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RESEARCH ARTICLE

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Assessment of variability of peat physicochemical properties, subsidence and their interactions within Selangor forests

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Abstract

Tropical peat swamp forests are carbon-rich ecosystems both above- and below-ground, which play a major role in the climate balance of the earth. The majority of the world's tropical peat forest cover is located in Southeast Asia and is increasingly threatened by anthropogenic disturbances. Despite their importance for biodiversity conservation and climatic balance of the earth, pristine peatlands are almost extinct in many parts of Southeast Asia. Peninsular Malaysia is one such region, where there are no undisturbed peatlands left in the west coast. We studied the largest peat forest area in the west coast of Malaysia, located in the state of Selangor. We evaluated variability of peat subsidence (for 1 year), peat physicochemical properties and macronutrient contents between forest regions and between different depths (not for subsidence) covering the top 50 cm, and the complex interactions between them. We found that there was significant peat subsidence in all the studied regions, however, there was no significant difference in subsidence between different forest regions. Physicochemical properties such as peat moisture, pH and carbon (C) content and all macronutrient contents except phosphorus (P), either varied between regions, or showed significant interactions between region and depth in Selangor peat forests. All the measured peat physicochemical properties varied with depth. Among macronutrients, only nitrogen (N), P and calcium (Ca) showed significant change with depth, while there were no changes with depth for sulphur (S), potassium (K) and magnesium (Mg) contents. These changes in each peat physicochemical property and macronutrient contents correlated with changes in other peat physicochemical properties and nutrient contents; however, there is a need for controlled experiments to further understand these significant interactions. The findings show continued carbon loss in secondary peat swamp forests through subsidence, indicating the long-term impact of selective logging and associated historical drainage. The significant variability of peat physicochemical properties and macronutrient contents with region and depth, also show the need for intensive sampling to characterise large secondary peat swamp forests.

KEYWORDS

peat drainage, peat macronutrients, peat subsidence, peat swamp forests, selective logging, tropical peatlands

1 | INTRODUCTION

Tropical peatlands are globally important ecosystems with unique biodiversity and high carbon storage, both above- and belowground in their natural state (Dargie et al., 2017; Page et al., 2011; Yule, 2010). These ecosystems are formed because of waterlogged conditions that inhibit microbial decomposition on the ground, and high carbon input through high primary production from tropical evergreen trees (Page et al., 2011). However, these conditions are fragile and are maintained by a delicate balance of different environmental factors, such as topography, climate, microbial ecology, hydrology, plant physiology and biogeochemistry (Page et al., 2011). Thus, any disturbance that affects this balance and the anaerobic conditions exposes millennia-old peat, that played (and continues to play) a crucial role in the climate balance of the Earth, to aerobic decomposition, which results in greenhouse gas emissions from the peat as well as peat subsidence (Couwenberg et al., 2010; Dhandapani, Ritz, Evers, & Sjögersten, 2019; Evans et al., 2019). This is particularly pertinent in Southeast Asia where the largest area of tropical peatlands in the world reside which is estimated to store 69 Gt of carbon (Page et al., 2011). Southeast Asian peatlands are also rich in floral and faunal biodiversity, and most notable iconic species such as Malayan tigers and orangutans inhabit these ecosystems (Adila et al., 2017; Dhandapani, 2015; Yule, 2010). Despite their importance for biodiversity conservation and the climatic balance of the Earth, pristine peatlands are almost extinct in many parts of Southeast Asia (Miettinen et al., 2016). Peninsular Malaysia is one such region, where there are no undisturbed peatlands left on the west coast, with only small pockets of undisturbed peatlands existing on the east coast (Azhar et al., 2011; Dhandapani, Ritz, Evers, Yule, et al., 2019). These Malaysian peat ecosystems are under-studied and therefore poorly understood (Yule, 2010), particularly in their current states. One of the major disturbances historically faced by the peat swamp forest was logging, both managed and illegal (Dohong et al., 2017). In recent decades the land-use changes are further aided by agricultural expansion and anthropogenic fires (Miettinen et al., 2016; Wijedasa et al., 2018). The majority of the peat forest cover in Southeast Asia is logged at a certain point of their existence (Miettinen & Liew, 2010). Logging in tropical peatlands usually involves drainage, construction of paths and timber transport canals. These disturbances associated with logging are known to negatively impact both the carbon storage and biodiversity (Costantini et al., 2016; Dhandapani, 2015). Drainage in particular is a major disturbance to peatland ecosystems, as it affects the necessary anoxic conditions for peat formation and accumulation. The legacy of drainage and logging disturbance is known to continuously affect peat properties (Too et al., 2018), and ecosystem functioning, decades after such disturbances originally occur (Dhandapani, Ritz, Evers, Yule, et al., 2019).

Highlights

- Peat physicochemical properties and macronutrient contents showed variability between regions and with depth.
- Peat physicochemical properties showed strong correlations with peat macronutrient contents.
- All forest regions showed significant subsidence with no significant regional differences.
- The findings raise concern for the sustainability of disturbed tropical peatlands.

Most tropical peat swamp forests are rainfed (i.e., ombrotrophic), and nutrient input to this ecosystem is dependent on leaf litter, rainfall and marine aerosols (Ong et al., 2017). This kind of external isolation in ombrotrophic peatlands creates concentric systems, where vegetation succession, nutrient movement, peat formation and accumulation occurs from the centre of the peat domes, creating distinct vegetation communities at different distances from the centre of the peat dome (Belyea & Baird, 2006; Phillips et al., 1997; Sjögersten et al., 2011; Winston, 1994). This leads to the formation of acidic and nutrient-poor peat in these systems. As peat is formed from semi-decomposed plant materials such as roots and leaves, the nutrient concentrations and other properties of peat are heavily influenced by aboveground peat-forming species (Page et al., 1999; Shimada et al., 2001). Thus, the variation in aboveground species distribution greatly impacts spatial variations of peat properties and nutrient concentrations in tropical peatlands (Too et al., 2018). This spatial variation is further prompted by logging disturbance, where drainage enables nutrient leaching (Dhandapani et al., 2021), and the removal of big mature trees which reduces leaf litter input. Cations are especially prone to leaching in acidic environments because of ample H+ ions available to replace them (Guicharnaud & Paton, 2006; Haynes & Swift, 1986; Leys et al., 2016). Such loss of cations is also reported in highly acidic tropical peatlands (Dhandapani & Evers, 2020; Dhandapani et al., 2021). This kind of nutrient profile change with high level of leaching in peat can have long-lasting impacts as they influence aboveground tropical forest tree species distribution (John et al., 2007), and the aboveground vegetation in turn, further affecting the nutrient dynamics of the peat.

Peat physicochemical properties are known to change with depth in tropical peatlands of different land uses (Dhandapani, Ritz, et al., 2020; Tonks et al., 2017). The varying degree of drainage in different areas of a historically drained forest would also result in varying degree of aeration of surface and subsurface peat layers, which have a big impact on carbon quality and other physicochemical properties of peat (Philben et al., 2014; Tonks et al., 2017). Furthermore, the removal of large trees during selective logging would result in the change of peat composition in the top layers of peat that were deposited after selective logging. Microbial community composition is another property that has significant interactions with peat physicochemical properties (Dhandapani, Ritz, et al., 2020; Dhandapani, Ritz, Evers, Yule, et al., 2019). Dhandapani, Ritz, et al. (2020) found consistent and coherent changes in microbial phenotypic community structure with depth going down to 2 m in North Selangor Peatlands, and they were significantly correlated with changes in peat physicochemical properties. Bacterial community analysis by Jackson et al. (2009) also found significant changes in community structure with depth in the top 50 cm peat layers of North Selangor peat swamp forests. These studies indicate the differences in peat properties with depth, which needs detailed analyses.

The physicochemical properties such as pH, electrical conductivity and redox potential (Eh) greatly influence biogeochemical reactions that form the complex interactions between soil and its environment and have great influence on life above- and belowground that depends on soil (Hinsinger et al., 2003; Husson, 2013). These physicochemical properties are also interdependent, and highly variable (Li, 2007). Some macronutrients in soils are available only in certain Eh-pH ranges, and some important microbial groups also only exist in certain Eh-pH combinations (Husson, 2013), further indicating the importance of measuring these properties for all biogeochemical field studies. Redox potential in particular can be used to indicate anaerobic conditions of peat or other such wetland soils (DeLaune & Reddy, 2005; Husson, 2013). These properties together regulate ionic forms of important macronutrients in soil, and their availability to aboveground flora, influencing the aboveground species growth, distribution and diversity (Baribault et al., 2012; Husson, 2013; John et al., 2007).

Peat subsidence is one of the important measures of peat degradation and carbon loss (Couwenberg et al., 2010; Hergoualc'h & Verchot, 2011). Anaerobic condition is a fundamental prerequisite for peat formation in tropical peatlands that have ideal temperature for high microbial activity and carbon decomposition. Peat subsidence is inevitable with drainage, which exposes peat to aerobic decomposition by lowering the water table (Couwenberg et al., 2010). This subsidence through drainage is aided by oxidation of top peat layers, shrinkage, contraction, compaction and consolidation of drained peat (Couwenberg et al., 2010; Hooijer et al., 2012). In addition, it is known that some forest species lack the chemical complexity for peat formation (Yule & Gomez, 2009). Thus, removal of large forest trees during selective logging may additionally contribute to peat subsidence, with lack of peat forming leaf materials and general reduction in leaf litter addition. There is a lack of understanding of the subsidence rates and their controls in tropical peat forests.

It is important to understand the spatial variation in peat physicochemical properties, nutrient contents, peat subsidence and their interactions in a large Southeast Asian peatland, that resembles other such under-studied peat swamp forests in the region. In this study, we report the variability of peat subsidence and physicochemical properties in Selangor peat swamp forests. We hypothesise that:

1. Peat physicochemical properties and nutrient contents vary significantly between different regions of the Selangor peat forests.
2. Peat physicochemical properties and nutrient contents vary significantly with depth.
3. The changes in each peat physicochemical property are correlated with other peat physicochemical properties and peat macronutrient contents.
4. Peat subsidence rate varies significantly between different regions of Selangor peat forests because of the variation in peat physicochemical properties and nutrient contents.

2 | MATERIALS AND METHODS

2.1 | Study sites

Peatlands in Selangor are comprised of two distinct peatland areas: North Selangor peatland and South Selangor peatland. The North and South Selangor peatlands are remnants of a natural peat forest that once occupied most of the coastal area before land-use changes (Azhar et al., 2011). In total, 30 sites were measured for this study—25 sites in North Selangor peat swamp forests and five sites in the South Selangor peat swamp forest. Site-specific information and locations are given in the Supplementary information (Table S1, Appendix A) and in Figure 1.

The North Selangor peatland is the second largest peat dome in Peninsular Malaysia and covers an area in excess of 76,000 ha. A large proportion has maintained a land cover of secondary peat swamp forest that was historically drained and logged (Charters et al., 2019), which is divided into four forest reserves that are protected and managed by different district authorities. These protected forest reserves are surrounded by industrial oil palm plantations and villages that are dependent on smallholder agriculture. The North Selangor peatlands are rich in biodiversity with 126 floral species and 262 faunal species (Adila et al., 2017). The forest vegetation includes *Macaranga pruinosa* (Miq.) Müll. Arg, *Campnosperma coriaceum* (Jack) Hallier f., *Blumeodendron tokbrai* (Blume) Kurz, *Shorea platycarpa* F.Heim, *Parartocarpus venenosus* Becc., *Ixora grandiflora* Ker Gawl, *Pternandra galeata* Ridl., *Stenoclaena palustris* (Burm. f.) Bedd., *Asplenium longissimum* Baker, *Nephrolepsis biserrata* (Sw.) Schott, *Crytostachys* sp., *Cyperus rotundus* L. and *Pandanus atrocarpus* Griff. (Yule & Gomez, 2009). Aboveground biomass in the North Selangor peat swamp forests ranges between 127 and 443 Mg ha^{-1} with an average of 320 Mg ha^{-1} (Brown et al., 2018). The peatland is drained by the Bernam River in the north and the Tengi River that runs from east to west through the middle of the peatland. In addition, there are several artificial canals present within the forest; these were constructed for timber extraction and irrigation of neighbouring paddy fields (Irvine et al., 2013). The average peat depth is 3.6 m, with the highest recorded depth at 10 m in some regions of North Selangor Peat Swamp forest (Global Environmental Centre, 2014). To assess the spatial variability, we used targeted sampling of different geographical regions of Selangor peat swamp forests and sampled as many replicate sites for each geographical region as logistically feasible. The sampling locations within each region were also limited by the logistical feasibility, and accessibility of field sites within each region. The sites in North Selangor are divided into four groups: (1) Sungai Karang (seven sites); (2) Sungai Tengi West (four sites); (3) Sungai Tengi (seven sites); and (4) Raja Musa (seven sites). All sites under Sungai Karang Forest are located in Sungai Karang Forest reserve, covering the northern part of the North Selangor peat swamp forests, and this

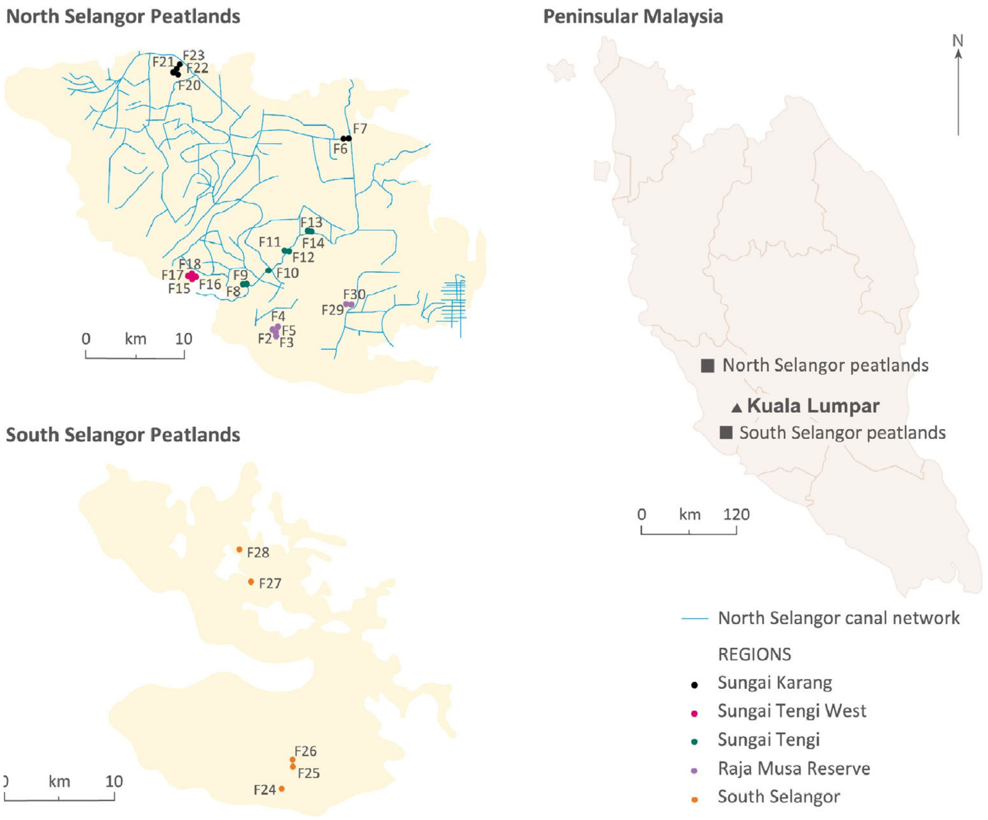

FIGURE 1 Site location.

reserve is administered by Klang district forestry department. All sites under Sungai Tengi West are located closer to River Tengi on the western edge of the forest within Raja Musa reserve. All sites under River Tengi are located in the central part of the peatlands, near to River Tengi, which runs through the middle of the peatlands dividing it into two halves. All sites under Raja Musa are located in the Raja Musa forest reserve, closer to the southern edge of the peatlands (Figure 1).

The South Selangor peatlands are relatively small in size but are even more diverse than the North Selangor peatlands in terms of land uses, including a large urban area and the Kuala Lumpur International Airport lying to the south. The South Selangor peat swamp forest is relatively less well characterised compared to the North Selangor peat swamp forest. However, it is reasonable to assume that these peat forests have a similar species composition and diversity, considering their proximity and comparable geographical location, topography and climatic conditions. However, it should be noted that the South Selangor peat swamp forests are smaller and more fragmented than North Selangor peat swamp forests, which may have impacted species diversity. Some of the larger tree species include *Koompassia malaccensis, Shorea teysmanniana*, *Tetramerista glabra* and *Gonystylus bancanus* (Global Environmental Centre, 2014). The South Selangor peat swamp forest is drained by the Langat River (Waldron et al., 2019) and supplemented by drainage canals. We selected five sites in South Selangor for this study. The sites were selected to have sampling locations spread across the south Selangor forest to represent the whole forest area, and limited by logistical feasibility and accessibility. The average peat thickness is estimated to be 3.3 m (Global Environmental Centre, 2014). Weather data, to indicate the wet and dry season of 2018 from the nearest towns to North and South Selangor sites, are given in Table 1.

2.2 | Peat analyses

Peat cores down to a depth of 50 cm were collected from each site for analyses. The cores were then separated to 10 cm layers for analyses. The procedures used for peat analyses were based on Dhandapani, Ritz, Evers, Yule, et al. (2019). Peat temperature was measured in situ, using a digital thermometer Cosmark PDT300 (Norwich, UK). Peat samples were collected for measuring gravimetric moisture. For this, fresh peat was dried in an oven at 105°C for 48 h. The gravimetric moisture was calculated based on mass of water lost in oven drying.

Bulk density was calculated by dividing the dry weight of 50 cm peat core from a Russian corer in grams by the volume of the Russian corer in cm^3.

For pH, redox and electric conductivity measurements, 5 mL volume of peat sample was diluted in 10 mL deionised water and shaken for 2 h. The pH of the supernatant was then measured using a Eutech pH 700 pH metre supplied by Thermo Scientific (Loughborough, UK). The redox potential and electrical conductivity were measured using Eutech Ion 2100 (Thermo Scientific, Loughborough, UK) and Groline HI98331 probes (Hanna, Leighton Buzzard, UK), respectively.

For analysing total carbon (C) and nitrogen (N) content, all samples were oven dried (105°C for 48 h) and finely ground using a Fritsch mortar grinder pulverisette 2 (Brackley, UK). The samples were then analysed in a Skalar primacs series SNC100 TC TN analyser (Breda, The Netherlands) for total C and N content.

2.3 | Nutrient analyses

The peat nutrient contents were analysed using inductively coupled plasma mass spectroscopy (ICP-MS). For this, approximately 0.15 g of oven-dried (105°C for 48 h)

TABLE 1 Indicative weather data for wet and dry season during the field sampling year.

Weather	Dry season (August 2018)		Wet season (December 2018)	
Region	N. Selangor	S. Selangor	N. Selangor	S. Selangor
Rainfall mm	37.67	64.97	412.3	360.8
Rainfall days	18	20	28	27
Average temperature °C	28	29	29	30
Sun hours	301.5	299.5	230	202
UV scale	7	7	7	7
Average humidity %	68	68	80	79
Average cloud cover %	19	22	52	53

Note: Data obtained from Worlds Weather Online (2020) for Kuala Selangor, Malaysia (closer to North Selangor Peatland sites) and Banting (closer to South Selangor peatland sites).

and ground peat were weighed in microwave digestion tubes (MARSXpress vessels, CEM Microwave Technology Ltd., Buckingham, UK), and 10 mL of nitric acid is added to each sample. The digestion tubes were then placed in a MARSXpress microwave (CEM Microwave Technology Ltd., Buckingham, UK) and run at 1600 W and 100% power with a ramp for 20 min and held for 20 min at 170°C. The digested samples were then filtered, diluted using milliQ water and were then analysed using 'Agilent Technologies' (Milton Keynes, UK) 7900 ICP-MS fitted with a 'SPS 4' autosampler.

2.4 | Peat subsidence

To measure subsidence, poles (three per site) were inserted through the peat and anchored into the underlying clay substrate. Pole height (in cm) from the peat surface was measured quarterly for all 30 sites for a 1-year study period. The subsidence was calculated by calculating the difference in pole height between the first measurement and each quarterly measurement period. PVC pipes of 15 mm diameter were used as poles for this purpose. The pipes which were 6 m in length were cut to 1-m pieces (poles) and connecting sockets were then used to connect 1-m poles during insertion. The poles are then inserted into the peat reaching the clay and then beneath the clay, until the pole reaches a point where it is fixed and cannot be physically pushed or hammered further. The depth of such insertion ranged from 4 to 8 m, with most locations having poles inserted at least to 5 m depth. Extra care was taken to ensure that the poles were inserted perpendicular to the ground at a right angle. The poles were inserted roughly 15 m away from each other in random spatial angles. A metal washer ring was put around the tube after the insertion process was complete, so that the length of the pole aboveground could be measured from the flat ring on the peat surface to the top of the pole. For the measurement to be more precise and consistent, the side on the top of the pole where the first measurement was made was marked with paint, so that the same side can be used for subsequent measurement of the pole length. Areas of hummock-hollow surface topography, further eroded by rainwater flow, were carefully avoided to reduce the influence of such erosion in our subsidence measurements.

2.5 | Statistical analyses

All statistical analyses were carried out using Genstat® 19th edition (VSN international, Hemel Hempstead). To determine the degree of spatial dependence (or spatial autocorrelations) of the peat physicochemical properties and subsidence across sampling points, experimental semi-variograms were calculated. The experimental semi-variograms showed significant spatial autocorrelations for all the measured peat physicochemical properties and peat subsidence (Appendix B). Hence, linear mixed models with individual sites as random effects were used to address our hypotheses. Different peat properties were modelled as dependent variables using linear mixed models with the interaction between region and depth as categorical fixed effects, and individual sites as the random effect.

Peat subsidence was modelled as dependent variable using linear mixed model with interactions between region and measurement period as categorical fixed effects, and individual poles nested in sites as random effects.

For all linear mixed models, normal distribution of residuals was assessed by examining four different residual plots, namely histogram of residuals, fitted values plot, normal plot and half normal plot. For data that did not meet normality assumptions, a log transformation of the dependent variable was performed, and residual plots of the log transformed model were further checked for normality. Such log transformations were performed for moisture, potassium (K) and phosphorus (P) to meet the normality assumptions for the linear mixed models. As normality assumptions were met for all models, either with original data or with log transformed dependent variables, Gaussian error distribution was deemed adequate. Model reduction was achieved by removing non-significant fixed effects until only significant effects remained. Where interactions were significant, non-significant main effects were left in the model. For all models, p-value <0.05 was deemed significant.

Principal component analysis (PCA) was performed for the dataset containing all the measured peat physicochemical properties and nutrient concentrations, to identify the main axes of variance within peat properties, existing patterns between measured properties and to visualise the difference between regions. The relationships between different peat properties were identified using a correlation matrix.

3 | RESULTS

3.1 | Peat physicochemical properties

Mean peat moisture level ranged from 268% to 811%. Log transformed peat gravimetric moisture increased with depth in all the regions except Sungai Tengi West, showing significant interaction between the different regions and depth (Figure 2a; Table S2, Appendix A). Surface moisture was the highest in the Sungai Tengi West region but was overtaken by all the other regions with increasing depth, while the moisture level showed decrease in 20–30 cm depth in Sungai Tengi West and stayed the same level in deeper layers.

Similar to moisture, pH (mean range 3.09–3.39) also significantly increased with depth for all regions except Sungai Tengi West, and hence showed significant interaction between region and depth (Figure 2b; Table S2, Appendix A). The Sungai Tengi West region showed higher pH than other regions in the top two peat layers. However, in deeper layers pH increased in all regions to similar level to that of the Sungai Tengi West region.

Peat electrical conductivity (mean range 214–428 μS cm^{-1}) was not significantly different between the peat forest regions (Table S2, Appendix A). Electrical conductivity showed a similar trend of significant decrease with depth for all the regions (Figure 2c), with no significant interaction between region and depth. The surface layer of Sungai Tengi West had lower electrical conductivity than all the other regions (which had an identical level); however, with increasing depth, electrical conductivity in all the other regions decreased to the level of the Sungai Tengi West. Peat redox potential (mean range 239–300 mV) did not significantly differ among different peat forest regions, but showed a significant increase with depth, with no interaction between region and depth (Figure 2d; Table S2, Appendix A).

3.2 | Peat carbon and nutrient content

Total C content (mean range 48%–59%) differed significantly between the Selangor peat forest regions, and also significantly increased with depth in all regions, with no interaction between region and depth (Figure 3a,b; Table S3, Appendix A). Mean total N content for different regions ranged between 1% and 2%. Sungai Tengi West showed slight increase in N content at 10–20 cm layer, while all the other regions showed consistent decrease in N content with depth, resulting in significant interactions between region and depth (Figure 3c; Table S3, Appendix A). The ratio between carbon and nitrogen content (C:N) also showed significant interactions between regions and depths (Figure 3d; Table S3, Appendix A).

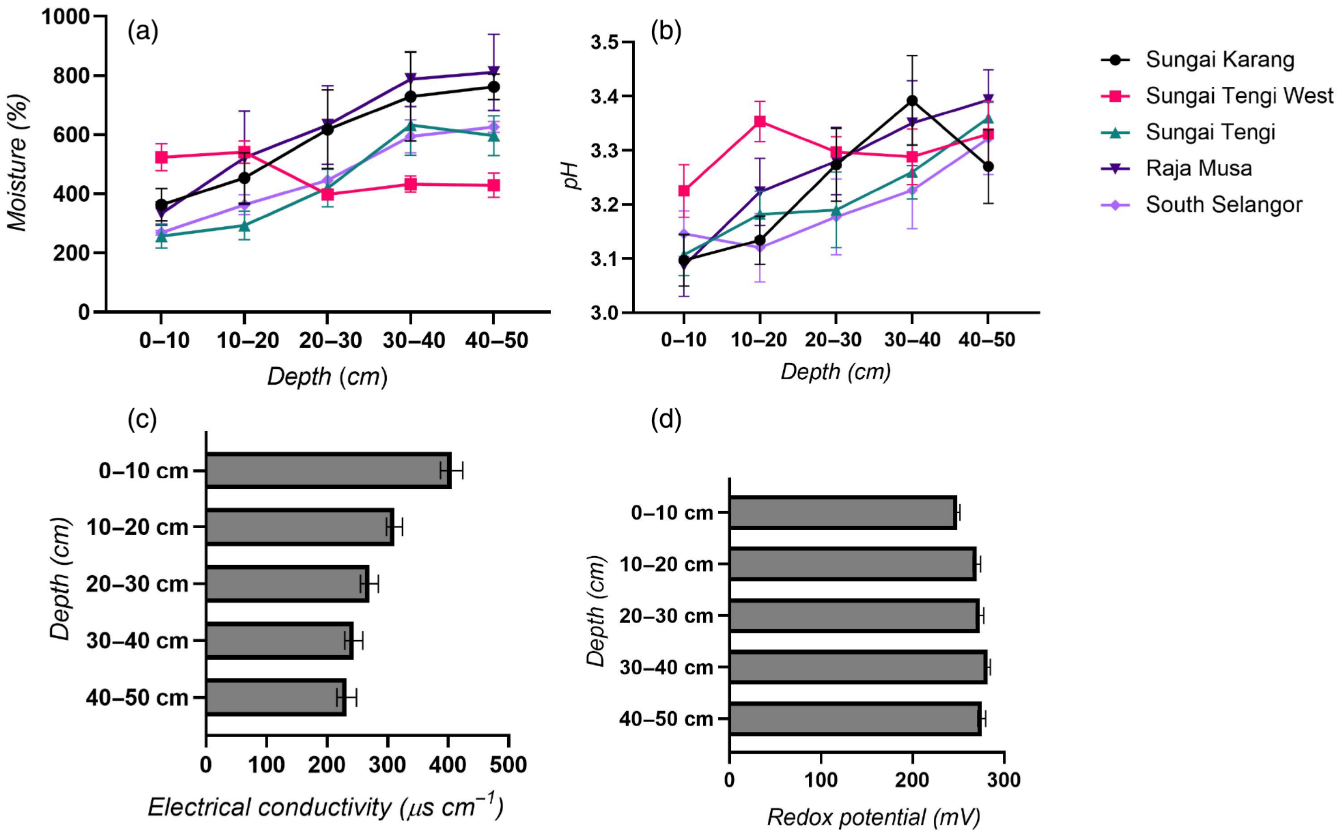

FIGURE 2 Mean values for significant results presented in linear mixed models (a) gravimetric moisture, (b) pH, (c) electrical conductivity and (d) redox potential. Points and bars denote mean values (*n* varies, see text). Whiskers denote SEs.

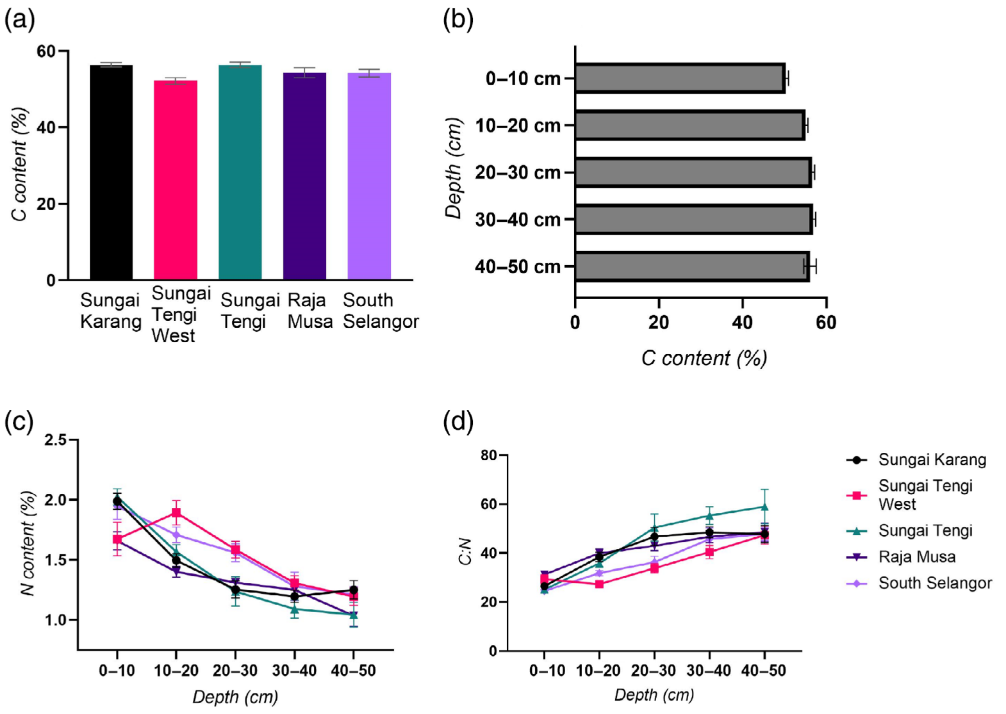

FIGURE 3 Mean values for significant results presented in linear mixed models (a) C content, (b) N content, (c) C:N ratio. Points and bars denote mean values (*n* varies, see text). Whiskers denote SEs.

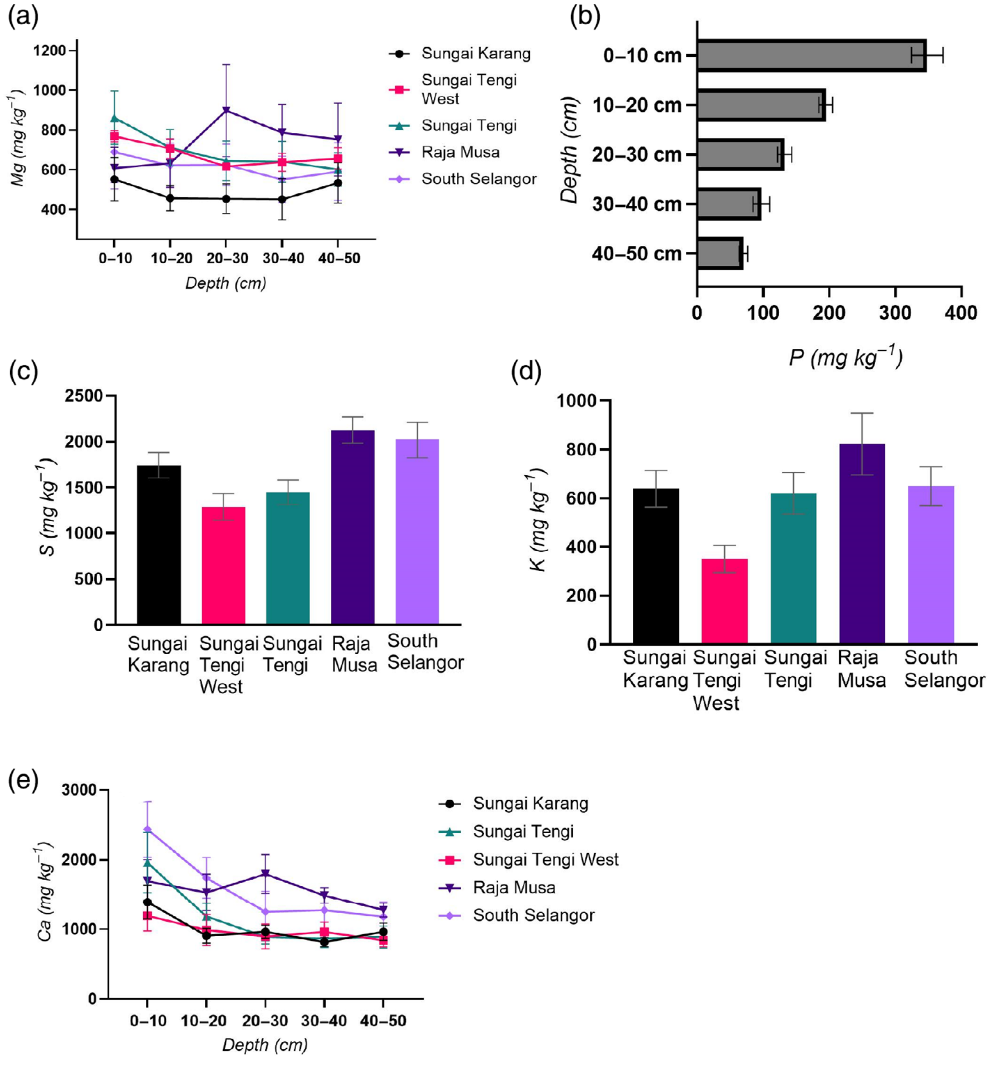

FIGURE 4 Mean values for significant results presented in linear mixed models (a) Mg content, (b) P content, (c) S content, (d) K content, (e) Ca content. Points and bars denote mean values (*n* varies, see text). Whiskers denote SEs.

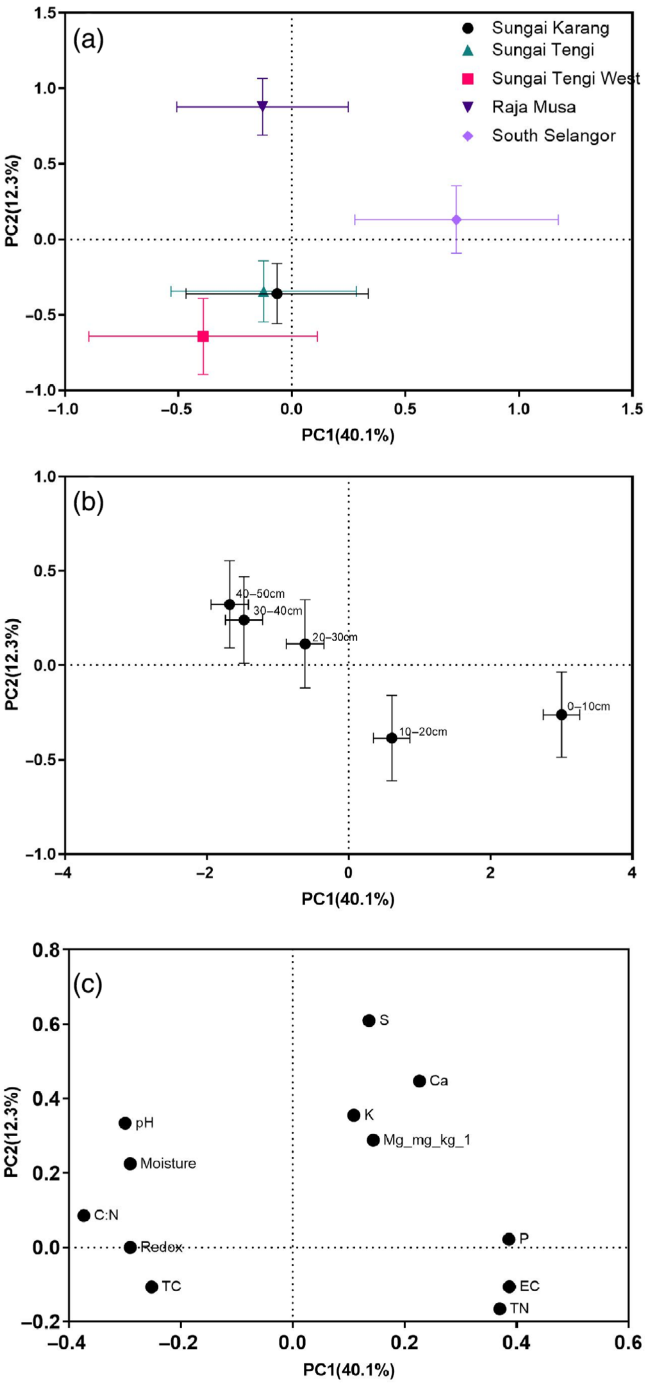

FIGURE 5 Effects of region and depth upon peat physicochemical properties and macronutrient contents, as shown by principal components (PC) analysis. (a) Ordination of PC1 and PC2 discriminating regions, (b) ordination of PC1 and PC2 discriminating the depths, (c) associated loading for individual physicochemical properties and macronutrient contents. Whiskers denote SEs.

Among other macronutrients only sulphur (S) and log transformed potassium (K) varied significantly between regions, while only log transformed phosphorus (P) significantly decreased with depth (Figure 4; Table S4, Appendix A). The interactions between region and depth were significant for magnesium (Mg) and calcium (Ca), both driven by Raja Musa region with sudden increase in Mg and Ca contents in 20–30 cm depth, varying from the general trend of decrease with depth shown in other regions.

PCA showed significant discrimination between regions and also significant and consistent change with depth (Figure 5a,b). Principal components (PC) 1 and 2 together accounted for 52% of the total variations. PC2 (12% of variations) separated the regions, with Raja Musa Reserve separated furthest away from the Sungai Tengi West, Sungai Karang and Sungai Tengi regions that were clustered together, while South Selangor region was in between the cluster and the South region. The loadings for individual peat properties show that all macronutrients except N and P, and other peat properties such as pH and moisture aided the separation of Raja Musa region from other regions by PC2 (Figure 5c).

PC1 (40% of variations) significantly separated the depth ranges, showing consistent change with increasing depth, and the deepest two layers 30–40 cm and 40–50 cm depth were grouped together (Figure 5b). The loadings for individual peat properties show that PC1 separated the properties to two groups with all macronutrients grouped towards the surface layers, and all the other properties such as pH, moisture and redox grouped together towards the deepest three layers studied, indicating an increase with increasing depth.

3.3 | Correlations among peat physicochemical properties and macronutrient contents

Peat moisture content was positively correlated with peat pH, redox potential and C content, and negatively correlated with peat electrical conductivity and all macronutrient contents except S and K (Table 2). Peat pH was positively correlated with redox potential, and negatively correlated with electrical conductivity, N and P contents (Table 2). Peat electrical conductivity was negatively correlated with redox potential and C content, and positively correlated with all macronutrient contents except K (Table 2). Peat redox potential was positively correlated with C content, and negatively correlated with all macronutrient contents except Mg and K contents (Table 2).

3.4 | Peat subsidence and bulk density

Peat subsidence from quarterly measurements across 30 site locations showed that the subsidence (mean range −1.3 to −3.6 cm year^{-1}) did not significantly vary

TABLE 2 Correlation matrix showing correlation coefficient for correlations between different peat physicochemical properties and macronutrient contents.

	Moisture	pH	EC	Redox	C	N	Mg	P	S	K
pH	0.4919	-								
EC	−0.5641	−0.7266	-							
Redox	0.3558	0.4422	−0.5487	-						
C	0.291	0.1463	−0.3585	0.3339	-					
N	−0.4237	−0.4756	0.5935	−0.3377	−0.29	-				
Mg	−0.4107	−0.2056	0.2865	−0.0575	−0.1536	0.0633	-			
P	−0.4001	−0.425	0.6463	−0.5742	−0.4292	0.7693	0.0673	-		
S	0.0475	−0.0255	0.2145	−0.1945	−0.1464	0.0875	0.2662	0.3086	-	
K	−0.0597	−0.0648	0.115	−0.0968	−0.1992	0.0945	0.1136	0.2046	0.1944	-
Ca	−0.1669	−0.0516	0.3564	−0.3351	−0.1948	0.3618	0.2814	0.3815	0.3725	0.1516

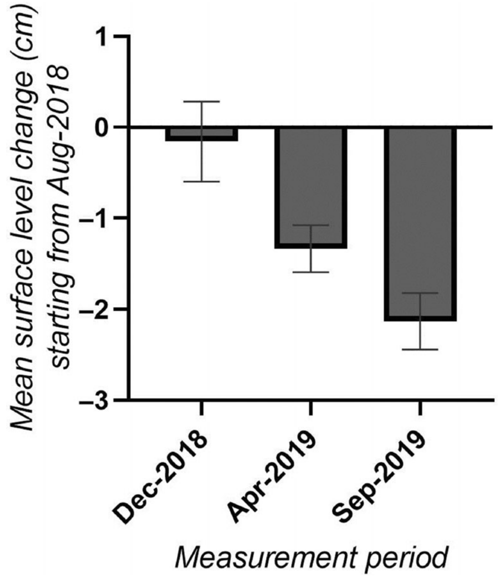

FIGURE 6 Mean peat surface level change (subsidence) from August 2018 to each measurement period (December 2018, April 2019 and September 2019). Bars denote mean values (n varies, see text). Whiskers denote SEs.

between regions ($F_{(4,23.89)} = 1.28$, $p = 0.307$), but significantly varied between measurement periods (Figure 6; $F_{(2,134.3)} = 33.07$, $p < 0.001$). There was no significant interaction between region and measurement period, as all the studied regions showed a significant subsidence in peat surface level over time. Bulk density (mean range 0.032–0.041 g cm^{-3}) did not significantly differ between the regions ($F_{(4,28)} = 1.26$, $p = 0.314$).

4 | DISCUSSION

Important peat physicochemical properties such as peat moisture content, pH, C content, C:N ratio and all macronutrient contents except P, either varied significantly between regions, or showed significant interactions between regions and depths, indicating regional variability of peat properties within Selangor peat swamp forests. Moisture showed a similar trend of change with depth, as observed previously in other drained and historically drained peatlands (Dhandapani & Evers, 2020). The Sungai Tengi West region, that was closer to the river, had wetter surface layers than other regions and also had relatively lower moisture level in deeper layers, opposed to other regions having higher moisture in deeper layers than in the surface, explaining the significant interactions between regions and depth. It should be noted that these peat forests were extensively drained for logging in the past, and those drainage canals run throughout the peat forest and impact drainage of surface layers (Brown et al., 2018; Waldron et al., 2019). North Selangor peat forest alone has a 500 km network of drainage canals (Global Environmental Centre, 2014), which enable drainage and carbon loss in the surface layers, explaining the increase in moisture with depth.

The higher pH in the surface layers may be due to increased aeration in the top surface layers, evident from similar trend of increase as moisture with depth and between regions. The North Selangor peat forests were also previously observed to have a higher pH in wet season than in the dry season (Dhandapani, Ritz, Evers, & Sjögersten, 2019). This trend is in contrast to the agricultural and fire affected peatlands in the region which showed decrease in pH with increasing depth and moisture (Dhandapani et al., 2023; Dhandapani & Evers, 2020). This contrast may be because both nutrient input and fire were known to increase pH (Dhandapani, Ritz, Evers, & Sjögersten, 2019), which influences the (already drained) surface layers the most (Dhandapani & Evers, 2020). Such manipulations are absent in studied forest ecosystem despite the historic drainage. Redox potential also exhibited a very similar trend to pH and moisture. It is plausible that both the redox potential and pH were controlled by moisture changes related to drainage, as shown by strong correlations between these properties in our study (Table 2). Higher redox potential in deeper layers indicates coexistence of water and oxygen in those layers ideal for oxidation and reduction (DeLaune & Reddy, 2005).

Peat electrical conductivity generally decreased with depth, reflecting the trend of decrease observed in concentrations of macronutrients such as N, P and Ca (Figures 2c, 3c, 4b,e; Table 2). This higher electrical conductivity in surface layers, also possibly indicate higher nutrient availability in those surface layers (Heiniger et al., 2003; Smith & Doran, 1997). The Sungai Tengi West region that had higher moisture, pH and redox in the surface layers than other regions had notably lower electrical conductivity in the surface compared to other regions. This lower electrical conductivity directly coincides with lower N, P and Ca content in that region (Figures 3c and 4b,e), further emphasising the strong relationships between nutrient contents and electrical conductivity observed in our study (Table 2).

The Selangor peat swamp forests were drained and selectively logged, thus anthropogenically influencing the change in aboveground species composition, and increase in aeration and decomposition of peat layers, both of which have great influence in peat nutrient contents. As peat are deposits of semi-decomposed plant materials, the removal of selected trees in logging directly impacts peat properties and especially nutrient contents by altering the aboveground litter input. Considering the large size of the Selangor peatlands, the mixture of variations in natural topography, environmental features and different gradients of anthropogenic disturbance affecting tree diversity and density (Brown et al., 2018; Charters et al., 2019), have left the belowground peat properties and nutrient contents significantly spatially variable across the forest, shown in our study either by significant difference in nutrient contents between regions, or by significant interactions between regions with depths.

The observed decrease in N content with depth is in line with previous observations in both the forest and agricultural ecosystems in the region (Dhandapani & Evers, 2020; Tonks et al., 2017). P and Ca concentrations also followed similar trend of decrease with depth (Figures 3c and 4b,e). Greater N content is associated with lower moisture, enabling Gram-positive dominance and greater CO_2 emissions in these ecosystems (Dhandapani, Ritz, et al., 2020; Dhandapani, Ritz, Evers, Yule, et al., 2019). Jackson et al. (2009) found greater microbial activity in surface layers that decreased with depth in the top 50 cm of peat in North Selangor peat swamp forests, which directly coincides with similar decrease in macronutrient contents with depth, indicating potential relationship between macronutrient contents and microbial activity. P contents in Selangor peatlands were much lower than what is observed in neotropical peatlands and indicate severe P limitation especially in deeper layers (Sjögersten et al., 2011). This could have significant impact on aboveground tree growth as observed in other tropical ecosystems (Baribault et al., 2012). The PCA clearly indicates that the peat property variations with depth were greater than the variations between regions. The macronutrient contents and electrical conductivity were relatively greater in surface layers, and properties such as moisture, pH, redox potential and C content were greater in deeper layers affecting this change. In terms of region, only Raja Musa and South Selangor regions showed significant variations in peat properties from other regions that are grouped together in PCA. This validates the first and second hypotheses that the peat properties significantly vary between region, and between depths.

The changes in each peat physicochemical property were strongly correlated with other peat physicochemical properties and macronutrient contents (Table 2). All the macronutrients showed strong correlation with at least one of the measured peat physicochemical properties such as pH, electrical conductivity, redox and moisture content (Table 2). These correlations provide new insights for the understanding of tropical peat biogeochemistry which further need to be tested in controlled experiments. Both high acidity and high alkalinity were known to contribute to increased electrical conductivity, as both indicate higher concentration of ions in soils (Mohd-Aizat et al., 2014). As the peat here is highly acidic, an increase in acidity indicates an increase in negatively charged ions and was correlated with increase in electrical conductivity. Soil pH and electrical conductivity along with redox potential are major drivers of plant–soil–microbe interactions through reduction/oxidation reaction and acid/base reactions (Husson, 2013). All biogeochemical reactions in complex plant–soil–microbe interaction would involve transfer of electrons and protons (measured by redox potential). These in turn change oxidation states and ionic forms of elements (measured by electrical conductivity), which also indicate transfer or consumption of H^+ ions (measured by pH) (Hinsinger et al., 2003; Husson, 2013). Hence, these three properties correlated with each other, and were all strongly correlated with N, P, Ca contents in tropical peatlands, further showing the importance of these macronutrients in biogeochemical interactions. These results validate the third hypothesis that peat physicochemical properties are correlated with each other, and with peat macronutrient contents.

All studied regions of Selangor peat forests showed significant subsidence over the study period, showing the legacy effect of historical drainage on subsidence. The subsidence rates are within the range observed previously in Southeast Asian peatlands (Evans et al., 2019). Even though there was no difference in bulk density or subsidence rates between the regions, the mean subsidence was numerically the greatest in South Selangor at 3.6 cm year^{-1}, all other regions had subsidence rate under 3 cm year^{-1}, all staying below subsidence rates observed in agricultural plantations in Southeast Asia (Evans et al., 2019; Hooijer et al., 2012). The significant subsidence in all regions is not a surprise considering a recent study found that the 90% of peatlands in Southeast Asia including forested peatlands are undergoing subsidence (Hoyt et al., 2020), and these Selangor peatlands are extensively drained and logged. Hoyt et al. (2020) also found peat in forest land use to have the greatest subsidence of all studied land uses that included industrial and smallholder plantations, burnt area, urban area, tall and small shrubs. The results show the lack of significant difference in subsidence of peat surface between different regions, therefore, the fourth hypothesis was dropped, nevertheless significant subsidence was observed in all the studied regions of the Selangor peat swamp forest.

5 | CONCLUSION

The observed significant variations of peat physicochemical properties and macronutrient contents between forest regions, and with depth, show the need for extensive sampling to characterise large secondary peat swamp forests. More research is needed on aboveground species variation and tree species contribution to the changes in peat nutrient contents. These changes in macronutrient contents showed significant correlations with other important physicochemical properties, such as pH, electrical conductivity and redox potential. These results further emphasise the importance of including peat nutrient analyses in understanding the biogeochemical dynamics in tropical peatlands. However, these field observed relationships need to be further explored in controlled experiments to fully understand these complex interactions. The peat subsidence rate did not significantly vary between regions, however, the significant subsidence of peat surface in all the studied regions of the forest shows the lack of peat accumulation and the long-term impacts of logging related historical drainage. The carbon reservoir of these tropical peatlands is important for global climate, and the continued carbon loss through subsidence could have an impact beyond the physical boundaries of these ecosystems.

AUTHOR CONTRIBUTIONS

Selva Dhandapani: Writing – review and editing; writing – original draft; conceptualization; methodology; investigation; formal analysis; visualization; data curation; software; resources. **Stephanie Evers:** Conceptualization; funding acquisition; methodology; writing – review and editing; investigation; resources. **Doreen S. Boyd:** Conceptualization; funding acquisition; writing – review and editing; visualization. **Gabriel Yesuf:** Writing – review and editing; formal analysis. **Lois Kinneen:** Formal analysis; writing – review and editing. **Alice Haughan:** Writing – review and editing; formal analysis. **Sofie Sjogersten:** Conceptualization; funding acquisition; writing – review and editing; methodology.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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