# Land use change alters carbon composition and degree of decomposition of tropical peat soils

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## SUMMARY

Drainage associated with land use change in tropical peatlands has increased the rate of decomposition of peat soils and contributed to $CO_2$ emissions. Increased decomposition may result in changes in the composition of the soil organic carbon (SOC). We examined the carbon functional group composition and degree of decomposition of peat soils under five different land uses to understand the effects of changing management intensity on tropical peatland soils. Samples were collected from seven sites spanning five different land uses (forest, shrubland, fernland, revegetation, smallholder oil palm) at the Pedamaran peatland in South Sumatra, Indonesia. SOC composition, measured by Solid-state $^{13}C$ Nuclear Magnetic Resonance (NMR) spectroscopy, was dominated by the alkyl carbon (C) functional group in managed peatlands. However, in the forest far from drainage canals, the SOC comprised predominantly O-alkyl C. The contributions of the functional groups ketone C, carbonyl C and O-aryl C were low and tended to occur in stable proportions throughout the soil profiles. Drainage and land use change significantly affected peat carbon chemistry. The effects were greatest under oil palm, where O-alkyl C had been depleted rapidly under aerobic conditions leading to a change in the dominant carbon functional group from O-alkyl C to alkyl C. Furthermore, our results indicate that the alkyl C:O-alkyl C ratio is a more useful and informative indicator of the degree of decomposition of peat soil than the traditionally used C:N ratio. This more nuanced understanding of the different types of carbon that make up tropical peat soils under different land uses can be applied to support peatland restoration. In particular, nutrient cycling and water availability are likely to be influenced by carbon functional group and degree of decomposition. In order to reduce fire risk and support Indonesia's aspirations to manage the national forest estate as a net carbon sink, further research into the links between peat soil organic carbon chemistry, revegetation performance and new peat accumulation is recommended.

**KEY WORDS:** $^{13}C$ NMR spectroscopy, Indonesia, oil palm plantation, peatland, restoration

## INTRODUCTION

The peatlands of Southeast Asia are estimated to cover a total area of 25 million ha (Page *et al.* 2011) and to store approximately 77 % (65 Gt) of the global tropical peat carbon stock (Page *et al.* 2011). Under undisturbed conditions, these peatlands are covered by forest, the biomass of which is the main contributor to peat accumulation. In Indonesia, peat deposits up to 20 m in depth accumulate and are estimated to store ~57 Gt of carbon (Page *et al.* 2011). Over the past 30 years, however, Indonesian peatland has been deforested, drained, and converted to other land uses (Sorensen 1993, Miettinen *et al.* 2012, Margono *et al.* 2014, Miettinen *et al.* 2016). Conversion of natural peatland combined with drainage leads to increased peat soil oxidation, resulting in an increased rate of peat decomposition and carbon dioxide ($CO_2$) emissions (Page *et al.* 2011, Hooijer *et al.* 2012, Itoh *et al.* 2017, Tonks *et al.* 2017, Cooper *et al.* 2020, Shiraishi *et al.* 2023).

The decomposition rate of tropical peat soils is influenced by several factors such as vegetation type, temperature, water content, microbial community, nutrient availability, and the availability of oxygen (Saidy 2002, Yule *et al.* 2009, Hirano *et al.* 2014, Itoh *et al.* 2017, Sangok *et al.* 2017, Ishikura *et al.* 2018, Mishra *et al.* 2021). The degree of peat decomposition can be determined either in the field or in the laboratory (Chambers *et al.* 2010, Drzymulska 2016). In the field, estimation from freshly extracted peat using the ten grades of the von Post scale is commonly used (Drzymulska 2016); although Wüst *et al.* (2003) have suggested that classification into just three categories (fibric, hemic, sapric) on the basis of rubbed fibre content is the most practical field method for tropical peat. These two methods provide rapid and direct assessments requiring no instrumentation (Chambers *et al.* 2010, Drzymulska 2016). However, they can be subjective and may result in inaccurate conclusions. Laboratory methods for determining degree of decomposition can be grouped into three types based on (i) physical properties such as fibrosity, (ii) chemical properties such as carbon functional groups, humic acids content and carbon to nitrogen (C:N) ratio, and (iii) microscopic analyses of the structure of plant tissues (Drzymulska 2016).

In the Northern Hemisphere, a range of field and laboratory methods have been used to measure peat decomposition (Grover & Baldock 2010). Solid-state $^{13}$C Nuclear Magnetic Resonance (NMR) spectroscopy is one of the methods that has been routinely used as a robust technique for characterising organic carbon composition and assessing degree of decomposition of *Sphagnum* moss peat (Hammond *et al.* 1985, Preston *et al.* 1987, Grover & Baldock 2010, Grover & Baldock 2012, Normand *et al.* 2017, Rodriguez *et al.* 2021). A more recent study on *Sphagnum* moss showed the change in C functional groups in relation to the water table (Trifiró *et al.* 2022). Solid-state $^{13}$C NMR spectroscopy allows the determination of organic functional groups present in peat soils that vary in molecular composition and microbial utilisation (Normand *et al.* 2017, Rodriguez *et al.* 2021). Baldock *et al.* (1997) reported four main groups of C including alkyl, O-alkyl, aromatic and carbonyl based on chemical shift values. $^{13}$C NMR spectroscopy has also been used as a sensitive technique for determining the degree of decomposition of peat soils (Baldock *et al.* 1997, Grover & Baldock 2012), with decreased O-alkyl C and increased alkyl C being correlated with the ongoing decomposition of organic materials (Baldock *et al.* 1997).

In the tropics, solid state $^{13}$C NMR has been applied to investigate the carbon composition of peat soil in relation to the rate of peat decomposition, the rate of peat accumulation, gas fluxes, and carbon and nitrogen mineralisation (Saidy 2002, Purwanto *et al.* 2005, Wright *et al.* 2011, Sangok *et al.* 2017, Sangok *et al.* 2020). However, there is no information on the organic carbon composition and degree of decomposition of tropical peat soils from different land uses and depth increments provided by $^{13}$C NMR spectroscopy. A more prevalent metric for the degree of decomposition of tropical peat soils is the so-called ‘C:N ratio’, evaluated as the quotient (C ÷ N or C/N) (Takakai *et al.* 2006, Lampela *et al.* 2014, Könönen *et al.* 2015, Nurulita *et al.* 2015, Itoh *et al.* 2017, Kurnianto *et al.* 2019, Anshari *et al.* 2022). This approach is based on the observed residual enrichment of N relative to C during the mineralisation of organic matter (Drzymulska 2016). The more-decomposed peat material is indicated by lower C/N (Krüger *et al.* 2015, Drzymulska 2016, Leifeld *et al.* 2020). However, evidence for such trends can be inconsistent due to external factors. For example, the C content may be affected by the occurrence of burnt material in the samples which can potentially magnify the C content. Moreover, the N content may also be affected by other factors - such as leaching and fertiliser application - in managed peatlands (Sakin *et al.* 2011).

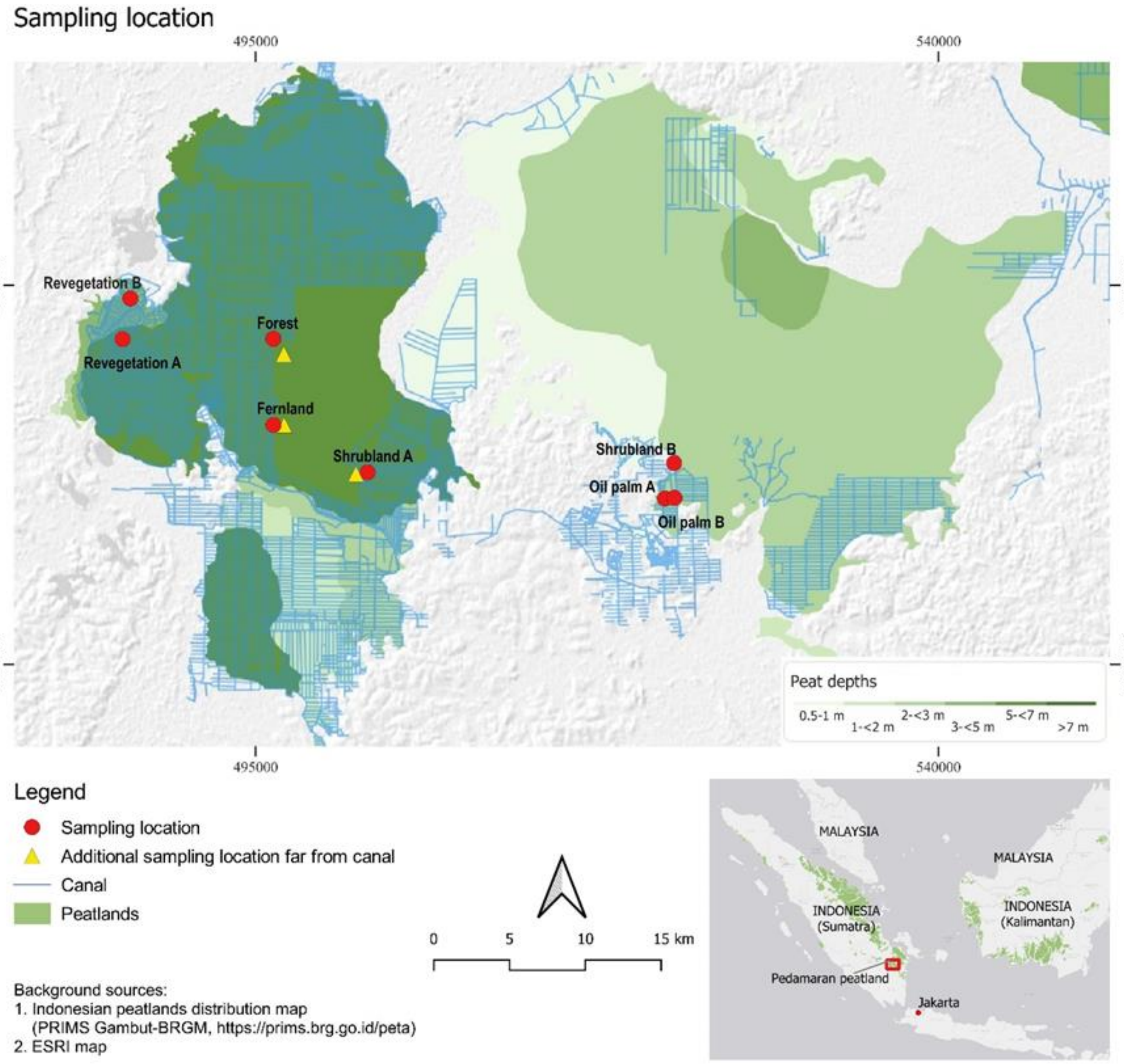
This study aimed to examine the C composition and degree of decomposition of tropical peat soils under different land uses and depth increments (0–100 cm depth) using $^{13}$C NMR spectroscopy. It provides new information about the changes in peat carbon chemistry and degree of decomposition resulting from changes of land use, which will be valuable to support improved success of peatland restoration, particularly planning of revegetation.

## METHODS

### Study location

This study was conducted at the Pedamaran peatland, a 191,000 ha tropical peatland area located on the eastern coastal plain of South Sumatra, Indonesia (Figure 1). As well as its importance for carbon storage and water retention, it hosts many indigenous flora and fauna species and is one of the few persisting peat swamp forest remnants in South Sumatra. This peatland also provides a range of livelihood options for local communities such as fishing and collecting *purun* (*Lepironia articulata*), a wild grass used as a raw material for woven handicrafts. The average annual rainfall between 2005 and 2022 was approximately 2,598 mm yr$^{-1}$. The average monthly rainfall during the dry (May–October) and wet (November–April) seasons is approximately 140 mm and 292 mm, respectively (Indonesian Meteorology and Geophysical Agency). The peat depth is > 9 m in the centre of the peat dome (Sumargana *et al.* 2019). Based on the fire hotspot data acquired from the NOOA and MODIS satellites (1997–2005) and the digital burnscar map (2006–2018) provided by South Sumatra Forest Service, recurrent fires including extensive fire events occurring in 1997, 2006 and 2015 have burnt > 60 % of the Pedamaran peatland.

Samples were collected between September 2019 and February 2020 from seven sites representing five different land uses, namely: forest, shrubland (two sites), fernland, revegetation (two sites) and oil palm (Figure 1). Site selection aimed to choose representative examples of the land uses, and was informed by: (i) land cover derived from satellite imagery; (ii) fire history derived from burnscar maps provided by South Sumatra Forest Service, and fire hotspot data from the NOAA and MODIS satellites; (iii) information on land use history provided by local stakeholders including the Head of the Forest Management Unit and local communities; and (iv) visual inspection by the first author, who had 15 years' local experience working in tropical peatlands. All of the sites were originally covered by forest, but logging, fires and establishment of oil palm plantations over the past century have been key drivers of land use change within this landscape. The forest site was located within an area of ~12,000 ha designated as a state forest. It had been affected hydrologically by being surrounded by privately-owned canals 6–8 m wide and 2–3 m deep that were constructed in the 2000s to drain excess water from adjacent oil palm plantations, and the most common tree species were *Combretocarpus rotundatus*, *Cratoxylon arborescens* and *Ploiarum alternifolium*. The two shrubland sites were characterised by medium-density *Melaleuca cajuputi*, which was naturally regenerating after fire. Shrubland A was near the centre of the peat dome and Shrubland B was located on peat of depth < 0.6 m at the edge of the dome. The fernland site was located within the state forest in an area that had been severely affected by recurrent fires, including the major fire events in 1997 and 2015; it was covered by fern and sedge



Background sources:
1. Indonesian peatlands distribution map (PRIMS Gambut-BRGM, https://prims.brg.go.id/peta)
2. ESRI map

Figure 1. Study area and soil sampling locations within the Pedamaran peatland area in South Sumatra.

dominated by *Stenochlaena palustris* and *Melastoma malabathricum*. The two pilot revegetation sites were initiated in 2010 (Revegetation A, 20 ha, last burned in 2006) and 2017 (Revegetation B, 4 ha, last burned in 2015) and are managed by the Indonesian Ministry of Environment and Forestry. Revegetation A was a ten-year-old revegetation site dominated by *Shorea balangeran*, *Dyera polyphylla* and *Gonystylus bancanus*. This site had been hydrologically affected by privately-owned drainage canals associated with oil palm plantations and the construction of a toll road near the site in 2019. The construction of canal blockings, initiated in 2017, had not significantly raised the water level in this area because of damage to the blocking due to flooding (Budiman *et al.* 2020) (see water table depth at the time of sampling in Table A1 in the Appendix). Revegetation B was a two-year-old revegetation site that had been affected by recurrent fires linked to slash-and-burn practices, including the fire event in 2015. This site incorporated a closed-loop canal for a fishery with embankments that were planted with native species, mainly *S. balangeran* (Budiman *et al.* 2020). The tree canopy cover was still low due to the early growth stage. The oil palm site was in a four-year-old community smallholder oil palm plantation. Intensive drainage canals including primary, secondary, tertiary and quaternary canals were established during land preparation before planting to drain excess water in the rainy season.

### Sample collection and preparation

A 1 m square, 1 m depth pit located ~100 m from the canal (near canal, NC) was excavated at each site. The distance of ~100 m from the canal was chosen to ensure that samples were not comprised of material excavated from the canal or compacted by machinery during canal establishment. Soil samples were collected from the undisturbed side walls of the pits at eight depths (0, 10, 20, 30, 40, 60, 80 and 100 cm) except at shrubland B, where the maximum peat depth was 60 cm. To observe the effect of distance from the canal, additional (far-from-canal, FC) samples were collected 700–1000 m from the same canal where conditions might be less aerobic, at Forest, Shrubland A and Fernland. Far-from-canal sampling was not possible at the revegetation and smallholder oil palm sites because the spacing of canals was < 700m.

Samples were stored in snap-lock plastic bags, returned to the laboratory and refrigerated at 4 °C within four days of collection. Samples were dried at 60 °C for 72 h and gamma irradiated to meet quarantine requirements. Finely ground homogeneous samples were prepared by grinding in a vibratory disc mill (Lab Technics LM1, Australia) for two minutes. A single litter sample was also collected from the surface of each soil sampling pit and stored and prepared following the same protocols.

### Carbon and nitrogen content

Total carbon (%) and total nitrogen (%) contents were determined by combustion with a LECO IR analyser in the Environmental Analysis Laboratory, Southern Cross University, Australia (accredited by the National Association of Testing Authorities, NATA). A certified reference material and a blank were analysed at the beginning of, and periodically (every 20 samples) throughout, each run. 44 samples were used for the calibration with RMS error of 0.096 and 0.028 for C and N, respectively. The C:N ratio was evaluated as the quotient (C (%) ÷ N (%)), written as ‘C/N’ in this article.

### Carbon composition: Solid state $^{13}$C NMR

All soil and litter samples were analysed by cross-polarisation / magic angle spinning (CP/MAS) solid-state carbon-13 nuclear magnetic resonance ($^{13}$C NMR) spectroscopy to determine the chemical composition of the organic carbon. Spectra were acquired using an Agilent DD2 500 MHz NMR Spectrometer equipped with a triple resonance MAS probe. Following procedures similar to those in previously published literature (Grover & Baldock 2010, Sangok *et al.* 2020), approximately 40 mg of dried and finely ground sample was tightly packed into a 4 mm $ZrO_2$ rotor with a Kel-F cap and spun at 10000±10 Hz under the following experimental conditions: spectral width 397.97 ppm, acquisition time 20 ms, 1000 data points, contact time 1 ms, recycle delay 1.5 s, 5000 scans. Spectra were referenced externally using the methine signal of adamantane ($\delta$c: 29.2 ppm). Raw data were processed using ACD Spectrus NMR Processor which included zero filling (2048 points), line broadening (150 Hz), phase correction and integration analysis. Baseline correction and spectra presentation were performed in R software version 4.2.1 (R Core Team 2021).

The NMR spectra were separated into regions and integrated based on carbon-containing functional groups as reported by Baldock *et al.* (2013). Defined regions used in this study are alkyl C (0–45 ppm), methoxyl and N-alkyl C (45–65 ppm), O-alkyl C (65–90 ppm), di-O-alkyl C (90–110 ppm), aryl and unsaturated C (110–145 ppm), O-aryl C (145–165 ppm), carbonyl and amide C (165–190 ppm) and ketone C (190–215 ppm). Aromatic C ortho to OH groups are often observed in the range 95–115 ppm as per Mao *et al.* (2017). For this work, these overlapping chemical shift ranges have been dissolved into di-O-alkyl and aromatic C regions. The relative carbon composition (%) of the samples was estimated from the area of each region compared to the total spectral area. The proportions of O-alkyl C and alkyl C were used to calculate the alkyl C:O-alkyl C ratio as an indicator of the degree of decomposition (Baldock *et al.* 1997, Cao *et al.* 2011, Asanopoulos 2020). The alkyl C : O-alkyl C ratio was evaluated as the quotient (alkyl C (%) ÷ O-alkyl C (%)), written as 'alkyl C / O-alkyl C' in this article.

### Statistical analysis

All statistical analyses were performed using R software version 4.2.1 (R Core Team 2021). Generalised Linear Models (GLM) were used to explore differences in carbon composition between land uses and depths. All variables were of normal distribution and homogeneity. To compare differences in carbon composition under different land uses, the organic carbon of soil from all pits under the same land use was allocated to one group. Only peat soil samples were used in the analysis, not litter samples. The effect of distance from the canal in Forest, Shrubland A and Fernland was investigated by comparing carbon composition between the two different distance categories (NC and FC) using one-way analysis of variance (ANOVA). Once the carbon functional groups that were affected by distance from the canal were identified, two-way ANOVA was used to test the differences in these carbon groups among identified land uses with increasing distance from the canal. The Tukey post hoc test was used following ANOVA and GLM for multiple comparisons, with statistical difference level set at 5 %. Linear regression and Principal Component Analysis (PCA) were used to examine the relationship between C/N and alkyl C / O-alkyl C. The 'ggplot2' package was used for data visualisation (Villanueva & Chen 2019).

## RESULTS

### Carbon and nitrogen content

The carbon (C) content of the peat soils ranged from 34.5 % to 59.8 % (Figure 2). Below the surface, the C content was mostly > 45.0 % and there was greater variation between the different land uses nearer the surface than at depth. In the upper part of the profile (0–30 cm), C content was generally higher in Fernland (FC) and Shrubland A (NC) and lowest in Forest (FC). Under all land uses, the nitrogen (N) content decreased from the surface to 40 cm depth, then remained relatively constant at approximately 0.83 % as depth increased. In the upper part of the profile, the higher N contents (> 1.4 %) were found in Forest (FC and NC) and the lowest N values (< 1.2 %) were recorded in Fernland (FC and NC) and Shrubland A. C/N increased from 23–52 at the surface to 47–82 at 40 cm depth and then remained relatively constant with depth below 40 cm for a given land use. The highest and lowest C/N values were measured in Fernland (NC) and Forest (FC), respectively.

### $^{13}$C NMR spectra and the proportions of carbon functional groups

The $^{13}$C NMR spectra of the peat soil from all land uses exhibited common major signals at 30, 32, 50, 56, 62, 73, 104, 115–117, 125, 127, 129, 147–148, 151 and 172–174 ppm (Table 1, Figure 3). In the forest land uses, the peak at 73 ppm was particularly intense in the upper layers (0–20 cm) and the deeper layers (80–100 cm). The peak at 73 ppm, which indicates carbohydrates, was also distinct in the spectra of all litter samples. Peaks at ~39 and ~82 ppm were present in the spectra from Forest (FC) but disappeared in the spectra for other land uses. In contrast, the peak at 56 ppm, which may be assigned to lignin, was distinct in Forest (NC) but weak in Forest (FC). The peaks at ~62, 104, 115–117, 125, 127, 129, 147–148, 151 and 172–174 ppm had low intensity in most of the spectra for all land uses (Figure 3). Peaks at 30–32 ppm may be assigned to aliphatic carbon, including long chain fatty acids, waxes and resins (Table 1), and were more intense in the shrubland and fernland than in the forest. In Shrubland A (FC), the peak at 73 ppm was more intense in the deeper layers, and larger overall, than in Shrubland A (NC) and Shrubland B. At the revegetation sites, the resonance at 30–32 ppm was most intense in the upper layers and decreased with depth, whereas the resonance at 73 ppm increased in intensity with depth. In the oil palm plantation, the peak signals at 30–32 ppm were the most intense.

The alkyl C functional group was dominant under all land uses except in the upper (0–20 cm) and lower (80 and 100 cm) layers at Forest (FC) and in the lower layers (60–100 cm) at Revegetation B (Figure 4). Under oil palm and shrubland, alkyl C was dominant in the upper (0–40 cm) layers and there was no clear trend in alkyl C with increasing depth, whereas O-alkyl C exhibited the opposite pattern. The contribution of O-alkyl C was higher in the upper and lower layers at Forest (FC) and in the lower layers at Revegetation B. Compared to alkyl C, the overall contribution of O-alkyl C was less dominant, varying from 11.7 % to 28.2 %. The combined contribution of alkyl C and O-alkyl C (the two main components of peat carbon) made up more than half

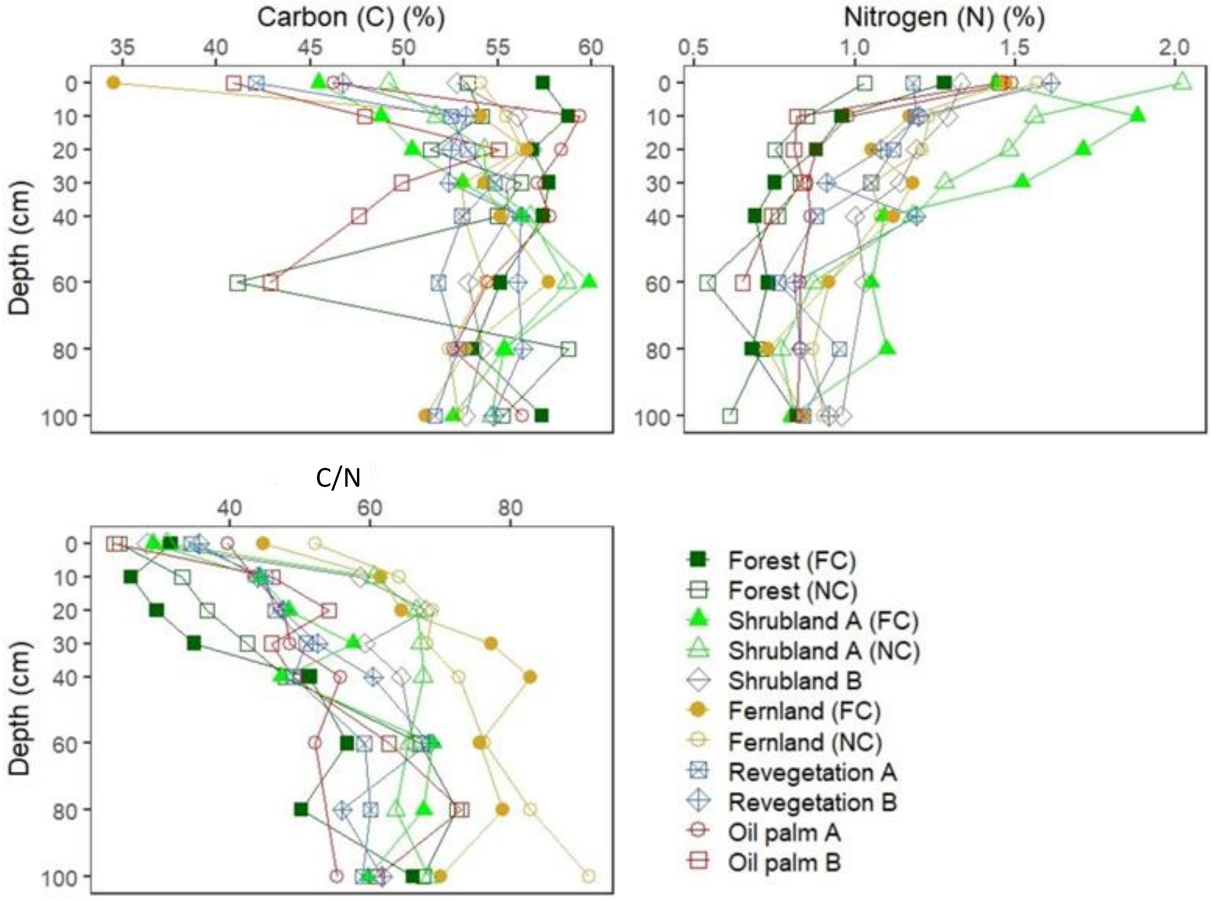


Figure 2. C and N concentrations and C/N of peat soil profiles from Pedamaran peatland, South Sumatra. N = 86. Different colours and point shapes indicate different land uses. Solid shapes show the sampling location far-from-canal (FC), open shapes show the sampling location near-to-canal (NC).

Table 1. Chemical shift assignment of major peaks in the $^{13}$C NMR spectra of litter and peat soil samples collected from the Pedamaran peatland, South Sumatra.

| Chemical shift (ppm) | Assignment | Reference |
|---|---|---|
| 30, 32 | Long-chain hydrocarbons | Skjemstad *et al.* (1983), Preston *et al.* (1987), Bates *et al.* (1991), Ono *et al.* (2015) |
| 39 | Highly branched aliphatic carbon | Quideau *et al.* (2001) |
| 50 | N-alkyl carbon | Quideau *et al.* (2001) |
| 56 | Methoxyl carbon of lignin | Bates *et al.* (1991), Segnini *et al.* (2013), Sangok *et al.* (2020), |
| 62 | Hydroxyl carbon | Skjemstad *et al.* (1983) |
| 73, 82 | Carbon in cellulose and hemicelluloses | Hammond *et al.* (1985), Preston *et al.* (1987), Quideau *et al.* (2001), Segnini *et al.* (2013) |
| 104 | Anomeric carbon in polysaccharides | Preston *et al.* (1987) (Ono *et al.* 2015) |
| 115–117 | Lignin, humic acids | Hammond *et al.* (1985), Preston *et al.* (1987) |
| 125 | Humic acids | Hammond *et al.* (1985) |
| 127, 129, 151 | Aromatic carbon | Skjemstad *et al.* (1983), Preston *et al.* (1987), Sangok *et al.* (2020) |
| 147–148 | Oxygen substituted aromatic carbon | Bates *et al.* (1991) |
| 172–174 | Carboxyl groups, oxidised cellulose | Skjemstad *et al.* (1983), Hammond *et al.* (1985), Bates *et al.* (1991), Segnini *et al.* (2013), Sangok *et al.* (2017), Sangok *et al.* (2020) |

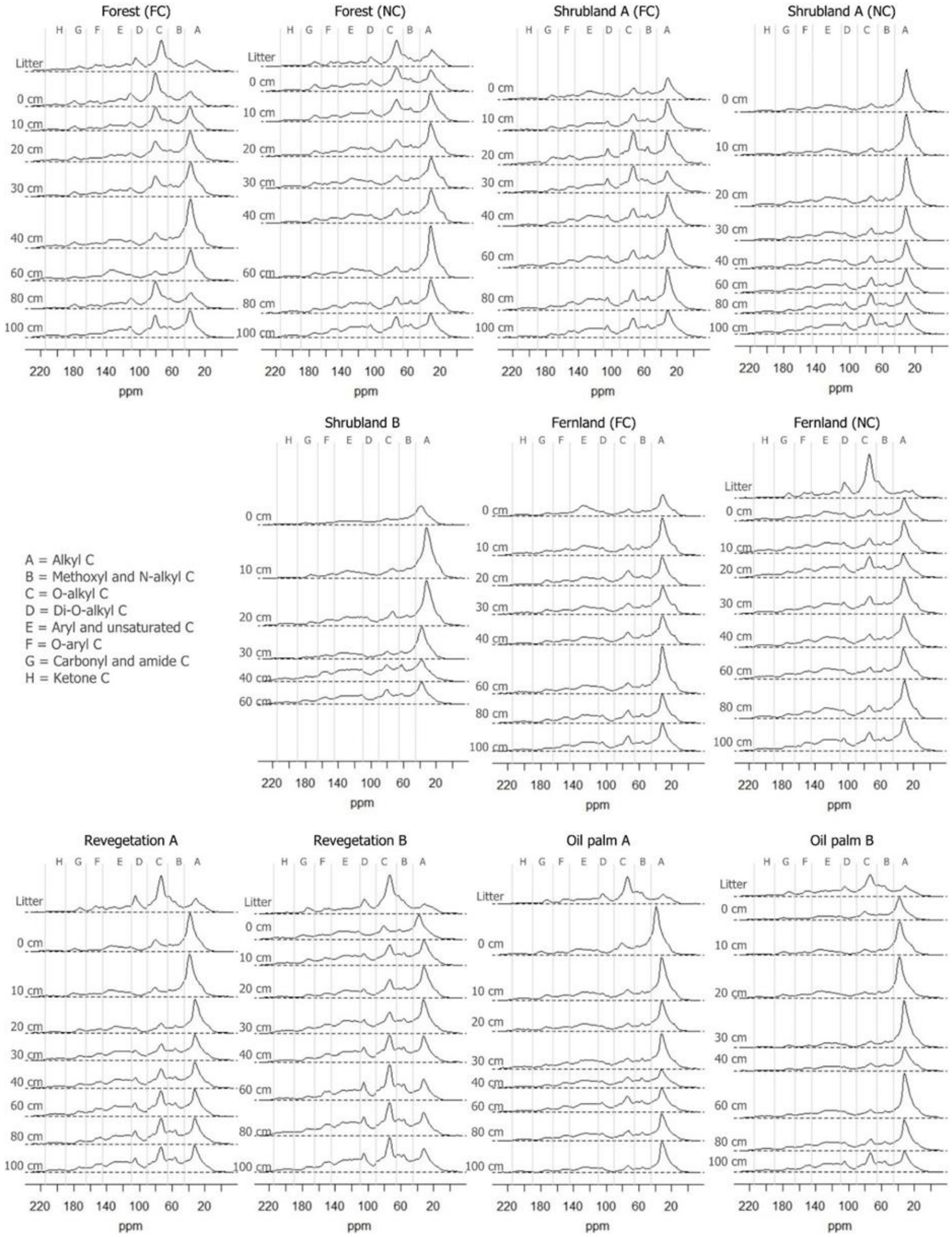


Figure 3. $^{13}$C NMR spectra of litter and peat soil samples collected from five different land uses and eight depths at the Pedamaran peatland, South Sumatra. Letters (A–H) indicate carbon functional group regions as shown in the legend.

(52.2 ± 5.8 %) of the NMR spectra for all land uses. On average, the contribution of aryl and unsaturated C to overall carbon composition under all land uses was 17.1 ± 2.2 % and tended to be constant across land uses and depths. The contributions of other functional groups, ranked in the order methoxyl and N-alkyl C > di-O-alkyl C > O-aryl C > carbonyl and amide C > ketone C, were low and proportionally similar throughout the NMR spectra for all land uses (Figure 4).

### Statistical analyses

*Carbon functional groups from all land uses*

The carbon functional groups that differed significantly ($P < 0.05$) between land uses and with depth below the peat surface were aryl and unsaturated C and O-aryl C (Figure A1 in the Appendix). The land uses that were most different from one another were Forest, with the lowest amount of aryl and unsaturated C (14.6–16.9 %) and Fernland, which had the highest amount of aryl and unsaturated C (16.6–19.7 %). Forest had the smallest amount of O-aryl C (4.9–5.9 %) at all depths, and significantly less than Fernland and Revegetation A at all depths. At 10 cm depth, Fernland had the highest amount of aryl and unsaturated C (17.0–22.7 %), and significantly more than other land uses. Compared to the other sites, O-aryl C was higher and significantly different in Fernland (6.2–7.3 %) and Revegetation B (4.5–8.3 %).

Carbon functional groups that differed significantly ($P < 0.05$) between land uses (but not with depth) were alkyl C, O-alkyl C, methoxyl and

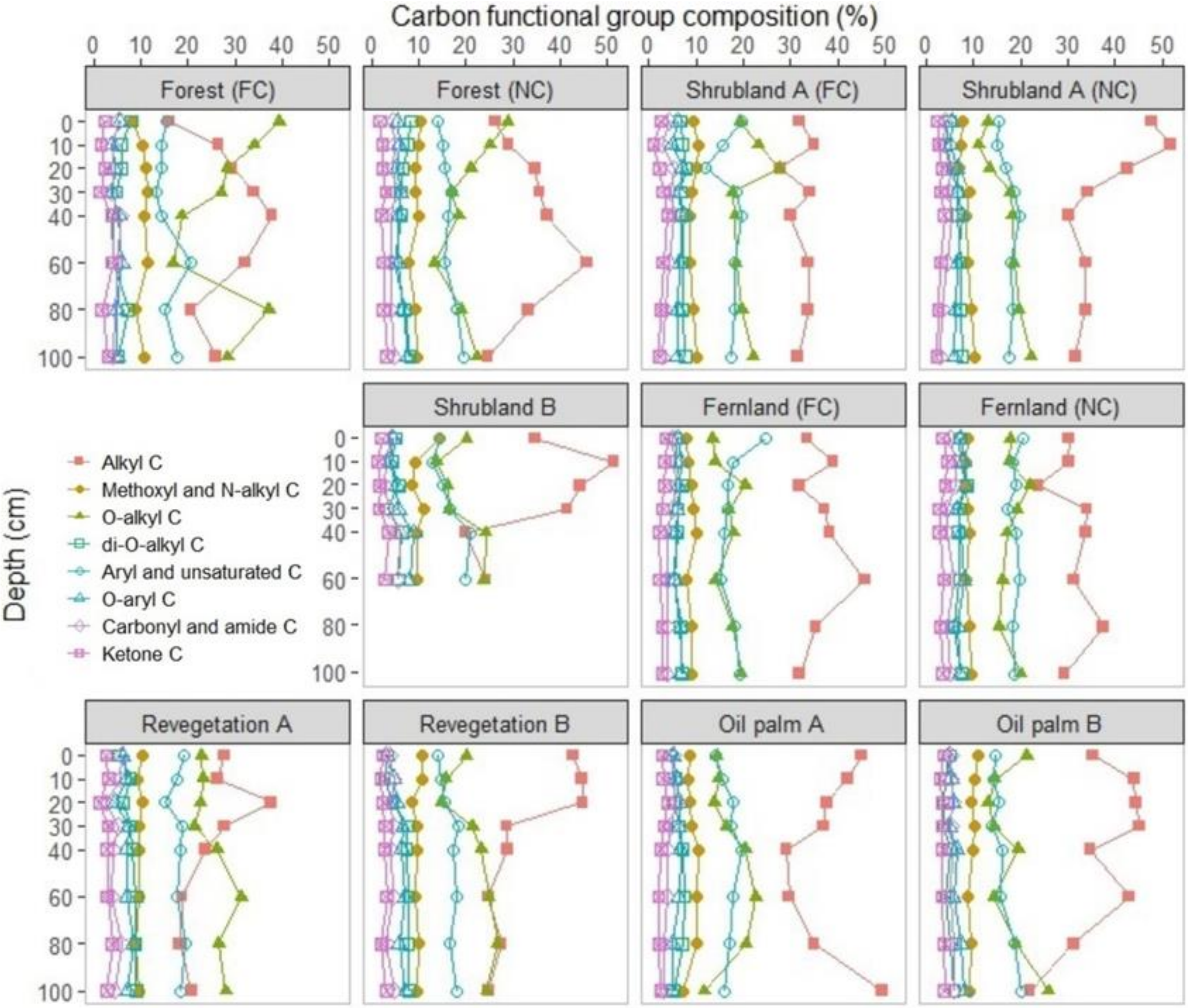


Figure 4. Distribution of organic carbon functional groups (%) in samples collected from five different land uses and eight depths at the Pedamaran peatland, South Sumatra, measured with $^{13}$C NMR spectroscopy. Different point colours and shapes indicate different carbon functional groups as shown in the legend.

N-alkyl C, di-O-alkyl C, and ketone C. The percentage of alkyl C was highest (37.6 %) under oil palm and lowest at Revegetation A (24.8 %) (Figure 5a). Forest had more O-alkyl C (29.1 %) than any other site except Revegetation A (25.8 %) (Figure 5b). Shrubland B had the highest amount of methoxyl and N-alkyl C (10.5 %), closely followed by Forest (Figure A2a). The lowest amount of methoxyl and N-alkyl C was measured at Fernland (8.7 %), while the contribution of methoxyl and N-alkyl C under other land uses ranged from 8.9 to 9.9 %. The most di-O-alkyl C (7.9 ± 0.45 %) was measured at Revegetation B, followed by Forest and Revegetation A. Significantly less di-O-alkyl C was present at the oil palm sites (5.7 ± 0.25 %) and Shrubland B (5.45 ± 0.40 %) (Figure A2b). Fernland had significantly more ketone C (3.5 %) than Forest (2.7 %), Shrubland B (2.4 %) and Revegetation A (2.7 %) (Figure A2c); however, there were only very small amounts of ketone C in all peats. Carbonyl amide C did not differ significantly between land uses or with depth (data not shown) and was also a minor component of the peat carbon.

### *Effects of distance from canal*

Comparison of carbon functional groups between the NC and FC samples from Forest, Shrubland A and Fernland shows that O-alkyl C, methoxyl and N-alkyl C, and O-aryl C differed significantly between NC and FC (Figure A3). O-alkyl C and methoxyl and N-alkyl C were significantly lower in NC (mean 18.5 % and 8.9 %, respectively) than in FC samples. Conversely, O-aryl C was significantly higher in NC (mean 6.6 %) than in FC samples. Other functional groups did not vary significantly with distance from canal (data not shown).

The largest differences between O-alkyl C and methoxyl and N-alkyl C occurred in Forest FC, which had significantly higher amounts of these carbon functional groups than Shrubland A FC and Fernland FC (Figure A4). O-alkyl C and methoxyl and N-alkyl C did not differ significantly between these three land uses in NC samples. O-aryl C was significantly higher in Fernland NC than in Fernland FC and Forest FC, and also differed significantly from O-aryl C in Forest NC and Shrubland A NC. The lowest contribution of O-aryl C was in the peat from Forest FC.

### Degree of decomposition

C/N showed significant differences across land uses and depths, being generally low in the top layer of soil and tending to increase in deeper layers under all land uses (Figure 6a). C/N was lowest in the forest, where it was significantly lower than in shrubland and fenland and slightly but not significantly lower than under the revegetation and oil palm land uses. C/N was highest under fernland.

The alkyl C : O-alkyl C ratio showed significant differences between land uses (Figure 6b). Peat under oil palm had the highest measured values of alkyl C / O-alkyl C while Revegetation B had the lowest. The values of alkyl C / O-alkyl C in Forest were significantly lower than under oil palm and higher

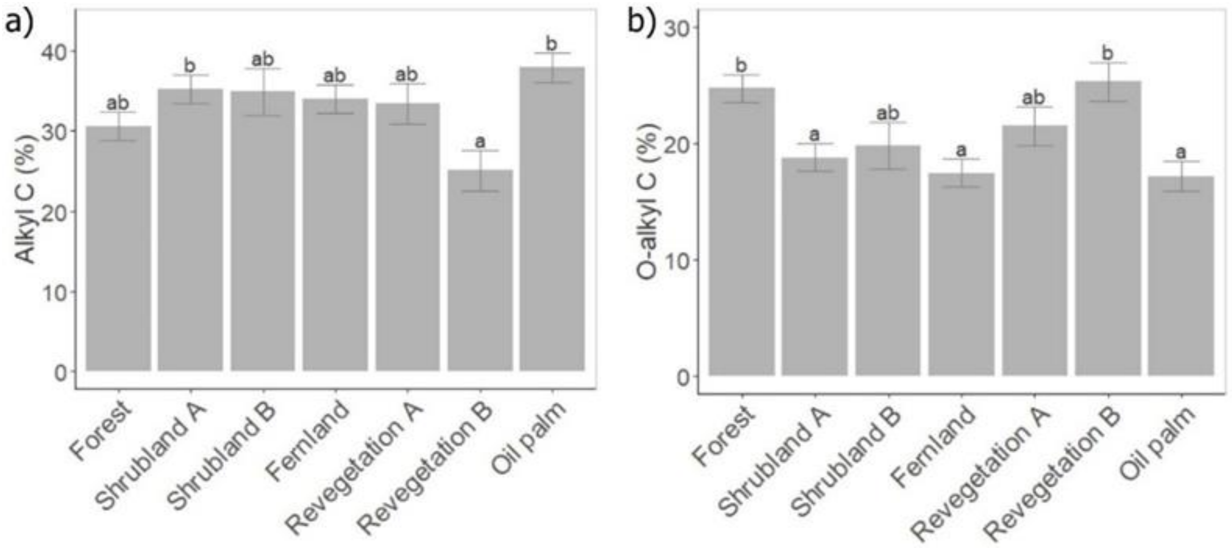


Figure 5. Means of composition of functional groups (%) of (a) alkyl C and (b) O-alkyl C across different land uses on the Pedamaran peatland, South Sumatra. Note the different scales on the y axes. Error bars represent standard errors and letters represent groupings from post-hoc pairwise comparisons, where distinct letters within a panel indicate statistically different means.

than in Revegetation B, but were not dissimilar from values for the other land uses.

There was no relationship between the C:N and alkyl C:O-alkyl C ratios. Linear regression of C/N against alkyl C / O-alkyl C yielded an $R^2$ of 0.0056 (Figure 7a), whilst C/N and alkyl C / O-alkyl C were orthogonal in a PCA biplot, indicating no relationship (Figure 7b).

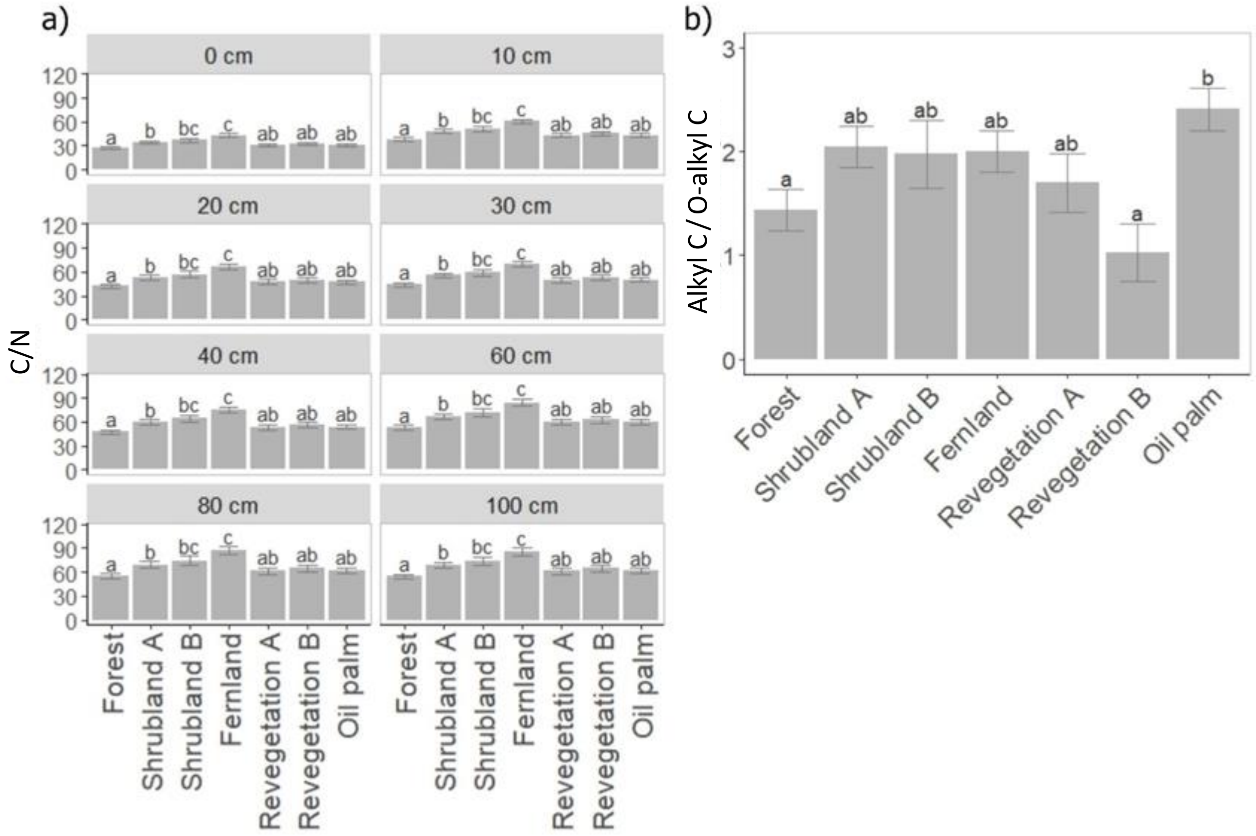


Figure 6. Means of (a) C/N and (b) alkyl C / O-alkyl C across different land uses in the Pedamaran peatland, South Sumatra. Note the different scales on the y axes. Error bars represent standard errors and letters represent groupings from post-hoc pairwise comparisons, where distinct letters within a panel indicate statistically different means.

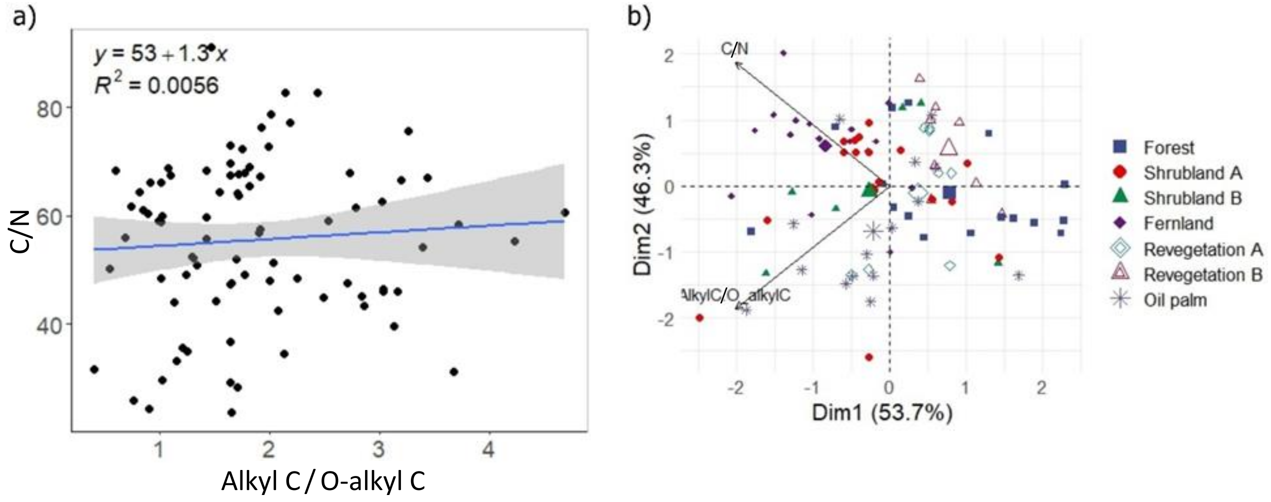


Figure 7. Analyses of the relationship between C/N and alkyl C / O-alkyl C in the Pedamaran peatland, using (a) linear regression and (b) PCA (points on the biplot are colour-coded according to land use; see legend).

## DISCUSSION

Characterising the carbon composition of tropical peatlands is important for improving our understanding of the stability of peat carbon and its susceptibility to loss under changing land use. By integration of the $^{13}C$ NMR spectra, we showed that the highest proportion of carbon in our study area was in the alkyl C region. However, peat soils under forest far from the canal contained a significant proportion of O-alkyl carbon, especially in the uppermost (0–20 cm) and deeper (80–100 cm) layers (Figure 4).

Our study demonstrated that drainage and land use change had a significant effect on the peat carbon chemistry of this tropical peatland. The established drainage canal system interrupts catchment hydrology, disturbing natural hydrological processes and the water balance in the peatland ecosystem (Wösten *et al.* 2008). Drainage accelerates the decomposition of peat due to lowering of the water table, enabling increased aerobic microbial activity (Couwenberg *et al.* 2009, Husnain *et al.* 2014, Itoh *et al.* 2017, Matysek *et al.* 2017). The effects on peat carbon chemistry were greatest on land used for oil palm, where O-alkyl carbon was depleted rapidly under aerobic conditions leading to a change in the dominant carbon functional group from O-alkyl C to alkyl C. Our results show increased alkyl C with increasing management intensity of the peatland, with highly decomposed peat located in the intensively managed peatland. The high contribution of alkyl C under oil palm was especially evident in the upper soil layers (0–30 cm), which are situated above the water table for most of the year. At this depth in this land use, microbial decomposition is expected to be more prevalent due to aerobic conditions (Segnini *et al.* 2013, Tonks *et al.* 2017, Anshari *et al.* 2022).

### Peat carbon chemistry under each land use

*Forest*

Our data demonstrated variability of C content from 0 to 40 cm depth, where the C content gradually increased with depth (Figure 2). However, a clear trend of variation in C content with depth has not been reported from previous studies on tropical peatlands. In earlier studies of peat swamp forests in Kalimantan (Indonesia), Anda *et al.* (2009), Könönen *et al.* (2015) and Könönen *et al.* (2018) reported an increase in C content with increasing depth. On the other hand, C content decreasing with depth was reported by Lupascu *et al.* (2020) and Funakawa *et al.* (1996). In the present study, C peaked at 60 cm depth, which is likely to be due to the occurrence of burnt material in the peat samples. The mean N content in the forest was higher than under other land uses. There was a clear trend of change in N content in relation to depth, with N content highest at the surface and decreasing with depth. Decrease of N content with depth has been reported from several other studies of tropical peatlands (Hadi *et al.* 2001, Anda *et al.* 2009, Arai *et al.* 2014, Könönen *et al.* 2015, Nurulita *et al.* 2015, Ishikura *et al.* 2016, Hergoualc'h *et al.* 2017, Itoh *et al.* 2017). The ombrotrophic peat swamp forest of the study area is a rainwater-fed ecosystem gaining nutrient inputs from rainwater. Most of the nutrient pool is internally cycled between dead and live biomass, with litter deposition and organic matter turnover occurring mainly in the surface layer (Lampela *et al.* 2014, Könönen *et al.* 2015), resulting in high concentrations of nutrients near the surface.

O-alkyl C was the most abundant soil organic carbon functional group under forest. O-alkyl C is present in many biomolecules - commonly in carbohydrates - and is prevalent in less-decomposed organic materials (Preston *et al.* 1989). Conversely, the concentration of alkyl C was low in the forest owing to waxy lipids and lignin compounds from woody vegetation. The contribution of the aryl and unsaturated C region (110–145 ppm) was about 16 % of total carbon and differed significantly between land uses and depths (Figure A1). The clear difference of aryl and unsaturated C at 10 cm depth may be due to the contribution of substituted and non-substituted aromatic carbon at ~128 ppm in the less decomposed samples (Hammond *et al.* 1985).

Our results indicate that the effect of peatland degradation on carbon composition depends on distance from the canal for O-alkyl C, methoxyl and N-alkyl C and O-aryl C (one-way ANOVA, $P < 0.05$) (Figure A3). The percentage of O-alkyl C in forest far from the canal was significantly higher than that in forest near the canal (Figure A4). This provides evidence of high concentrations of carbohydrate compounds in less decomposed organic materials, which can accumulate due to the lower hydrological impact on peat and predominantly slow anaerobic microbial activity far from canals. The contribution of di-O-aryl C (145–190 ppm) was significantly higher in forest near the canal compared with forest far from the canal. This could be due to contributions from oxygenated aromatic carbons such as those in phenols and aryl ethers (Hammond *et al.* 1985), which are generally found in well decomposed peat.

### *Shrubland and fernland*

The shrubland and fernland sites have regenerated naturally after recurrent severe fires. Fires and changes in the surface biomass structure may affect peat soil chemistry under these land uses. The C content varied particularly within the top 40 cm, with no clear trend of C content relative to depth. Compared to the forest land use, the mean C content in Shrubland A and Fernland were slightly higher. On average, the lowest C content was at Shrubland B (47.4 %), probably due to the removal of organic material by recurrent fires and the influence of mineral soil where peat depth was only 60 cm. This was in accordance with the finding of Hikmatullah *et al.* (2014) that C content decreased as sampling approached the boundary with underlying mineral soil. N content was high at the surface and our data demonstrated that it decreased gradually with depth. The mean N content in fernland was 0.8 %, which was lower than in shrubland (1.01 %). The mean N content in shrubland and fernland was lower than in forest. The mean N content under fernland in the present study was somewhat similar to that reported for the same type of land use on peatland in Central Kalimantan by Könönen *et al.* (2015), but lower than that found in the same landscape by Armanto (2019). The volatilisation of N during combustion and leaching of N due to rainfall are factors that may result in low N content under these land uses. Fires, peat compaction and changing vegetation types may affect the soil's chemical properties. Reduced fresh litter input, that comes almost entirely from the *M. cajuputi* only, may have contributed to the lower soil N content under shrubland. On fernland, the vast exposures of vegetation-free peat are likely to cause high temperatures in the soil and thus accelerate the leaching process, leading to decreased N content.

The contribution of alkyl C in shrubland peaked at 10 cm depth, indicating advanced decomposition in this layer (Figure 4). The resonance at 30–32 ppm was stronger than that in the spectra of peat from the forest (Figure 3), indicating a shift of functional group dominance from O-alkyl C in forest to alkyl C in shrubland and fernland. The presence of carbohydrate was clear from the prominent resonances at 73 ppm in surface peat from Shrubland A and in deeper peat from Shrubland B (Figure 3). A sharper resonance (at ~56 ppm) from methoxyl carbon indicates the presence of lignin (Bates *et al.* 1991, Segnini *et al.* 2013).

A comparison of distance from canal in shrubland and fernland suggested that there was no significant difference in the O-alkyl C region (two-way ANOVA, $P < 0.05$) (Figure A4a). In the past, smouldering fires completely removed the tree cover and may have led to enhanced peat decomposition in both NC and FC sites. There was also no significant difference in methoxyl and N-alkyl C between NC and FC sites on shrubland and fernland. Conversely, O-aryl C at NC fernland was significantly higher than at FC fernland, probably due to the high content of lignin in less decomposed fernland peat.

### *Revegetation*

The mean C content at Revegetation A (54.0 %) and Revegetation B (51.5 %) was less than reported by Nurulita *et al.* (2016) for a 3.5 year old revegetation site in Riau Province with relatively similar species. The low C content may arise from ground cover management/weeding during establishment of the plantation. In deeper layers of peat, the C content was relatively higher, possibly due to the presence of burnt materials. The mean C and N contents in the revegetation sites were lower than in the forest. The N content was high at the surface and gradually decreased with depth. The high N content in the surface layer may be derived from fertiliser applications, particularly during the first two years of the planting stage of this land use. In general for this land use, the nutrient cycle may change directly via leaching due to drainage and fire and indirectly via change of vegetation structure from peat forest to low-density plantation species.

The contribution of alkyl C (25 %) at Revegetation B was significantly lower than under other land uses (Figure 5). Conversely, the percentage of O-alkyl C was high, as shown by the prominent resonance at 73 ppm attributed to carbohydrate (Hammond *et al.* 1985) (Figure 3). The abundant presence of O-alkyl C in the deeper layers (40–100 cm) at Revegetation B provides evidence of the persistent contribution of less decomposed material to the tropical peat matrix at this site.

### *Oil palm plantation*

There was no clear trend in C content at the oil palm plantation sites in relation to depth. The C content was lowest at the surface in Oil palm B (34.6 %). The mean C content was 53.3 %, which was slightly lower than under forest (54.1 %). Compared to previous studies, the mean C content was higher than in an oil palm plantation of similar age that was studied by Nurulita *et al.* (2015) and Anshari *et al.* (2010). The high C content was mostly found in the lower layers (30–60 cm), probably due to the presence of burnt materials. The low C content of the surface layer may be related to several factors: (i) the recurrent fires before the plantation was established may have reduced organic material in the surface layer; (ii) intensive management including regular chemical weeding could have killed the ferns and sedges resulting in reduced vegetation litter inputs; and (iii) intensive drainage to lower the water table exposes the peat to aerobic conditions causing loss of carbon. The N content gradually decreased with depth from the surface to 40 cm depth, then remained relatively constant below 40 cm. The high N content at the surface is probably due to fertiliser application, as oil palm plantation requires high fertiliser inputs to increase productivity. In this study the mean N content (1.09 %) was lower compared than under forest. N losses for the oil palm land use are potentially high through leaching due to intensive drainage. Previous studies suggest that N losses from drained peatlands are significantly higher compared to undrained peatlands (Frank *et al.* 2014, Wang *et al.* 2016). It has also been indicated that high precipitation and time since drainage influence nitrogen releases from drained peatlands (Wang *et al.* 2016, Nieminen *et al.* 2017).

The smallholder oil palm had the highest alkyl C content (38 %) compared to other land uses, indicating advanced decomposition. The spectra for oil palm contain a dominant resonance at 30–32 ppm, which indicates very high aliphatic carbon content (Skjemstad *et al.* 1983, Preston *et al.* 1987). Preston *et al.* (1987) examined the influence of cultivation and depth on the chemical structure of peat and obtained a similar result. They suggested that alkyl C content increased while O-alkyl C tended to decrease as the duration of cultivation increased.

### Alkyl C / O-alkyl C is more informative than C/N as an indicator of degree of peat decomposition

Our results suggest that the alkyl C : O-alkyl C ratio may be a more informative indicator of the degree of decomposition than the C:N ratio. Our statistical analyses showed no relationship between C/N and alkyl C/O-alkyl C (Figure 7). Our C/N results showed a positive trend with depth, where C/N was lowest in the topmost layer and increased with depth (Figure 6a). However, in the context of land use, C/N did not show a consistent trend in relation to degree of decomposition in that the forest soil, which generally consists of less decomposed peat, had lower C/N than the other land use categories (Figure 6a). Previous studies that have measured C/N in tropical peats under different land uses have yielded inconsistent results, with five studies demonstrating that managed peatlands have higher C/N than unmanaged peatlands (Hergoualc'h & Verchot 2011, Könönen *et al.* 2015, Nurulita *et al.* 2015, Dhandapani *et al.* 2019, Kurnianto *et al.* 2019) and four demonstrating the opposite (Hadi *et al.* 2001, Melling *et al.* 2005, Anshari *et al.* 2010, Cooper *et al.* 2020) (Table 2). The unreliabiality of C/N as an indicator of degree of decomposition for peat soils is in accordance with the conclusions of Ostrowska & Porębska (2015), who suggest that it is difficult to assess the usefulness of C/N as an indicator of mineralisation of soil organic matter in mineral soils because mineralisation is affected by multiple factors including climate change, land management, the application of fertilisers, and N deposition. Therefore, even if C/N decreases significantly or remains the same, this does not prove unequivocally that decomposition of organic matter is progressing (Ostrowska & Porębska 2015).

Values of alkyl C / O-alkyl C in the forest were low, indicating less decomposed materials than under the more intensively managed land uses. Degree of decomposition was highest in the oil palm plantation, where alkyl C / O-alkyl C was significantly higher than under the other land uses. Intensive management of the oil palm plantation including land preparation, weed control, fertiliser application and establishment of intensive drainage canals evidently accelerates peat decomposition. Considering depth in the peat layer, alkyl C / O-alkyl C values tended to be higher near the surface (at 0–30 cm depth) in the managed peatlands than in the forest, but not statistically different (data not shown) from the values for lower layers. The 0–30 cm peat is above the water table for most of the year, enabling more rapid microbial decomposition due to oxygen availability.

### Implications for peatland restoration and future research

The dominance of alkyl C in most of our soil samples suggests that the peat soil in the study area is highly decomposed. The construction of drainage canals to lower water tables in the Pedamaran peatland accelerates peat decomposition. When the water table is drawn down, the surface layers of peat are exposed to air, enhancing peat oxidation and leading to peat subsidence, carbon emissions and increased risk of fire (Hooijer *et al.* 2012, Holden *et al.* 2014). Couwenberg *et al.* (2009) and Hooijer *et al.* (2010) estimated that $CO_2$ emissions increase by about 0.9 Mg $ha^{-1}$ $year^{-1}$ for every centimetre increase of drainage depth in tropical peatlands. Thus, decomposition of peat soils makes a huge contribution to Indonesia's $CO_2$ emissions. Hergoualc'h and Verchot (2011) estimated that the carbon emissions from peat decomposition were about 50 % of the total 2216 Mg $CO_2$ eq $ha^{-1}$ of carbon released over 25 years of conversion of tropical peat swamp forest to oil palm plantation; 26 % of this was from biomass changes and the rest resulted from fire.

Table 2. Trends in C/N in more and less intensively managed peatlands from previous studies of tropical peat soils. The minimum (Min) and maximum (Max) values were calculated from the means and standard deviations of the original data.

| Reference | Land use | Sampling depth (cm) | Mean | Min | Max | Trends in C/N |
|---|---|---|---|---|---|---|
| Dhandapani *et al.* (2019) | Forest | 0–5 | 19.8 | 18.2 | 21.4 | managed peat > unmanaged peat |
| | Cleared peatland | 0–5 | 30.0 | 25.0 | 35.0 | |
| | 1-year-old oil palm with yam intercrop | 0–5 | 31.0 | 28.2 | 33.8 | |
| | 1–2-year-old oil palm with pineapple | 0–5 | 26.5 | 22.7 | 30.3 | |
| | 3–5-year-old oil palm monocrop | 0–5 | 32.0 | 28.7 | 35.3 | |
| | 15-year-oil palm | 0–5 | 26.0 | 24.0 | 28.0 | |
| Hergoualc'h *et al.* (2017) | Forest | 6–15 | 31.5 | 26.9 | 36.1 | managed peat > unmanaged peat |
| | 1-year-old oil palm plantation | 6–15 | 39.9 | 34.7 | 45.1 | |
| | 6-year-old oil palm plantation | 6–15 | 57.1 | 37.9 | 76.3 | |
| Könönen *et al.* (2015) | Undrained forest | 10–85 | 47.6 | 44.2 | 5.03 | managed peat > unmanaged peat |
| | Drained forest | 10–115 | 63.0 | 54.4 | 71.6 | |
| | Degraded open peatland | 10–115 | 75.9 | 69.3 | 82.5 | |
| | Agricultural open peatland | 10–115 | 74.9 | 57.8 | 92.0 | |
| Kurnianto *et al.* (2019) | Burned forest | 50–550 | 62.9 | n/a | n/a | managed peat > unmanaged peat |
| | undrained logged-over forests | 50–550 | 62.5 | n/a | n/a | |
| | Seral | 50–550 | 75.2 | n/a | n/a | |
| | 5-year-old oil palm | 50–550 | 77.6 | n/a | n/a | |
| Nurulita *et al.* (2015) | Forest | 0–15 | 24.2 | n/a | n/a | managed peat > unmanaged peat |
| | 5–6-year-old oil palm | 0–15 | 41.5 | n/a | n/a | |
| | Restoration area | 0–15 | 41.3 | n/a | n/a | |
| Anshari *et al.* (2010) | Coastal peat forest | 0–200 | 41.9 | 7.16 | 76.6 | managed peat < unmanaged peat |
| | Inland peat forest | 0–200 | 73.1 | 23.5 | 122.6 | |
| | Logged over forest | 0–200 | 56.5 | 21.2 | 91.8 | |
| | Early industrial timber | 0–200 | 42.4 | 21.2 | 63.6 | |
| | Early oil palm (< 5 yr.) | 0–200 | 17.2 | 10.4 | 24.0 | |
| | Intermediate oil palm (5–10 yr.) | 0–200 | 32.9 | 0.00 | 79.0 | |
| | Mature oil palm (15–20 yr.) | 0–200 | 15.4 | 11.8 | 19.0 | |
| | Community agriculture | 0–200 | 17.5 | 13.1 | 21.9 | |
| Cooper *et al.* (2019) | Forest | 0–5 and 50–55 | 34.5 | 29.1 | 39.9 | managed peat < unmanaged peat |
| | Drained forest | 0–5 and 50–55 | 28.2 | 25.8 | 30.6 | |
| | 6 months-old oil palm | 0–5 and 50–55 | 37.9 | 29.9 | 45.9 | |
| | 10–15-year-old oil palm | 0–5 and 50–55 | 29.1 | 22.1 | 36.1 | |
| Hadi *et al.* (2001) | Secondary forest | n/a | 20.7 | n/a | n/a | managed peat < unmanaged peat |
| | Paddy field | n/a | 10.7 | n/a | n/a | |
| | Paddy-soybean rotation | n/a | 24.0 | n/a | n/a | |
| Melling *et al.* (2005) | Forest | 0–25 | 27.2 | 25.3 | 29.2 | managed peat < unmanaged peat |
| | Sago | 0–25 | 22.6 | 21.1 | 24.2 | |
| | Oil palm | 0–25 | 23.4 | 21.2 | 25.7 | |

To reduce further decomposition, fire risk and $CO_2$ emissions, rewetting by blocking the drainage canals is key to the restoration of degraded tropical peatlands. Rewetting, which includes constructing canal blockings, has been identified as the most important measure for the successful restoration of degraded tropical peatlands (Dohong *et al.* 2017, Graham *et al.* 2017). In 2018 and 2020, 51 dams were constructed in the canals surrounding the forest area of the Pedamaran peatland (http://prims.brg.go.id). Previous studies reported that the water table level increased immediately after dams were installed in the peatlands of Kalimantan (Suryadiputra *et al.* 2005, Ritzema *et al.* 2014). However, the effect of dams at our study area has not been investigated. Moreover, there is no information about the maintenance of dams is available, and this is likely to need more attention.

Shrubland and fernland have been subjected to high frequency fires and the natural vegetation has been replaced by a less structured plant community dominated by *M. cajuputi*, ferns and sedges. Under these conditions, natural regeneration back to forest may be prevented by one or more regeneration barriers such as limited seed dispersal, low soil nutrient availability or seasonal flooding (Page *et al.* 2009, Graham *et al.* 2017). To support forest re-establishment, Graham *et al.* (2017) proposed a stepwise procedure for addressing regeneration barriers including:

(i) understanding the environmental conditions, identifying the critical regeneration barriers and, hence, determining targeted restoration activities (e.g. canal blocking and revegetation);

(ii) selection of priority areas based on knowledge of site disturbance history to assist identification of revegetation techniques that may be applied (natural regeneration, assisted natural regeneration or direct revegetation); and

(iii) selection of species based on their ecological tolerance of the site-specific regeneration barriers.

This approach may be adapted to support large-scale restoration programmes of the study area.

The previous attempt at revegetation in our study area showed promising results in terms of survival rate ten years and two years after planting. However, this effort may not have contributed to increasing peat accumulation and soil carbon stocks. A ten-year period of revegetation is unlikely to be sufficient to produce both the above-ground and below-ground biomass and the associated carbohydrates that would contribute to peat accumulation. The dominance of alkyl C in the upper (0–40 cm) soil layers of the ten-year revegetation site indicates that re-establishing peat accumulation is challenging once the peat soil has become degraded, as the accumulation of new organic material is very slow. Long-term monitoring is needed to evaluate the potential of revegetation to re-establish peat accumulation. Similar to revegetation efforts that have been carried out in other degraded peatlands of Indonesia, this revegetation involved small-scale (20 ha and 2 ha) planting with a small number of native species (mainly *S. balangeran* and *D. polyphylla*). Lessons from small-scale revegetation efforts may then be incorporated into the larger-scale restoration action plan with many different native species. Giesen (2013) provides information on the 534 native peat swamp species that can support restoration. However, the germination rates of these species tend to be very low. Further investigation of species selection is needed to promote the success of large-scale restoration efforts.

On peatland that is being used for production purposes such as oil palm plantation, maintaining the water table at the highest level that the oil palms can tolerate will help to reduce peat subsidence and $CO_2$ emissions. The prescribed water level of 40–60 cm below ground surface has been recommended to fulfil crop and field requirements, support productivity, and reduce fire and carbon emissions (Haasjes 2014, Ginting & Darlan 2019); however, significant $CO_2$ emissions of about 60 tonnes $ha^{-1}$ $year^{-1}$ can still be expected from oil palm plantations on peat soils that are drained to this degree (Page *et al.* 2011, Hooijer *et al.* 2012). Proper water management is also critical to minimise the effects of drainage from the plantation area into the adjacent peatland (off-site impacts) (Parish *et al.* 2019). To support the success of peatland restoration, the involvement of smallholder farmers is required, especially in maintaining canal-blocking structures.

In conclusion, these new results indicate that alkyl C / O-alkyl C is more informative as an indicator of the degree of decomposition of peat soil than C/N. While prior studies on northern and southern hemisphere peat soils have found a consistent relationship between decreasing O-alkyl carbon and increasing alkyl carbon with increasing degree of decomposition (Baldock *et al.* 1997, Grover & Baldock 2010, Rodriguez *et al.* 2021), this is the first study of tropical peat soils to assess the degree of decomposition on the basis of alkyl C / O-alkyl C. Due to the high variability of tropical peat soils, further spectroscopy studies are recommended to validate this approach across the full range of vegetation, climate, fire history and land use conditions. The structure and degree of decomposition of tropical peat may vary among land uses and with depth due to long-term accumulation of peat and external factors such as fire that can burn beneath the surface, hence increasing the decomposition of peat in deeper layers. Moreover, organic matter inputs to tropical peat soils are mostly derived from woody vegetation which is different from the better-understood moss-based peat soils of the Northern and Southern Hemispheres. In order to successfully restore tropical peatlands, eliminate hazardous fires and re-establish carbon sequestration, spectroscopy can be a useful tool that yields rapid insights into soil conditions.

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## AUTHOR CONTRIBUTIONS

AK and SG conceptualised the study. Collection and preparation of samples was performed by AK and DR together with many other people including SG. $^{13}$C NMR spectra were collected by AK and KH. KH contributed to method development in NMR spectral acquisition and integration. RF contributed to developing the R script in presenting spectra. AK did statistical analyses, created all Figures, and wrote the first draft of the manuscript with input from all authors. SG and EWB provided supervisory advice and critical comments during the research, and improved the manuscript. All authors contributed to interpreting the results, discussion, and associated improvements of the article. Funding acquisition SG.

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## Appendix

Table A1. Descriptions of the sampling sites.

| | **Forest** | **Shrubland A** | **Shrubland B** | **Fernland** | **Revegetation A** | **Revegetation B** | **Oil palm** |
|---|---|---|---|---|---|---|---|
| |  |  |  |  |  |  |  |
| GPS location | 3° 26' 01" S<br>104° 58' 18" E | 3° 30' 21" S<br>103° 00' 53" E | 3° 29' 56" S<br>105° 12' 12" E | 3° 29' 10" S<br>104° 57' 55" E | 3° 25' 24" S<br>104° 52' 41" E | 3° 24' 02" S<br>104° 52' 50" E | 3° 31' 12" S<br>105° 11' 52" E |
| Date of sampling | 03 Sep 2019 | 11 Dec 2019 | 06 Feb 2020 | 05 Sep 2019 | 02 Feb 2020 | 03 Feb 2020 | 05 Feb 2020 |
| Land use history# | Logging, drainage, fire in 1997 | Logging, drainage, fires in 1997, 2015 | Logging, drainage, fires in 1997, 2006, 2015 | Logging, drainage, fires in 1997, 2006, 2015 | Logging, drainage, fires in 1997, 2006 | Logging, drainage, fires in 1997, 2006, 2015 | Clear cut, drainage, fires in 1997, 2006, 2015 |
| Primary vegetation | *Combretocarpus rotundatus*, *Cratoxylon arborescens*, *Ploiarum alternifolium* | *Melaleuca cajuputi* | *Melaleuca cajuputi* | *Stenochlaena palustris*, *Melastoma* spp | *Shorea balangeran*, *Dyera polyphylla*, *Gonystylus bancanus* | *Shorea balangeran*, *Stenochlaena palustris* | *Elaeis guineensis* |
| Water table depth at sampling (cm): | | | | | | | |
| Pit near the canal | 112* | 117* | 38** | 110* | 60** | 15** | 70 and 80** |
| Pit far from canal | 93* | 110* | | 50* | | | |

# Sources: fire history derived from 1997–2005 fire hotspot data acquired from NOAA and MODIS satellites; digital burnscar maps 2006–2018 provided by South Sumatra Forest Service.
* Dry season; **Rainy season

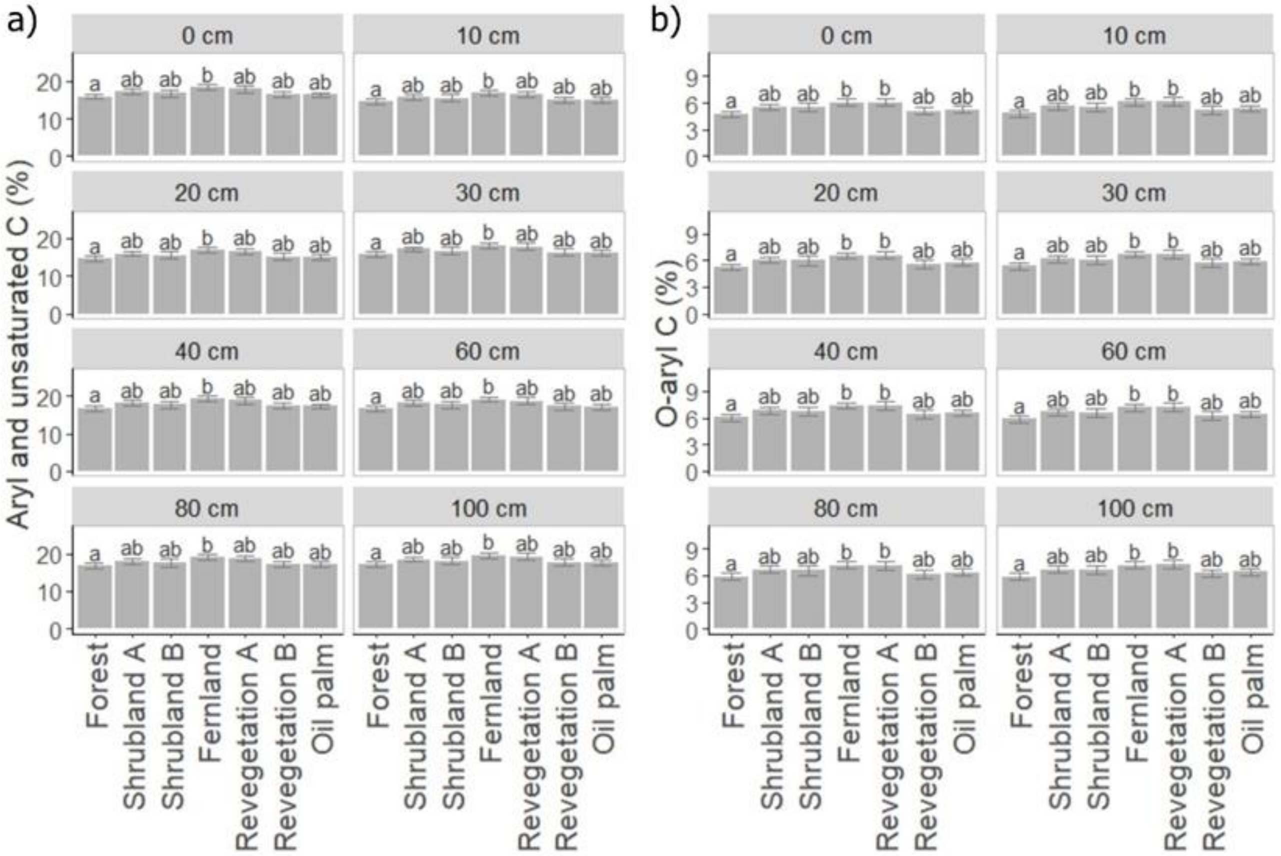

Figure A1. Means of composition of functional groups (%) of (a) aryl and unsaturated C and (b) O-aryl C in samples collected from eight depths under five different land uses at the Pedamaran peatland, South Sumatra, measured with $^{13}$C NMR spectroscopy. Note the different scales on the y axes. Error bars represent standard errors and letters represent groupings from post-hoc pairwise comparisons, where distinct letters within a panel indicate statistically different means.

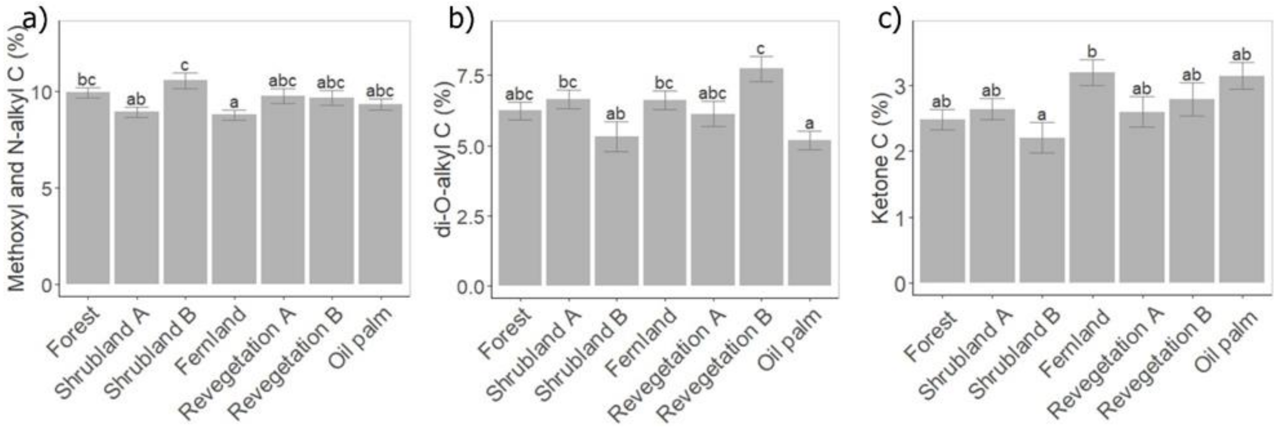

Figure A2. Means of composition of functional groups (%) of (a) methoxyl and N-alkyl C, (b) di-Oalkyl C, and (c) ketone C across different land uses at the Pedamaran peatland, South Sumatra. Note the different scales on the y axes. Error bars represent standard errors and letters represent groupings from post-hoc pairwise comparisons, where distinct letters within a panel indicate statistically different means.

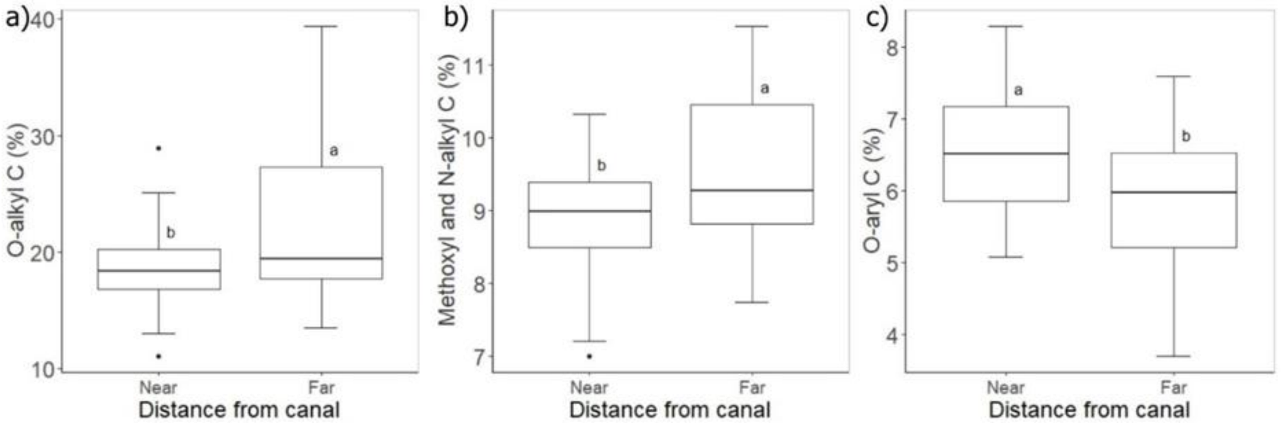

Figure A3. Means of composition of functional groups (%) of (a) O-alkyl C, (b) methoxyl and N-alkyl C, and (c) O-aryl C at two different distances from the canal (near ~100 m and far ~700–1000 m) under forest, shrubland A and fernland land uses at the Pedamaran peatland, South Sumatra. Note the different scales on the y axes. Error bars represent standard errors and letters represent groupings from post-hoc pairwise comparisons, where distinct letters within a panel indicate statistically different means.

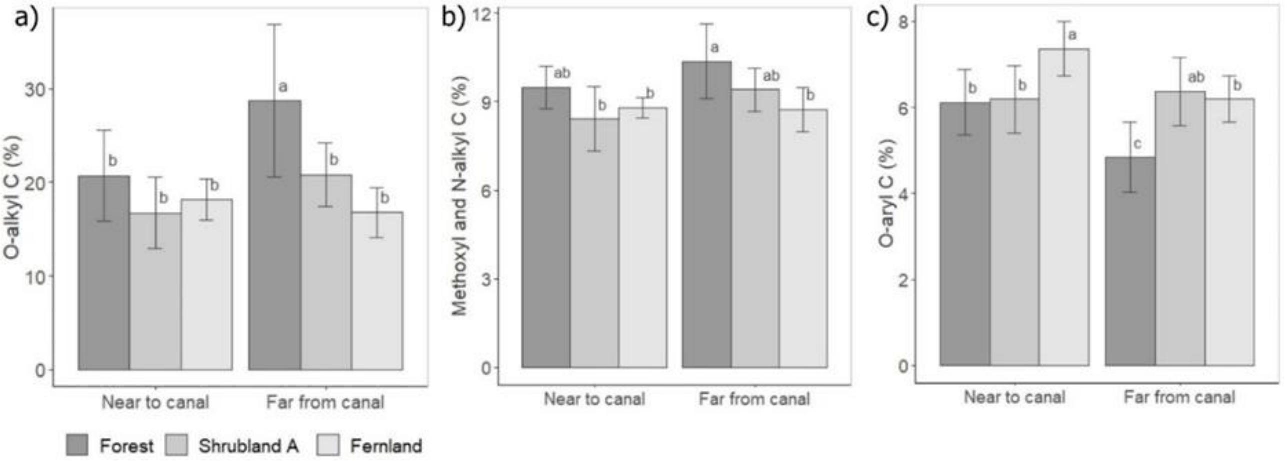

Figure A4. Means of composition of functional groups (%) of (a) O-alkyl C, (b) methoxyl and N-alkyl C, and (c) O-aryl C from Forest, Shrubland A and Fernland, near to the canal and far from the canal, in the Pedamaran peatland, South Sumatra. Note the different scales on the y axes. Error bars represent standard errors and letters represent groupings from post-hoc pairwise comparisons, where distinct letters within a panel indicate statistically different means.