 – 27.17)

## DISCUSSION

The carbon-to-nitrogen (C/N) ratio is used as an indicator of the degree of humification and soil fertility. A lower C/N ratio indicates higher mobile nitrogen reserves, implying increased fertility and enhanced humification. The plantation peat (Sebungan Estate: 60.31 – 66.97 and ASPA Estate: 24.66 – 53.17) exhibited a higher C/N ratio compared to the forest peat (Sabaju Forest: 40.94 – 41.88 and Pekan Forest: 14.31 – 27.17). The higher nitrogen content in the forest peat compared to the plantation peat aligns with the findings of Muniandy *et al.* (2009), which investigated peat soil properties following the conversion of secondary forest to oil palm plantation.

When peat soils are drained, organic nitrogen is first converted into ammonium, which is subsequently oxidized to nitrate ions through nitrification. These nitrate ions are then reduced to nitrous oxide and nitrogen gas via microbial denitrification, releasing nitrogen compounds into the atmosphere (Jauhiainen *et al.*, 2012). Under aerobic conditions, reduced litter input and accelerated decomposition further deplete soil nitrogen (Jakusné Sári & Forró, 2008; Klavins & Purmalis, 2013; Könönen *et al.*, 2015). Lowering of the water table enhances nitrification activity in drained peat soils (Regina *et al.*, 1996). Moreover, fertilization exerts an even stronger influence than fluctuating soil moisture by stimulating microbial activity, thereby accelerating both nitrification and nitrogen mineralization, and ultimately increasing nitrogen loss to the environment (Ariffin *et al.*, 2019).

These findings of lower nitrogen content in oil palm plantations were also observed in our previous studies comparing secondary forest peat and cultivated peat for sago and oil palms (Sim *et al.*, 2017; Sim *et al.*, 2019). Ch'ng *et al.* (2009) also reported a significant decrease in nitrogen content of peat in oil palm plantations, with longer plantation periods leading to lower nitrogen content. The nitrogen-cycling and nitrogen-transforming microbial community in natural and drained peatlands were found to vary. The denitrification and nitrogen-fixing potential were lower in cultivated peatland (organic N → NH<sub>3</sub> → NO<sub>2</sub><sup>-</sup> → N<sub>2</sub>O → N<sub>2</sub>), whereas in natural peatlands, denitrification and dissimilatory nitrate reduction to ammonium

(DNRA) pathways are the controlling mechanisms, encouraging the conversion of NO<sub>2</sub><sup>-</sup> to NH<sub>4</sub><sup>+</sup> (Espenberg *et al.*, 2018). A lower C/N ratio was observed in the upper layer of plantation peat. Typically, the C/N ratio decreases with depth as older and deeper peat undergoes more extensive microbial decomposition (Leifeld *et al.*, 2020). The reversed pattern observed in this study suggests spatial variability in nitrogen mineralization, likely driven by alternating wet and dry soil conditions (Biester *et al.*, 2014). In our previous study, we recorded pronounced temporal variability in water table levels across years, where during the dry season, the water table could fall far below the target range of 30 – 60 cm (Ngau *et al.*, 2022). Furthermore, nitrogen mineralisation may be influenced by management practices such as fertilizer application timing, fertilizer type, and soil disturbances (e.g., drainage), which increase nitrogen availability in surface soils while altering carbon inputs, thereby modifying the C/N ratio distribution with depth. Lazicki *et al.* (2020) demonstrated that mineralised N in soil varied with substrate type, application timing, and dosage; however, it was only after 84 days that mineralised N corresponded closely with the C/N ratio across all materials. Nitrogen mineralisation is also influenced by soil moisture, with higher moisture content enhancing mineralisation rates (Wang *et al.*, 2018). As the C/N ratio reflects total N relative to C and is often used as an indicator of N availability, it should be interpreted with consideration of additional factors, including environmental conditions, beyond management practices. The H/C and O/C ratios serve as indicators of structural changes in humic matter (Sim & Mohamed, 2007; Klavins & Purmalis, 2013; Moore *et al.*, 2018). As humification progresses, humic matter typically becomes enriched with carboxylic and aromatic characteristics, indicating the prevalence of more persistent lignin moieties over polysaccharides (Norden *et al.*, 1986). The H/C ratio serves as an index of aromaticity, while the O/C ratio indicates the abundance of oxygen-containing functional groups. It is expected that the H/C and O/C ratios will decrease with increasing degrees of humification. However, in this study, no significant difference was observed in the H/C and O/C ratios between forest and plantation peat. Although the carbon content was similar in both plantation and forest

peat, the quality of carbon may vary. Accelerated decomposition of peat due to permanent lowering of the water table could result in a greater prominence of recalcitrant C in cultivated peat (Könönen *et al.*, 2016; Könönen *et al.*, 2018). The van Krevelen diagram confirms that the samples are characteristic of peat, showing the expected elemental ratios. As decomposition progresses from vegetation through organic matter into peat and coal, decreasing O/C and H/C ratios are expected (Large & Marshall, 2015). Typical peat soil exhibits O/C and H/C ratios in the ranges of 0.1 to 0.67 and 0.7 to 1.5, respectively. This is attributed to lignin/carboxylic-rich compounds with more aromatic and aliphatic characteristics (Ide *et al.*, 2017).

As illustrated in Figure 3, the humification index suggests that the plantation peat is more humified than the forest peat. However, the C/N ratio did not align with the humification indices (Figure 4). Correlation coefficients between the C/N ratio and the H/C, O/C,  $A_{1700}/A_{1030}$ ,  $A_{1605}/A_{1030}$  and  $A_{1510}/A_{1030}$  were calculated according to sites. Statistically, no significant correlation was found between the C/N and other indices. Zaccone *et al.* (2018) examined the relationships between the C/N ratio with 21 humification proxies of physical, chemical, spectroscopic and thermal parameters. The study revealed a lack of correlation between the C/N ratio and most of the indices. Kivinen (1933) investigated the correlation between the C/N and humification degree determined based on the von Post scale and the two parameters also did not agree.

Humification occurs in two stages. Initially, microbial degradation of labile, plant-derived compounds leads to the formation of products enriched in nitrogen. As humification progresses, nitrogen and methoxyl groups are gradually replaced by carboxyl and carbonyl moieties. Therefore, it is hypothesized that forest peat, which has a higher nitrogen content and a lower abundance of carboxyl/carbonyl groups,

represents an earlier stage of humification compared to plantation peat. However, this hypothesis contradicts the general principle that forest peat, which in this study was characterized by lower C/N ratios, has undergone a more advanced degree of humification than plantation peat. Does this raise doubts about the validity of the C/N ratios as an index of humification degree? This parameter has been widely used among soil scientists as an indicator of humification degree. The establishment of the C/N ratio as an indicator can be traced back to early soil science research which emphasized its significance in relation to soil nitrogen content and the decomposition of organic matter (Waksman, 1938; Stevenson, 1982). A consistent trend of decreasing C/N ratio was observed during the decomposition of various plant materials but cross-comparisons of these ratios between different plant materials were not evaluated. Hence, cross comparisons of C/N ratios between two different ecosystems may not be meaningful due to differences in N-cycling dynamics. As discussed earlier, plantations have a higher potential for N-loss through nitrification, which can be significantly increased with fertilization (Silver *et al.*, 2005). In contrast, forest predominantly undergo anaerobic denitrification and DNRA pathways, converting  $\text{NO}_3^-$  to  $\text{N}_2\text{O}$  and  $\text{NH}_4^+$ , respectively. This implies that changes in land use would modify nitrogen dynamics, resulting in shifts in soil carbon and nitrogen stoichiometry. Hence, comparing the C/N ratio across varying nitrogen dynamics lacks significance. Although this observation of lower C/N in forest peat over plantation peat and disagreement in humification degree was first noted, numerous literature sources have indirectly validated this occurrence. Table 5 tabulates the literature C/N ratio of peat in natural and disturbed state. Consistently, drained peat has been observed to display a notably higher C/N ratio, primarily attributed to its diminished N content. This further strengthens the proposition that the C/N ratio as a measure of humification is appropriate when the nitrogen dynamics are comparable.

**Table 5.** Literature C/N ratio of peat in natural and disturbed state

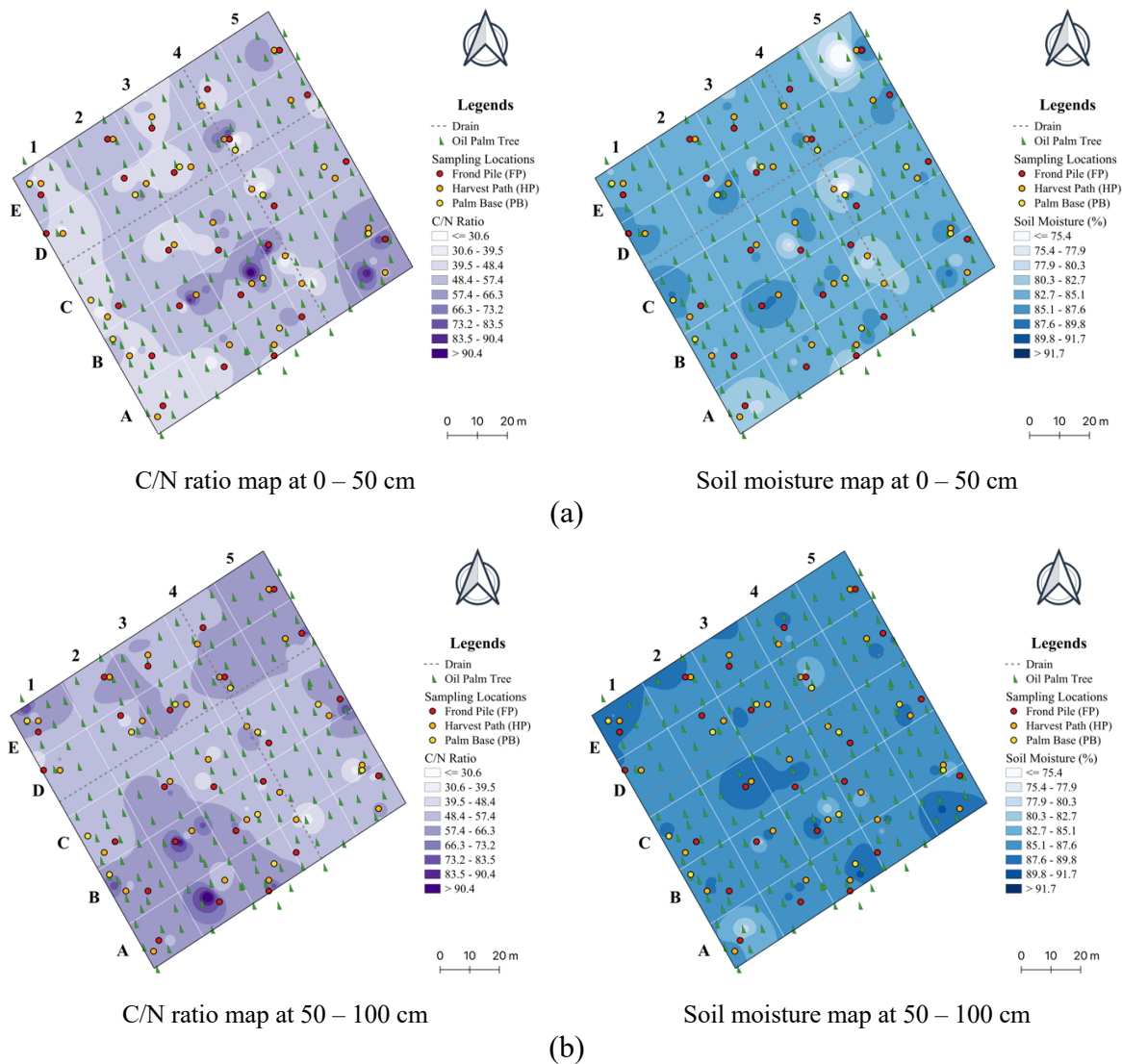
| System/location  | C/N ratio reported   | Reference  |  |
|--|--|--|--|
| Secondary forest and Woodman oil palm plantation Kuala Tatau, Sarawak, Malaysia. | <u>Soil depth 0 – 25 cm</u>                                    | Muniandy <i>et al.</i> (2009)  |  |
|  | Secondary forest: 20.822                                       |  |  |
|  | 1-yr old plantation: 22.127                                    |  |  |
|  | 3-yr old plantation: 38.641                                    |  |  |
|  | 4-yr old plantation: 32.968                                    |  |  |
|  | 5-yr old plantation: 34.841                                    |  |  |
|  | <u>Soil depth 25 – 50 cm</u>                                   |  |  |
|  | Secondary forest: 20.045                                       |  |  |
|  | 1-yr old plantation: 40.904                                    |  |  |
|  | 3-yr old plantation: 43.802                                    |  |  |
| 4-yr old plantation: 36.178  |  |  |  |
| 5-yr old plantation: 47.993  |  |  |  |
| Riau province, Sumatra, Indonesia  | Natural peat swamp forest: 33.85<br>Oil palm plantation: 44.97 | Nurulita <i>et al.</i> (2015)  |  |
| Tropical peat swamp forest (PSF) in Sibuluan, Sarawak.                           | Undisturbed: 60.967<br>Logged: 70.407                          | Satrio <i>et al.</i> (2009)  |  |
| In the upper catchment of Sabangau River, Central Kalimantan, Indonesia.         | <u>PF site</u>   | Könönen <i>et al.</i> (2015)<br>Jauhainen <i>et al.</i> (2014)   |  |
|  | 10 – 15 cm: 34.8 ± 0.6   |  |  |
|  | 40 – 45 cm: 36.1 ± 1.0   |  |  |
|  | 80 – 85 cm: 72.0 ± 3.5   |  |  |
|  | <u>AL site</u>   |  |  |
|  | 0 – 10 cm: 48.5 ± 11.4   |  |  |
|  | 40 – 50 cm: 66.5 ± 3.9   |  |  |
|  | 110 – 150 cm: 83.2 ± 2.9                                       |  |  |
|  |  | <i>PF: Undrained peat swamp forest, forest area was not intact as selective timber removal was undertaken previously</i> |  |
|  |  | <i>AL: Clear-felled, drained abandoned land, was subjected to fire previously</i>  |  |

The spatial maps reveal heterogeneity in the degree of humification in both the plantation and forest. Figure 8, Figure 9 and Figure 10 show the spatial maps of the C/N ratio and the corresponding soil moisture maps at different depths for Sebungau Oil Palm Estate, Sabaju Forest, ASPA Oil Palm Estate and Pekan Forest Reserve, respectively. A significant positive correlation ( $p = 0.03$ ) was found between the C/N ratio and soil moisture at a depth of 0 – 50 cm. Although the C/N ratio and moisture at 50 – 100 cm displayed a similar pattern, no significant correlation was identified ( $p = 0.28$ ). In the Sabaju Forest, no significant correlations were found at either soil depth. Similarly, for the

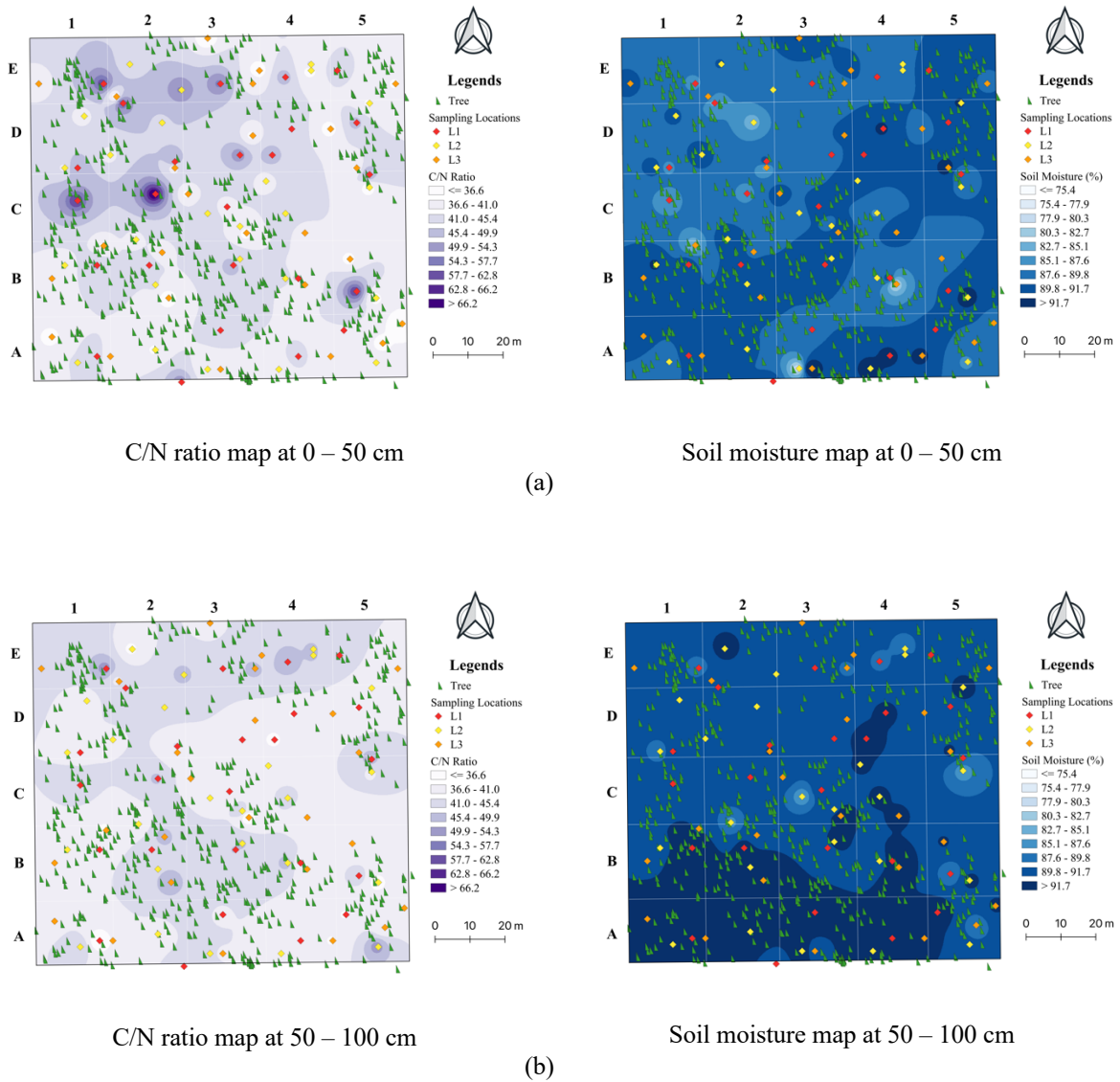
ASPA Estate and Pekan Forest, no significant correlations were observed at any soil depth. The weak correlation between soil moisture and humification degree suggests that peat decomposition is influenced by multiple factors beyond moisture alone. The effect of moisture content and humification on decomposition rate of peat-forming plants found that moisture had a comparatively smaller influence on carbon loss than substrate type and temperature in long-term experiments (Nikonova *et al.*, 2023). In Sebungau Estate, the CV for the 0 – 50 cm soil profile is 0.28, and for the 50 – 100 cm profile, it is 0.20. This indicates that the lower soil profile is comparatively more homogeneous than the

surface soil. In contrast, Sabaju Forest shows noticeably lower CV values than the plantation, with a CV of 0.18 for the upper layer and 0.11 for the lower layer. This suggests that the forest exhibits less variability in the degree of humification compared to the plantation. In ASPA Estate and Pekan Forest, the CV values are more comparable, ranging between 0.24 and 0.27. The observed differences in CV values

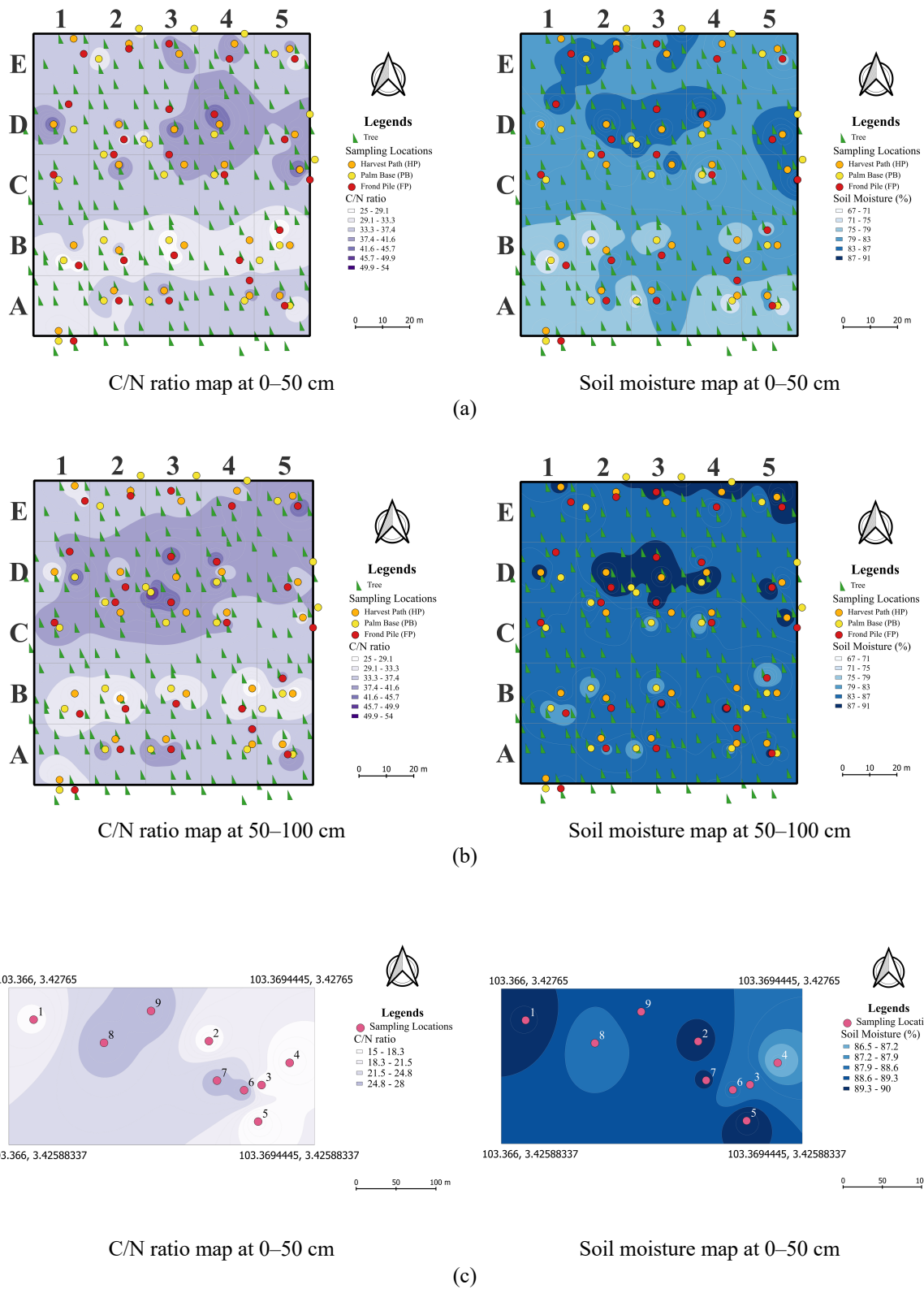
reflect the heterogeneity of peat properties under different land uses. Higher CV values in plantation sites, particularly in the surface layer, indicate greater spatial variability in peat composition and humification degree, which can be attributed to variability in plantation management whereas lower CV values reflect more homogeneous peat conditions, probably under more stable hydrological regimes.



**Figure 8.** Maps of C/N ratio and peat soil moisture maps at Sebungan Oil Palm Estate at different depths. Peat soil moisture maps as reported in Ngau *et al.*, 2022



**Figure 9.** Maps of C/N ratio and peat soil moisture maps at Sabaju Secondary Forest at different depths. Peat soil moisture maps as reported in Ngau et al., 2022



**Figure 10.** Maps of C/N ratio and peat soil moisture maps at (a-b) ASPA Oil Palm Estate at different depths and (c) Pekan Forest Reserve

## CONCLUSION

The assessment of the humification degree in oil palm plantation and forest peat of two regions in Malaysia was performed based on elemental ratios C/N, H/C and O/C ratios as well as humification indices derived from FTIR analysis. The spatial distribution of the humification degree was mapped using GIS. The study established several important findings:

- i. The C/N ratio of the forest peat was notably lower than that of the oil palm plantation when comparing Sebunggan Estate with Sabaju Forest and ASPA Estate with Pekan Forest. The variation in the C/N ratio reflects changes in both carbon and nitrogen contents. A lower C/N ratio means there is either less carbon, more nitrogen, or both in the sample. This suggests that the lower C/N ratio in forest peat may be associated with higher nitrogen accumulation relative to carbon.
- ii. The humification degrees determined using the C/N ratio and indices of FTIR-spectroscopy contradicted each other. The FTIR humification indices demonstrated that plantation peat was more humified than forest peat, which was expected due to accelerated oxidation. However, the C/N ratio suggested the reverse.
- iii. The unexpected humification degree of plantation and forest peat, as interpreted based on the C/N ratio, may result from altered nitrogen-cycling processes in the plantation peat, making the nitrogen content incomparable. The study suggests that the C/N ratio can only be used as an index of humification degree when the nitrogen dynamics of the samples are comparable. In addition, the H/C and O/C ratios did not differ significantly between land uses, further supporting the interpretation that land-use impacts are more specific to nitrogen dynamics.
- iv. The heterogeneity in peat humification degree is influenced by factors beyond moisture, as the surface peat often exhibits greater variability that may be attributed to plantation management practices.

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## REFERENCES

- Ariffin, M.R., Ahmed, O.H., Md Isa, I. & Khairuddin, M.N. (2019). Effects of moisture level on nitrogen availability in tropical peat soil cultivated with oil palm (*Elaeis guineensis* Jacq.). *Journal of Agricultural Science*, 41 (1): 166–174. DOI: 10.17503/agrivita.v41i1.2007.
- Awang, A.H., Rela, I.Z., Abas, A., Johari, M.A., Marzuki, M.E., Mohd Faudzi, M.N.R. & Musa, A. (2021). Peat land oil palm farmers' direct and indirect benefits from good agricultural practices. *Sustainability*, 13 (14). DOI: 10.3390/su13147843.
- Beer, J., Lee, K., Whiticar, M. & Blodau, C. (2008). Geochemical controls on anaerobic organic matter decomposition in a northern peatland. *Limnology and Oceanography*, 53, 1393–1407. DOI:10.2307/40058261.
- Biester, H., Knorr, K.H., Schellekens, J., Basler, A. & Hermanns, Y.M. (2014). Comparison of different methods to determine the degree of peat decomposition in peat bogs. *Biogeosciences*, 11, 2691–2707. DOI: 10.5194/bg-11-2691-2014.
- Campos, J.R.D.R., Silva, A.C., Fernandes, J.S.C., Ferreira, M.M. & Silva, D.V. (2011). Water retention in a peatland with organic matter in different decomposition stages. *Revista Brasileira de Ciencia do Solo*, 35 (4): 1217–1228. DOI: 10.1590/S0100-0683201100040001.
- Canellas, L.P. & Façanha, A.R. (2004). Chemical nature of soil humified fractions and their bioactivity. *Pesquisa Agropecuária Brasileira*, 39: 233–240. DOI:10.1590/S0100-204X2004000300005.
- Ch'ng, H.Y., Nik Majid, N.M., Ahmed, O.H. & Jalloh, M.B. (2009). Effects of converting secondary forest on peat to oil palm plantation on carbon sequestration. *American Journal of*

- Agricultural and Biological Science*, 4 (2): 123–130. DOI:10.3844/ajabssp.2009.123.130.
- Cook, S., Whelan, M.J., Evans, C.D., Gauci, V., Peacock, M., Garnett, M.H., Kho, L.K., Teh, Y.A. & Page, S.E. (2018). Fluvial organic carbon fluxes from oil palm plantations on tropical peatland. *Biogeosciences*, 15: 7435–7450. DOI: 10.5194/bg-15-7435-2018.
- Espenberg, M., Truu, M., Mander, U., Kasak, K., Nolvak, H., Ligi, T., Ookaup, K., Madison, M. & Truu, J. (2018). Differences in microbial community structure and nitrogen cycling in natural and drained tropical peatland soil. *Scientific Reports*, 8: 1–11. DOI: 10.1038/s41598-018-23032-y.
- European Commission. (2021). *Land use sector. Climate Action*. [https://climate.ec.europa.eu/eu-action/land-use-sector\\_en](https://climate.ec.europa.eu/eu-action/land-use-sector_en).
- Farnham, R. S. & Finney, H. R. (1965). Classification and properties of organic soils. *Advances in Agronomy*, 17: 115–162. DOI: 10.1016/S0065-2113(08)60413-7.
- Goel, P. & Dhingra, M. (2021). Humic substances: Prospects for use in agriculture and medicine. In Abdelhadi, M. (Ed.), *Humic Substances*. IntechOpen. DOI:10.5772/intechopen.99651.
- Holmgren, A. & Norden, B. (1988). Characterization of peat samples by diffuse reflectance FT-IR spectroscopy. *Applied Spectroscopy*, 42 (2): 255–262. DOI: 10.1366/0003702884428284
- Ide, J., Ohashi, M., Takahashi, K., Sugiyama, Y., Piirainen, S., Kortelainen, P., Fujitake, N., Yamase, K., Ohte, N. & Moritani, M. (2017). Spatial variations in the molecular diversity of dissolved organic matter in water moving through a boreal forest in eastern Finland. *Science Reports*, 7: 1–13. DOI: 10.1038/srep42102.
- Jakusné Sári, S. & Forró, E. (2008). Relationships between humification and productivity in peat-based and peat-free growing media. *Horticultural Science*, 35 (2): 45–49. DOI: 10.17221/638-HO-RTSCI.
- Jauhiainen, J., Silvennoinen, H., Hämäläinen, R., Limin, S., Raison, R.J. & Vasander, H. (2012). Nitrous oxide fluxes from tropical peat with different disturbance history and management. *Biogeosciences*, 9: 1337–1350. DOI: 10.5194/bg-9-1337-2012.
- Jong, F.S., Watanabe, A., Hirabayashi, D., Matsuda, S., Purwanto, B.H., Kakuda, K. & Ando, H. (2006). The growth performance of sago palms (*Metroxylon sagu*, Rottb.) on peat of different depth and soil water table. *Sago Palm*, 14 (2): 59–64. DOI: 10.57418/sagopalm.14.2\_59.
- Kaila, A. (1956). Determination of the degree of humification in peat samples. *Agricultural and Food Science*, 28 (1): 18–35. DOI: 10.23986/afsci.71402.
- Kivinen, E. (1933). Suokasvien ja niiden kasvualustan kasvin ravintoaine suhteista. *Acta Agriculturae Fenniae*, 27.
- Klavins, M. & Purmalis, O. (2013). Properties and structure of raised bog peat humic acids. *Journal of Molecular Structure*, 1050: 103–113. DOI: 10.1016/j.molstruc.2013.07.021.
- Könönen, M., Jauhiainen, J., Laiho, R., Kusin, K. & Vasander, H. (2015). Physical and chemical properties of tropical peat under stabilised land uses. *Mires and Peat*, 16 (8): 1–13. DOI: 10.19189/001c.128547.
- Könönen, M., Jauhiainen, J., Laiho, R., Spetz, P., Kusin, K., Limin, S. & Vasander, H. (2016). Land use increases the recalcitrance of tropical peat. *Wetlands Ecology and Management*, 24 (6): 71–731. DOI: 10.1007/s11273-016-9498-7.
- Könönen, M., Jauhiainen, J., Strakova, P., Heinonsalo, J., Kusin, K., Limin, S. & Vasander, H. (2018). Deforested and drained tropical peatland sites show poorer peat substrate quality and lower microbial biomass activity than unmanaged swamp forest. *Soil Biology and Biochemistry*, 123: 229–241. DOI: 10.1016/j.soilbio.2018.04.028.
- Kuhn, K.M. & Maurice, P.A. (2014). Accessibility of humic-associated Fe to a microbial siderophore: Implications for bioavailability. *Environmental Science & Technology*, 48: 1015–1022. DOI: 10.1021/es404186v.
- Kulikova, N.A. & Perminova, I.V. (2021). Interactions between humic substances and microorganisms and their implications for nature-like bioremediation technologies. *Molecules*, 26: 1–32. DOI: 10.3390/molecules26092706.
- Large, D.J. & Marshall, C. (2015). Use of carbon accumulation rates to estimate the duration of coal seams and the influence of atmospheric dust deposition on coal composition. In: Smith, D.G., Bailey, R.J., Burgess, P.M. & Fraser, A.J. (eds.). *Strata and time: Probing the gaps in our understanding*. London, Geological Society,

- Special Publications. pp. 404. DOI: 10.1144/SP404. 15.
- Leifeld, J., Klein, K. & Wüst-Galley, C. (2020). Soil organic matter stoichiometry as indicator for peatland degradation. *Scientific Reports*, 10. DOI: 10.1038/s41598-020-64275-y.
- Lewis, K., Rumpang, E., Kho, L.K., McCalmont, J., Teh, Y.A., Gallego-Sala, A. & Hill, T.C. (2020). An assessment of oil palm plantation aboveground biomass stocks on tropical peat using destructive and non-destructive methods. *Scientific Reports*, 10. DOI: 10.1038/s41598-020-58982-9.
- Liu, Z.N., Yu, X.Y., Jia, L.F., Wang, Y.S., Song, Y.C. & Meng, H.D. (2021). The influence of distance weight on the inverse distance weighted method for ore-grade estimation. *Scientific Reports*, 11. DOI: 10.1038/ s41598-021-82227-y.
- Lazicki, P., Geisseler, D. & Lloyd, M. (2020). Nitrogen mineralization from organic amendments is variable but predictable. *Journal of Environmental Quality*, 2020 (49): 483–495. DOI: 10.1002/jeq2.20030.
- Lourenco, M., Fitchett, J.M. & Woodborne, S. (2023). Peat definitions: A critical review. *Progress in Physical Geography*, 47 (4): 506–520. DOI: 10.1177/03091333221118353.
- Malaysian Palm Oil Board. (2006). *Environmental Impact Assessment for the Proposed SOP Sebungan & Lavang OPEs, Bintulu Division*. Malaysian Palm Oil Board, Danum Jaya Sdn Bhd., Bintulu, Malaysia.
- Malaysian Palm Oil Board. (2016). *Soils of Ladang ASPA Sungei Miang & Pekan Forest Reserve (Compartment 75)*. Malaysian Palm Oil Board, Mukim Bebar, Daerah Pekan, Pahang Darul Makmur, Malaysia.
- Manning, F.C., Kho, L.K., Hill, T.C., Cornulier, T. & Teh, Y.A. (2019). Carbon emissions from oil palm plantations on peat soil. *Frontiers for Global Change*, 2 (37). DOI: 10.3389/ffgc.2019.00037.
- Minasny, B., Adetsu, D.V., Aitkenhead, M., Artz, R.R.E., Baggaley, N., Barthelmes, A., Beucher, A., Caron, J., Conchedda, G., Connolly, J., Deragon, R., Evans, C., Fadnes, K., Fiantis, D., Gagkas, Z., Gilet, L., Gimona, A., Glatzel, S., Greve, M.H., Habib, W., Hergoualc'h, K., Hermansen, C., Kidd, D.B., Koganti, T., Kopansky, D., Large, D.J., Larmola, T., Lilly, A., Liu, H., Marcus, M., Middleton, M., Morrison, K., Petersen, R.J., Quaife, T., Rochefort, L., Rudiyanto, Toca, L., Tubiello, F.N., Weber, P.L., Weldon, S., Widyatmanti, W., Williamson, J. & Zak, D. (2024). Mapping and monitoring peatland conditions from global to field scale. *Biogeochemistry*, 167: 383–425. DOI: 10.1007/s10533-023-01084-1.
- Moore, T.R., Large, D., Talbot, J., Wang, M. & Riley, J.L. (2018). The stoichiometry of carbon, hydrogen, and oxygen in peat. *Journal of Geophysical Research: Biogeosciences*, 123: 3101–3110. DOI: 10.1029/ 2018JG004574.
- Muniandy, M., Ahmed, O.H., Nik Majid, N.M. & Yusop, M.K. (2009). Effects of converting secondary forest to oil palm plantation on peat soil carbon and nitrogen and other soil chemical properties. *American Journal of Environmental Sciences*, 5 (3): 406–412. DOI:10.3844/ajessp.2009.406.412.
- 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 peat in Sarawak. *Mires and Peat*, 28 (13). DOI:10.19189/MaP.2022.OMB.StA.2370.
- Niemeyer, J., Chen, Y. & Bollag, J.M. (1992). Characterization of humic acids, composts, and peat by diffuse reflectance fourier transform infrared-spectroscopy. *Soil Science Society of America Journal*, 56 (1): 135–140. DOI: 0.2136/sssaj1992.03615995005600010021x.
- Nikonova, L., Kurganova, I., Lopes de Gerenyu, V., Rogova, O. & Golovatskaya, E. (2023). Impact of temperature and moisture on the decomposition of peat-forming plants: Results of a two-year incubation experiment. *Forests*, 14: 2355. DOI: 10.3390/f14122355 .
- Norden, B., Fyfe, C.A. & McKinnon, M.S. (1986). <sup>13</sup>CCP/MAS NMR study of peat in the solid state. *International Peat Journal*, 1: 153–164.
- Nurulita, Y., Adetutu, E.M., Kadali, K.K., Zul, D., Mansur, A.A. & Ball, A.S. (2015). The assessment of the impact of oil palm and rubber plantations on the biotic and abiotic properties of tropical peat swamp soil in Indonesia. *International Journal of Agricultural Sustainability*, 13: 150–166. DOI: 10.1080/14735903.2014.986321.
- Othman, H., Mohammed, A.T., Darus, F.M., Harun, M.H. & Zambri, M.P. (2011). Best management practices for oil palm cultivation on peat: Ground water-table maintenance in relation to peat subsidence and estimation of CO<sub>2</sub> emissions at

- Sessang, Sarawak. *Journal of Oil Palm Research*, 23: 1078–1086.
- Philben, M., Sutler, S., Billings, S. A., Benner, R., Edwards, K. A. & Ziegler, S. E. (2015). Biochemical and structural controls on the decomposition dynamics of boreal upland forest moss tissues. *Biogeosciences*, 15 (21): 6731–6746. DOI: 10.5194/bg-15-6731-2018.
- Purwanto, B.H., Kakuda, K., Ho, A., Jong, F.S., Yamamoto, Y., Watanabe, A. & Yoshida, T. (2002). Nutrient availability and response of sago palm (*Metroxylon sagu* Rottb.) to controlled release N fertilizer on coastal lowland peat in the tropics. *Soil Science and Plant Nutrition*, 48 (4): 529–537. DOI: 10.1080/00380768.2002.10409235.
- Putra, F.N., Soermano, S. & Suntari, R. (2016). Humification degree and its relationship with some soil physical characteristics on robusta coffee (*Coffea canephora*) plantation. *Journal of Degraded and Mining Lands Management*, 3 (4): 649–658. DOI:10.15243/jdmlm.2016.034.649.
- Rauf, A., Harahap, F.S. & Rahmawaty. (2019). Evaluation of peat soil properties for oil palm plantation in nine years of plant at Kubu Raya District, West Kalimantan, Indonesia. *The 8<sup>th</sup> International Symposium for Sustainable Humanosphere, IOP Conference Series: Earth and Environmental Science*, 374. DOI: 10.1088/1755-1315/374/1/012040.
- Regina, K., Nykänen, H., Silvola, J. & Martikainen, P.J. (1996). Fluxes of nitrous oxide from boreal peatlands as affected by peatland type, water table level and nitrification capacity. *Biogeochemistry*, 35: 401–418. DOI: 10.1007/BF02183033.
- Satrio, A.E., Gandaseca, S., Ahmed, O.H. & Majid, N.M.A. (2009). Effect of logging operation on soil carbon storage of a tropical peat swamp forest. *American Journal of Environmental Sciences*, 5 (6): 748–752. DOI: 10.3844/ajessp.2009.748.752.
- Silver, W.L., Thompson, A.W., Reich, A., Ewel, J.J. & Firestone, M.K. (2005). Nitrogen cycling in tropical plantation forests: Potential controls on nitrogen retention. *Ecological Applications*, 15 (5): 1604–1614. DOI:10.1890/04-1322.
- Sim, S.F. & Mohamed, M. (2007). Chemical characterization of humic substances occurring in the peats of Sarawak, Malaysia. *Organic Geochemistry*, 38 (6): 967–976. DOI: 10.1016/j.orggeochem.2006.12.010.
- Sim, S.F. & Ting, W. (2012). An automated approach for analysis of Fourier Transform Infrared (FTIR) spectra of edible oils. *Talanta*, 88: 537–543. DOI: 10.1016/j.talanta.2011.11.030.
- Sim, S.F., Wasli, M.E., Yong, C.M.R., Howell, P.S., Jumin, C., Safie, N.A. & Samling, B. (2017). Assessment of the humification degree of peat soil under sago (*Metroxylon sagu*) cultivation based on Fourier Transform Infrared (FTIR) and Ultraviolet-Visible (UV-Vis) spectroscopic characteristics. *Mires and Peat*, 19 (24): 1–10. DOI: 10.19189/MaP.2017.OMB.296.
- Sim, S.F., Jumin, C. & Kho, L.K. (2019). Mapping the characteristics of tropical forest peat and cultivated peat under oil palm plantation in Sarawak, Borneo. *Journal of Oil Palm Research*, 31 (3): 459–467. DOI: 10.21894/jopr.2019.00039.
- Stevenson, F. J. (1982). *Organic forms of soil nitrogen*. In F. J. Stevenson (Ed.), *Nitrogen in agricultural soils* (pp. 67-122). American Society of Agronomy, Crop Science Society of America, Soil Science Society of America. DOI: 10.2134/agronmonogr22.c3.
- Szajdak, L.W., Jezierski, A., Wegner, K., Meysner, T. & Szczepański, M. (2020). Influence of drainage on peat organic matter: Implications for development, stability and transformation. *Molecules*, 25: 1–27. DOI: 10.3390/molecules25112587.
- Tohiruddin, L., Prabowo, N.E. & Foster, H.L. (2006). Comparison of the response of oil palm to fertilisers at different locations in North and South Sumatra. In *International Oil Palm Conference (IOPC)*, 19-23 June 2006, Nusa Dua, Bali, Indonesia. pp. 188-200.
- Trevisan, S., Verbeke, F.O., Quaggiotti, S. & Nardi, S. (2010). Humic substances biological activity at the plant-soil interface. *Plant Signaling & Behaviour*, 5 (6): 635–643. DOI: 10.4161/plsb.5.6.11211.
- Veloo, R., van Ranst, E. & Selliah, P. (2015). Peat characteristics and its impact on oil palm yield. *NJAS – Wageningen Journal of Life Sciences*, 7273, 33–40. DOI: 10.1016/j.njas.2014.11.001.
- Verbeke, B.A., Lamit, L.J., Lilleskov E.A., Hodgkins S.B., Basiliko, N., Kane, E.S., Andersen, R., Artz, R.R.E., Benavides, J.C., Benscoter, B.W., Borken W., Bragazza, L., Brandt, S.M., Bräuer, S.L., Carson, M.A., Charman, D., Chen, X., Clarkson B.R. Cobb, A.R. & Chanton, J.P. (2021). Latitude, elevation, and mean annual temperature predict

- peat organic matter chemistry at a global scale. *Global Biogeochemical Cycles*, 36 (2). DOI: 10.1029/2021GB007057.
- von Post, L. (1924). Das genetische System der organogenen Bildungen Schwedens (The genetic system of the organogenic formations of Sweden). In: Comité International de Pédologie, IVème commission (commission pour la nomenclature et la classification des sols, commission pour l'Europe, président: B. Frosterus, ed.), *Mémoires sur la Nomenclature et la Classification des Sols (Memoirs on the Nomenclature and Classification of Soils)*, Helsingfors/Helsinki. pp. 287–304 (in German).
- Waksman, S. A. (1938). *Humus: origin, chemical composition, and importance in nature*. William & Wilkins.
- Wang, X.W., Xu, J.C., Long, C.Z., Shu, W., Lu, M.J. & Yang, W.T. (2018) Effect of nitrogen rates and soil water contents on soil nitrogen mineralization under ryegrass returning into red soil. *Journal of Plant Nutrition and Fertilizers*, 24 (2): 365–374. DOI: 10.11674/zwyf.17373.
- Woittiez, L.S., van Wijk, M.T., Slingerland, M., van Noordwijk, M. & Giller, K.E. (2017). Yield gaps in oil palms: A quantitative review of contributing factors. *European Journal of Agronomy*, 83: 57–77. DOI: 10.1016/j.eja.2016.11.002.
- Yang, F., Tang, C. & Antonietti, M. (2021). Natural and artificial humic substances to manage minerals, ions, water, and soil microorganisms. *Chemical Society Reviews*, 50: 6221–6339. DOI: 10.1039/D0CS01363C.
- Zaccone, C., Miano, T.M. & Shotyk, W. (2007). Qualitative comparison between raw peat and related humic acids in an ombrotrophic bog profile. *Organic Geochemistry*, 38: 151–160. DOI: 10.1016/j.orggeochem.2006.06.023.