Research Article

Driving Mechanism Controlling Cultivated Tropical Peat Physicochemical Characteristics and Stoichiometry: Case Study of a Microtopographical Sequence

Mekanisme Pendorong yang Mengontrol Karakteristik Fisikokimia dan Stoikiometri Gambut Tropis yang Dibudidayakan: Studi Kasus pada Sekuen Mikrotopografi

Heru Bagus Pulunggono[1]*, Othari Gusman[2], Moh Zulfajrin[2,3], Lina Lathifah Nurazizah[3,4], Syaiful Anwar[1]

[1] Department of Soil Science, Faculty of Agriculture, IPB University, Bogor, 16680, West Java, Indonesia

[2] Bachelor of Agriculture, Department of Soil Science, Faculty of Agriculture, IPB University, Bogor, 16680, West Java, Indonesia

[3] Researcher at Soil Chemistry and Fertility Laboratory, Faculty of Agriculture, IPB University, Bogor, 16680, West Java, Indonesia

[4] Bachelor of Agriculture, Department of Agronomy and Horticulture, Faculty of Agriculture, IPB University, Bogor, 16680, West Java, Indonesia

*Email: heruipb@yahoo.co.id

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Abstract: Contrasting to the large body of knowledge documenting peatland characteristics and their trends across major rivers, limited study was found in studying peat physicochemical and stoichiometry variability at the drained and cultivated site across microtopographical sequence. This study aimed to investigate peat physicochemical properties and stoichiometry in an old oil palm plantation/OPP in North Sumatra Province, Indonesia, across a 3.1 km of a topo-hydrosequence transect perpendicular to the Leidong River and raised hummock. 20 peat cores (0-50 and 50-100 cm depth) from 10 sampling points were collected to determine their physicochemical properties and stoichiometry and analyze the driving mechanisms controlling them. This current study suggested that the long-term drainage and cultivation practices may partially alter the trends and patterns of peat's physicochemical properties. It was indicated by diverse trends, in which several peat properties behave oppositely against their natural patterns. The soil's chemical characteristics and stoichiometry throughout 0-100 cm depth were considered homogeneous, which exhibited oppositely with peat physical parameters. The prominent properties and stoichiometry mainly controlled peat variances were bulk density, pH, total N, available P, C:N, and N:K. Flooding experience and distance from the river were the driving mechanisms controlling peat properties and stoichiometry at the study site. This study's results demonstrated peat physicochemical characteristics and stoichiometry trends that were observed at microtopographical features with a relatively small tributary may resemble those studies representing the extensive landscapes.

Keywords: micro-topo-hydrosequence transect, oil palm, peat properties, stoichiometry

Abstrak: Berbeda dengan banyaknya pengetahuan yang mendokumentasikan karakteristik lahan gambut dan trennya di sungai-sungai besar, penelitian yang mempelajari variabilitas fisikokimia dan stoikiometri gambut di lokasi yang didrainase dan dibudidayakan pada sekuen mikrotopografi masih terbatas. Penelitian ini bertujuan untuk menginvestigasi sifat fisikokimia gambut dan stoikiometri pada perkebunan kelapa sawit/OPP tua di Provinsi Sumatera Utara, Indonesia, sepanjang 3,1 km transek tegak lurus Sungai Leidong dan gundukan gambut kecil. Sebanyak dua puluh contoh gambut (kedalaman 0-50 dan 50-100 cm) yang berasal dari sepuluh titik pengamatan dikumpulkan untuk ditetapkan sifat fisikokimia dan stoikiometrinya serta dianalisis faktor-faktor pengontrolnya. Studi terbaru ini menunjukkan bahwa drainase dan budidaya dalam jangka panjang telah mengubah sebagian tren dan pola sifat fisikokimia gambut. Hal ini ditunjukkan oleh beragam tren, dimana beberapa sifat gambut berperilaku berlawanan dengan pola alaminya. Sifat kimia dan stoikiometri tanah pada kedalaman 0-100 cm tergolong homogen, namun bertolak belakang dengan parameter fisik gambut. Sifat dan stoikiometri yang menonjol dari gambut yang diamati adalah berat jenis, pH, N total, P tersedia, dan C:N. Jarak dari sungai dan pengalaman banjir merupakan mekanisme pendorong pengendalian sifat gambut dan stoikiometri di lokasi penelitian. Hasil penelitian ini menunjukkan karakteristik fisikokimia

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gambut dan tren stoikiometri yang diamati pada fitur mikrotopografi dengan anak sungai yang relatif kecil mungkin mirip dengan penelitian yang mewakili lanskap luas.

Kata kunci: kelapa sawit, sifat gambut, stoikiometri, transek mikro-topo-hidrosekuen

INTRODUCTION

Peat is a soil type with high carbon content (organic matter > 65%; organic C > 12%; Polak, 1952; Soil Survey Staff, 2014; Subardja et al., 2014) derived from organic parent materials. Peatlands developed under prolonged water inundation, which predominantly occurs in the riverine and coastal backswamp of lowland areas. The undergoing condition restricts aerobic decomposition and promotes organic matter accumulation (Noor et al. 2018). Peatlands are considered one of the most carbon-dense ecosystems, containing around 600 Gt C (Yu et al., 2010) and sequestering around 0.14 Gt C year^{-1}−(IPCC 2007). Tropical regions stored around 100 Gt C (Ribeiro et al., 2020), covering approximately 44 million hectares (Page et al. 2011). Indonesia possesses about 13.4 million hectares of peatlands spread primarily in Sumatra, Kalimantan, and Papua, and a small portion is on Sulawesi island (Ritung et al., 2019; Anda et al., 2021), which estimated around 13.6 to 40.5 Gt C (Warren et al., 2017). The limited availability of arable mineral soils leads to expanding agricultural land to peatlands, which consequently be seen as precious natural resources ((Ditjen Perkebunan, 2011; Koh et al., 2011).

In nature, spatial variability of peat characteristics is found to be regulated by distance from river and peat thickness. Peat close to the river generally had less thickness and undergone constant flood, especially at the peak of the rainy season. This condition generates eutrophic-mesotrophic or topogeneous peats as a result of an enrichment of mineral nutrients transported horisontally and vertically from periodical flood and mineral soil subtratum, respectively. Contrastingly, the peat developed at the peatlands dome is relieved from a similar condition as a results from higher elevation and thicker peat layer, resulting an oligotrophic peat (Kawahigashi and Sumida 2006; Lampela et al. 2014; Page et al. 1999). A similar condition were occurs at vertical gradient after the conversion of land use from peatswamp forest to oil palm plantation. The artificial drainage and exposure to direct sunlight generate ideal environment for decomposition. A high rate of organic decomposition cause more sapric peats at peatland adjacent to the river and the surface compared to hemic-fibric-dominated peats at the peatland dome and deeper layer, respectively (Jauhainen et al. 2014; Könönen et al. 2015).

Many researchers emphasized documenting spatial variability of tropical peat physicochemical characteristics at extensive landscape scales and their relationships with the big, primary, and old rivers over mineral soil terraces or alluvium (e.g., Sabiham 1988; Page et al. 1999). Indeed, most of these studies were intended to elucidate peat formation, biogeocemical processess or general physicochemical properties trends in peatswamp forest as previously discussed (*e.g.*, Sjögersten et al. 2010). However, limited study was found in capturing peat physicochemical variability at the drained and cultivated site, explaining their driving mechanism throughout microtopographical structures, e.g., Lampela et al. (2014). Furthermore, the differences in the topogeneous and ombrogeneous peat properties as a function of long-term nutrient deposition due to flooding experience were widely reported. Yet, their response under current artificial drainage systems and crop estates which manipulate the water inflows and limit the inundated areas across the distance perpendicular to the river, is rarely reported. As far as we know, the combination of long-term artificial drainage, amelioration, and fertilization reshapes peat's chemical, physical, and biological properties (Anshari et al. 2010; Könönen et al. 2015; Könönen et al. 2018; Kunarso et al. 2022; Kurnain 2018). However, how the trade-offs resulted from mineral nutrients deposition against ameliorant and fertilizer dilutions during flooding experiences at the drained and cultivated peatlands, were not well understood and documented, especially at the peatlands developed at tributary's backswamps. As aforementioned, distance from the river and sampling depth naturally affect peat properties, yet, their influence, might be modulated by artificially-constrained flood events.

The peat stoichiometry (*e.g.,* C:N, C:P, C:K, N:P, N:K, C:N:P, C:N:P:K) is one of the essential measures of soil organic matter quality, portraying links of peatlands to global and regional nutrient cycles. As a rule of thumb, lower C:N indicates more N contained by organic matter with respect to the amount of C, thus generating a higher decomposition rate. Many researchers revealed that peat stoichiometry might link to peat degradation (Krüger et al. 2015; Leifield et al. 2020). Peat stoichiometry and their driving mechanisms are heavily researched across boreal and temperate peatlands (Moore et al. 2018; Wang et al. 2014; Yin et al. 2022; Zhang et al. 2017); however, remained understudied in tropical regions. At the global scale, Tipping et al. (2016) studied peat stoichiometry and their intercomparisons as a proxy for the degree of nutrient enrichment from ombrotrophic peats originating across various climate types. They stated that the interrelationships between the peat stoichiometric components represent the parallelization of N, P, and K enrichments under a relatively high C content. Peat stoichiometry may also reflect the variation of vegetation types (Zhang et al. 2017) and microbial transformation (Krüger et al. 2015), since vegetation and microorganisms were diversely adapted to nutrient limitations (Hoyos-Santillan et al. 2017; Kaiser et al. 2014; Malik et al. 2019; Page et al. 1999; Yule and Gomez 2009; Zhang et al. 2019).

This study, therefore, aimed to explore the variability of peat physicochemical properties and stoichiometry (0 – 50 and 50 – 100 cm) and their driving mechanisms along a micro-topo-hydrosequence transect perpendicular to Leidong River, Indonesia, in an old drained and oil palm-cultivated tropical peatland. We hypothesized that (1) the distance from Leidong River, sampling depth, and flooding experience diversely affect peat physicochemical properties and stoichiometry, (2) long-term artificial drainage and cultivation alter the trends and patterns of peat physicochemical properties and stoichiometry compared to their natural state, (3) similar mechanisms also halt the natural influence of flooding, which cause strong difference towards flooded and unflooded areas, and (4) the information, trends and patterns revealed in our transect representing microtopographical feature might be use to approximate similar processess that occur at the extensive scale.

MATERIALS AND METHODS

Site Description

This research was conducted in an old oil palm-cultivated peatland estate owned by private company, Labuhanbatu Regency, North Sumatra Province, as shown in Figure 1. As indicated by satellite imagery, the research site was firstly cleared and artificially drained for oil palm and rubber plantations during 1996-1997. The peatlands at the study site categorized as coastal peatlands that developed around 1 ka BP (Dommain et al. 2014) under influence of brackish to marine ecosystems, as indicated by the secondary pyrite containing-mineral soil substratum (BIOREF IPB, 2021). Determined during the field campaign and existing mapping data (scale 1:50.000), the peat materials at the study site were 261 to 364 cm depth and dominated by sapric and sapric-hemic decomposition types.

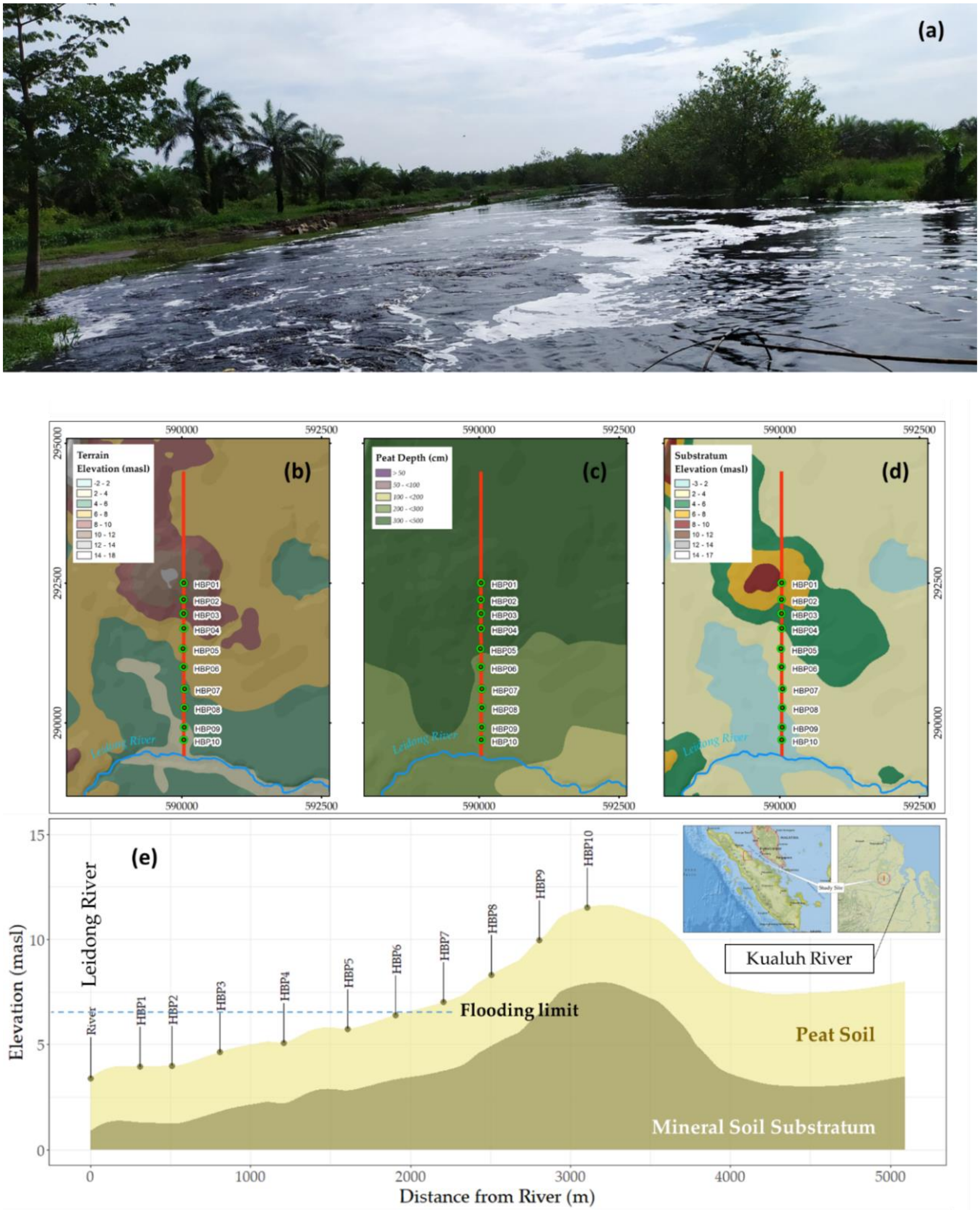

Figure 1. Study location and sampling design depicting (a) Leidong River, (b) terrain elevation, (c) peat depth, (d) substratum elevation, and (e) elevation profile/cross section of the study site. Note that the x axis was highly exagreggated towards y axis.

The research site represents a microtopographical feature that consisted of a small raised hummock extending with gradual increment. It peaked at approximately 3.1 km from the Leidong River (Figures 1a and 1b). Furthermore, the Leidong River is a small river (8 – 10 m wide; Figure 1a) that serve as tributary for the Kualuh River. This river had a relatively flat levee, occupied by bushes and oil palms throughout its length (Figure 1a). The study site is also periodically and partially flooded (up to five meters depth at the closest distance) during the peak of the rainy season (Figure 1e).

Sampling Design

Field sampling and laboratory analysis were carried out from November 2021 to May 2022. Peat was sampled at two depth classess (0-50 and 50-100 cm, hereinafter referred to as "Depth" and "Depths") using a side-filling Russian type Eijelkamp peat corer (50 cm length; ±500 cm^3 volume) according to a single topo-hydrosequence transect from the Leidong River at 10 sample points (henceforth to be referred to as "Distance" and "Distances"). Every sampling point is separated around 200 to 300 m. During the rainy season, sampling points closest to the river (HBP01 to HBP06) experience flooding. However, farther points (HBP07 to HBP10) were free from inundation, thus had undergone a shallow water table (Figure 1). The entire points were also pooled to this flooding experience factor containing two categories (flooded and unflooded), which accordingly referred to as "Flood" and/or "Flooding Experience" (Table 1).

A cross-section of the study site showing peat thickness with the spatial gradient of surface elevation is presented in Figure 1, as well as their numerical detailed information in Table 1. Digital terrain model/DTM (contour interval 1 m) was generated from detailed topographical survey conducted previously by the plantation company. Peat thickness spatial data was derived from Peat Hydrological Unit Inventory Survey points (mapping scale 1:50.000; grid 500 m × 2 km) that conducted concurrently during the field campaign. Then, DTM and peat thickness points were interpolated to 10 m resolution rasters based on *Topo to Raster* algorithm in ArcGIS 10.5 (Hutchinson 1988; Hutchinson 1989). Substratum elevation was obtained by subtracting the surface elevation from the peat thickness layer. Lastly, the elevation, peat thickness, and substratum elevation data overlapping the entire sampling points were extracted from all correspoding raster (Figure 1) to vector points and summarized at Table 1.

Table 1. Numerical information of each sampling points

Field Code	Distance from River	Peat Thickness	Elevation	OP Age	Flooding Experience
	----- km -----	----- cm -----	---- masl ----	----- year -----	
HBP01	0.3	261.1	4.0	26	Flooded
HBP02	0.5	279.7	4.0	26	Flooded
HBP03	0.8	295.1	4.8	26	Flooded
HBP04	1.2	299.1	5.2	26	Flooded
HBP05	1.6	393.5	5.7	26	Flooded
HBP06	1.9	307.9	6.4	25	Flooded
HBP07	2.1	342.2	7.2	25	Unflooded
HBP08	2.5	351.7	8.5	25	Unflooded
HBP09	2.8	355.7	9.9	25	Unflooded
HBP10	3.1	363.7	11.5	15	Unflooded

Laboratory and Other analyses

The laboratory analysis was carried out in the Soil Chemistry and Fertility and Land and Water Conservation Laboratories, Department of Soil Science and Land Resource, Faculty of Agriculture, IPB University. The analyzed peat chemical properties were actual and potential peat acidity (pH H_2O and KCl, respectively), organic C, total N, P, and K, CEC, and exchangeable cations (Ca, Mg, K and Na). Peat pH was measured using H_2O and 1N KCl, both using ratio of 1:5. Organic C was analyzed using the lost-on ignition/LoI method. Total N was determined using the Kjeldahl method. Total P and K were determined using HCl 25%, whereas available P (Av-P) using Bray 1. CEC and exchangeable cations (thereafter referred to as "Ex-") were determined using ammonium acetate 1 N pH 7.0. Base saturation (BS) was calculated as sum of all exchangeable cations divided by CEC.

Physical characteristics included peat moisture content (SM), bulk density (BD), and porosity were determined using gravimetry method. Peat bulk density at each depth was calculated using gravimetric converted with Eijelkamp core volume determined approximately at 500 cm^3. Step by step calculations follow Tonks et al (2017). The peat particle density for sampling depths 0 – 50 and 50 – 100 cm were determined as 1.57 and 1.44 g cm^{-3}, respectively (Madani 2022). Furthermore, peat stoichiometry (*i.e.,* C:N, C:P, CK, N:P, N:K) was calculated after all corresponding parameters were converted to percent values.

Statistical analyses

Data listing was done using Microsoft Excel, whereas statistical analyses were performed in an R environment using RStudio (R Core Team 2023). One-way analysis of variance/Anova was used to observe the soil properties and stoichiometry as affected by the Distance, Depth, and Flood factors with 90% confidence interval. The relationships between peat stoichiometric and actual acidity as well as C:P against C:N were plotted using `tidyverse` package (Wickham et al. 2019). Ordination analysis using principal component analysis/PCA was performed to examine the multivariate effect of factors on peat's physicochemical properties and stoichiometry. PCA was carried out using `FactomineR` (Husson et al. 2020) and `Factoextra` packages (Kassambara and Mundt 2020). The PCA's observation plots were grouped according to three studied factors, with their ellipses were set at 90% confidence intervals.

RESULTS

Peat Physicochemical Properties and Stoichiometry

All of the average values of peat properties and stoichiometry in this study were in accordance with the general values that previously reported from tropical peats that occupied by various land uses (Hikmatullah and Sukarman 2014; Könönen et al. 2015; Lampela et al. 2014; Sabiham 1988; Sabiham 2010; Yin et al. 2022; Watmough et al. 2022; Table 2). The average of SM, BD, and porosity of studied peat were 1,004.10%, 0.10 g/cm^3, and 93.67%, respectively, with their median values were relatively close, particularly for BD and porosity (961.50%, 0.10 g/cm^3, and 93.57%, respectively; Table 2). Similar values were exhibited by soil chemical properties, except for the total P and K (their difference resulted in 33.84 and 26.13 mg/kg, respectively). Peat stoichiometry had high variation as indicated by a relatively high standard deviation with respect to their average values (Table 2).

Trends and Patterns towards Distances, Depths, and Flooding Experiences

Several peat chemical properties, i.e., pH H_2O, pH KCl, Total N, and Available P were strongly governed by the distance from Leidong River (P<0.001, P<0.001, P<0.1, and P=0.11, respectively; Figure 2; Table 3). All peat physical properties, *i.e.,* SM, BD, and porosity (P<0.05, P<0.05, P<0.1, respectively) and two peat chemical properties (BS and CEC; P<0.01 and P<0.05, respectively) were significantly controlled by sampling depth (Figure 3; Table 3). Similar effects were also exhibited by flooding experience (P<0.05, P<0.01, P<0.01, respectively; Figure 4; Table 3). This study also found that the interaction between depth and flooding experience insignificantly affect entire peat properties and stoichiometry, except for exhangeable Ca (P<0.1).

Table 2. Descriptive statistics of peat physicochemical properties and its stoichiometry

Peat Properties	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	StDev.	Skw.	Krt.
Physical Properties									
SM (%)	532.10	773.60	961.50	1,004.10	1,172.60	2,041.00	366.16	1.17	2.19
BD (g/cm^3)	0.02	0.07	0.10	0.10	0.11	0.20	0.05	0.35	0.34
Porosity (%)	87.41	92.53	93.57	93.67	95.21	98.92	2.86	-0.19	0.19
Chemical Properties									
pH H_2O	3.24	3.76	3.87	3.81	3.92	4.13	0.23	-1.50	2.41
pH KCl	2.58	2.70	2.76	2.81	2.93	3.14	0.16	0.58	-0.81
Org C (%)	50.93	56.23	56.61	56.24	56.84	57.46	1.41	-3.06	11.09
Total N (%)	0.33	0.74	1.06	1.08	1.33	2.02	0.52	0.40	-0.71
Total P (mg/kg)	37.91	110.60	156.39	190.23	244.64	426.73	113.45	0.80	0.01
Available P (mg/kg)	4.06	7.14	9.34	10.06	12.56	20.71	4.14	0.86	0.93
Total K (mg/kg)	43.31	83.40	133.47	159.60	157.48	504.00	123.64	1.92	3.09
Ex-K (cmol(+)/kg)	0.03	0.06	0.08	0.09	0.11	0.20	0.05	1.06	0.65
Ex-Ca (cmol(+)/kg)	0.13	0.20	0.46	0.55	0.71	1.61	0.43	1.30	1.23
Ex-Mg (cmol(+)/kg)	0.18	0.27	0.39	0.41	0.54	0.73	0.14	0.46	-0.37
Ex-Na (cmol(+)/kg)	0.10	0.15	0.17	0.16	0.17	0.21	0.03	-0.65	0.6
BS (%)	0.24	0.34	0.43	0.51	0.67	1.04	0.23	1.01	0.27
CEC (cmol(+)/kg)	171.30	211.90	264.00	247.60	275.20	297.10	41.52	-0.72	-1.02
Stoichiometry									
C:N	27.9	41.9	53.1	67.9	80.2	171.8	40.2	1.28	0.86
C:P	1,283.0	2,299.0	3,603.0	4,452.0	5,294.0	15,127.0	3,406.8	1.90	4.08
N:P	18.1	39.9	57.5	74.1	106.3	167.1	46.2	0.70	-0.8
C:K	1,086.0	3,582.0	4,235.0	5,152.0	6,772.0	11,760.0	2,881.2	0.85	0.44
N:K	11.8	32.3	82.0	106.4	164.2	289.2	85.9	0.84	-0.56

Note: words "Min.", "Qu.", "Max.", "StDev.", "Skw.", "Krt." represents "Minimum", "Quartile", "Maximum", "Standard Deviation", "Skewness" and "Kurtosis", respectively.

The lowest C:N was found at 0.3 km distance from the Leidong River, which continued to incline along with the increase of the distance and peaked at 2.1 km. A similar trend was also observed at C:P. Moreover, decreasing patterns were exhibited by C:K, N:P, and N:K (Figure 5). Distance regulated C:N, C:K, and N:K (P<0.01, P<0.1, and P=0.01, respectively; Table 3). However, none of the peat stoichiometry was governed by depth (P>0.1). C:N in peat materials sampled at 0-50 cm was insignificantly lower than the deeper layer. Opposite patterns were observed at C:K and N:K. Furthermore, C:P and N:P were comparable at both sampling depths (Figure 5). Significant differences were found in peat's C:N, N:P, and N:K in flooded areas compared to those sampled in unflooded area (P<0.01, P<0.05, and P<0.01, respectively; Table 3).

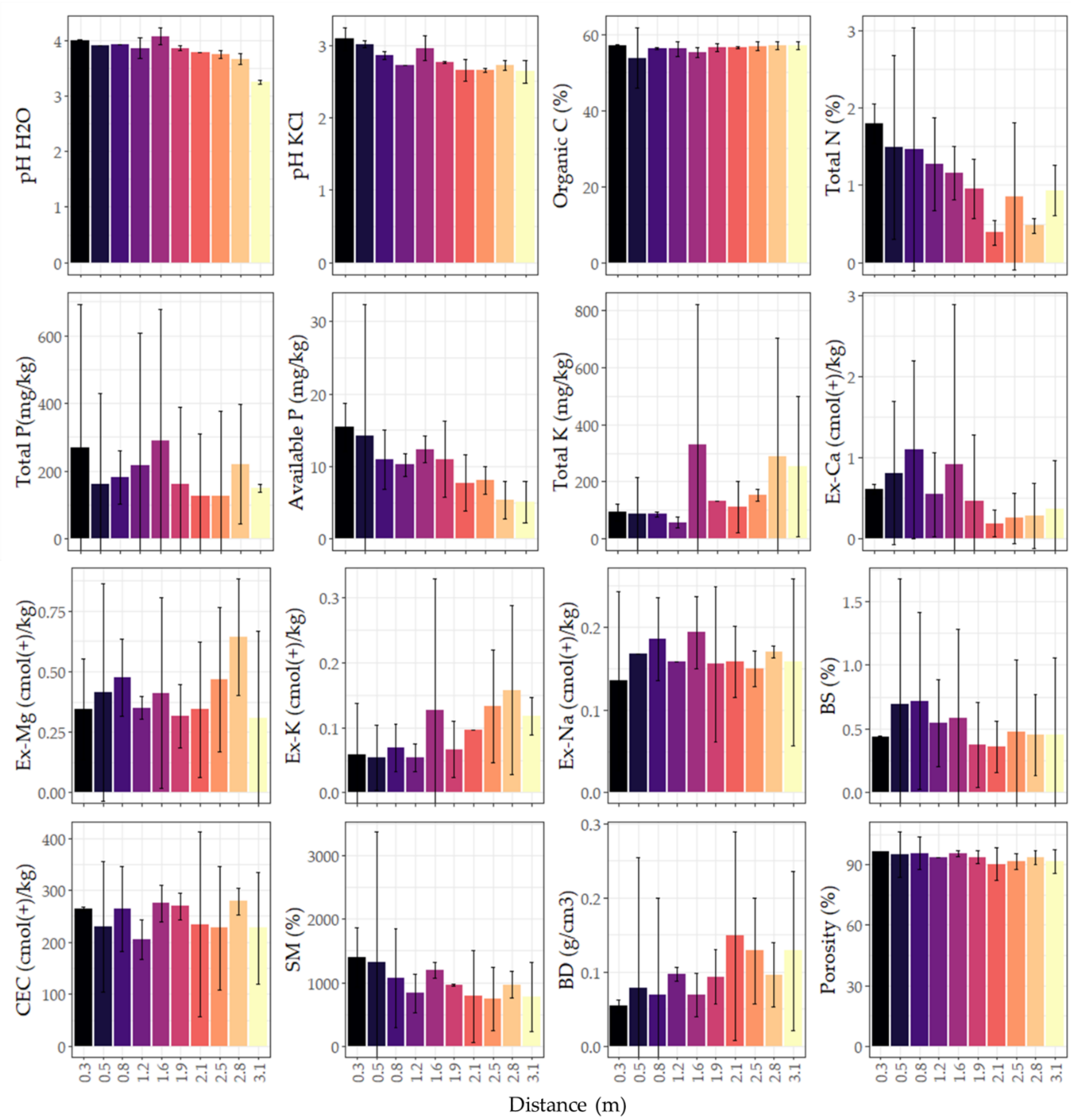

Figure 2. Soil physicochemical properties of the studied peats, pooled by the distance from Leidong river

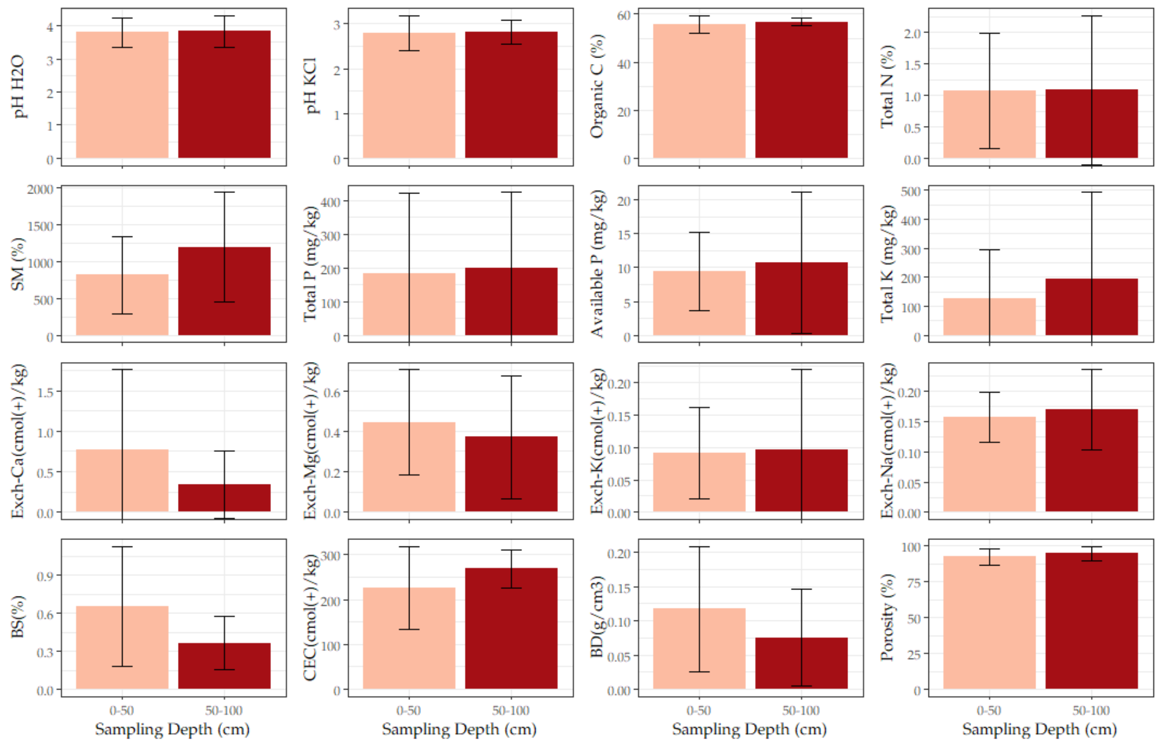

Figure 3. Peat physicochemical properties pooled by the depth of sample collected (left: 0-50 cm; right:50-100 cm)

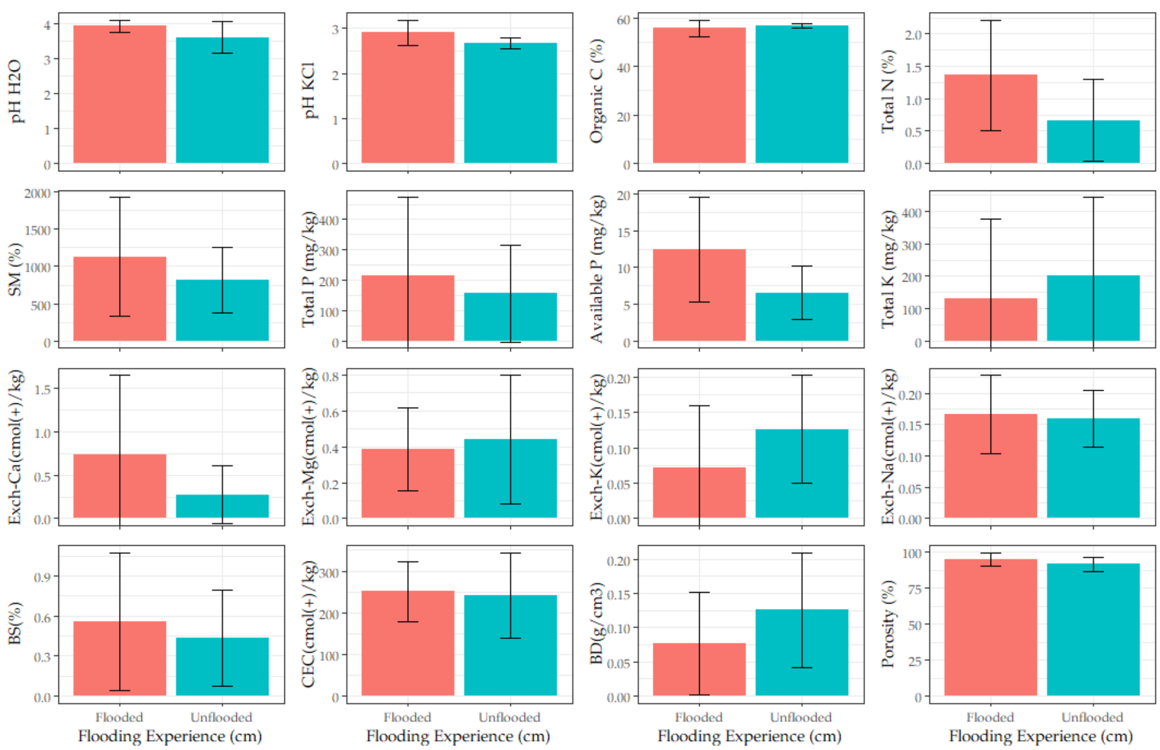

Figure 4. Peat physicochemical properties pooled by the flooding experience (left: flooded; right: unflooded)

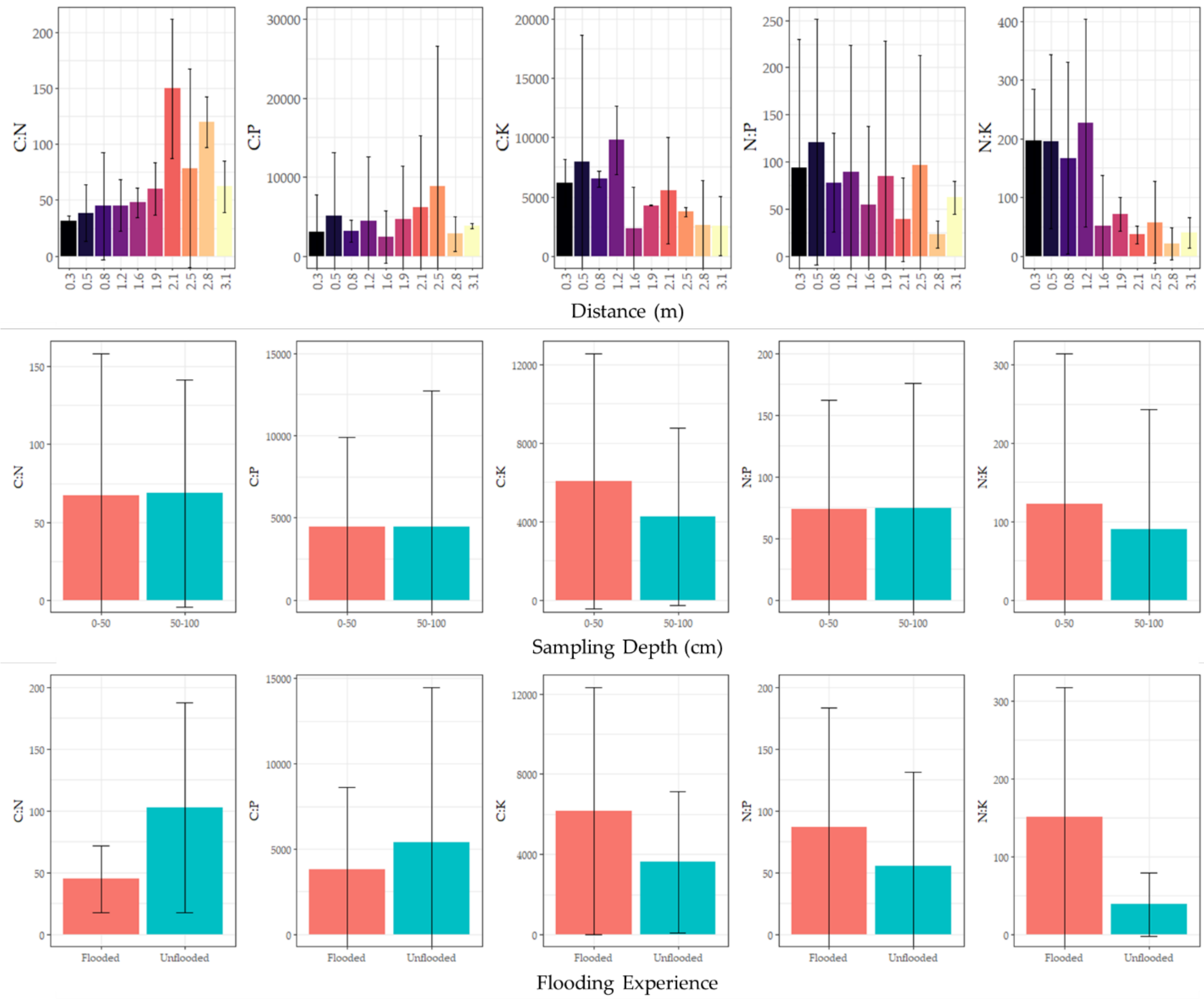

Figure 5. Peat stoichiometry pooled by distance from the Leidong River (above), sampling depth (middle) and flooding experience (bottom)

Table 3. Anova's P-value representing the effect of the distance from Leidong River, sampling depth, flooding experience and their interaction to peat physicochemical properties

Peat Properties	*p-value*			
	Distance	**Depth**	**Flood**	**Depth*Flood**
Physical properties				
SM	0.699	**0.018****	**0.034****	0.554
BD	0.592	**0.035****	**0.007*****	0.715
Porosity	0.506	**0.079***	**0.006*****	0.814
Chemical Properties				
pH H_2O	**0.000*****	0.717	**0.001*****	0.889
pH KCl	**0.000*****	0.875	**0.001*****	0.372
Organic C	0.421	0.220	0.104	0.865
Total N	**0.058***	0.964	**0.001*****	0.399
Available P	**0.105***	0.528	**0.001*****	0.284
Total P	0.932	0.741	0.308	0.998
Total K	0.275	0.232	0.232	0.792

Peat Properties	*p-value*			
	Distance	**Depth**	**Flood**	**Depth*Flood**
Ex K	0.270	0.824	**0.015****	0.918
Ex Ca	0.500	0.023	**0.002*****	**0.065***
Ex Mg	0.476	0.272	0.416	0.555
Ex Na	0.755	0.279	0.613	0.681
BS	0.896	**0.002*****	0.141	0.296
CEC	0.754	**0.015****	0.583	0.253
Peat Stoichiometry				
C:N	**0.003*****	0.946	**0.001*****	0.689
C:P	0.851	0.993	0.296	0.553
C:K	**0.062***	0.162	0.216	0.609
N:P	0.703	0.983	**0.025****	0.799
N:K	**0.010*****	0.420	**0.000*****	0.658

Note: ***(P<0.01), **(0.05), *(~0.1)

Multivariate and polynomial analyses, as presented in Figure 6 and 7, respectively, supported the findings from the analysis of variance reported in Table 3. As shown in the observation plot (Figure 6), the flooding experience had clear ellipses separation with no overlap. Meanwhile, the grouping based on sampling depth yielded slightly overlapping ellipses. These results indicated that the peat's physicochemical properties and stoichiometry were significantly different at both factor levels. Similar pattern was also partially depicted by polynomial analysis (Figure 7). It can be observed that the influence of flooding experience (color grouping) was more substantial compared to sampling depth (shape grouping).

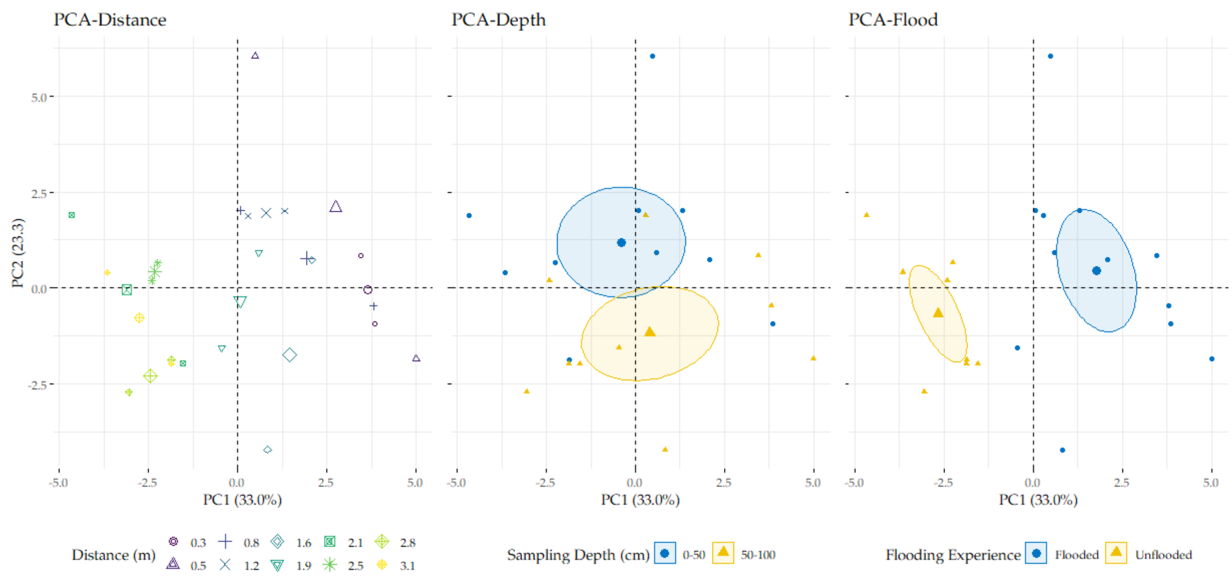

Figure 6. Principal component analysis on all data (physicochemical properties+stoichiometry) used in this study

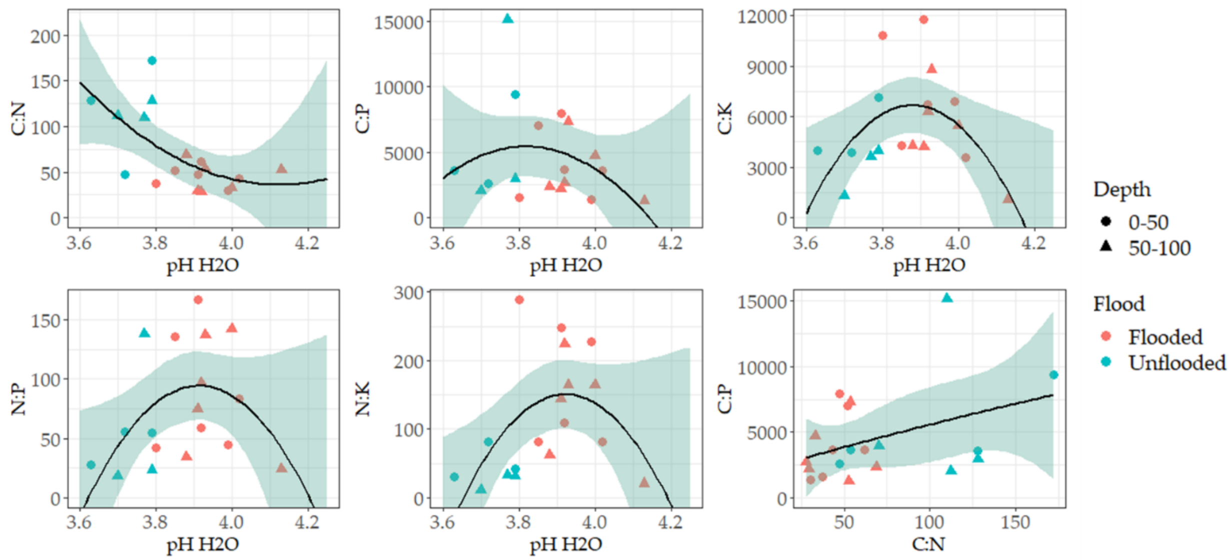

Figure 7. Peat stoichiometry relationships with (a-e) peat acidity and (f) C:P and C:N relationship, grouped by Depth and Flooding Experience

DISCUSSION

The distance from the Leidong River, sampling depth, and flooding experience exhibited diverse influences on peat physicochemical properties and stoichiometry, which is in accordance with our first hypothesis. Detected using the combination of analysis of variance (Table 3), multivariate principal component analysis (Figure 6), and polynomial regression (Figure 7), the flooding experience had the most substantial effect on all peat parameters observed in this study. Sampling depth had more profound effects on peat physical properties, while its influence on peat chemical properties was greatly reduced. Our study site demonstrated that peat physicochemical characteristics and stoichiometry observed at microtopographical features with a relatively small tributary might resemble those recorded in wider landscapes. Also, this study provides evidence that the process at the local scale may be appropriate to approximate the processes that occur on the extensive scale, for example, at peatland ecosystems developed across the major rivers (*e.g.,* Sabiham 1988; Page 1999).

The results of this study indicated that long-term artificial drainage might constrain the flooded area, which changes the degree of nutrient deposition as far as 0.9 km (Figure 1; Table 3). This is according to the assumption that the entire transect of the study site was once naturally waterlogged, allowing an extensive deposition of sediment and nutrients. This assumption was based on two reasons: (1) the high discharge of the Leidong River, which occurs annually during the rainy season and (2) the landform and physiography according to the legacy land system data (Figure 1; BIOREF 2021; RePPPRoT 1987).

Our findings suggested that the long-term drainage and cultivation practices had likely affected the soil chemical characteristics and stoichiometry throughout 0-100 cm depth, resulting in more homogeneous properties. This was indicated by the number of insignificant differences in sampling depth compared to the distance and flooding experience factors (Table 3). Considering the long-term artificial draining and cultivation (±27 years), our study site might have undergone extensive decomposition throughout the studied depth. With minimum incorporation of plant litter under oil palm canopy, this condition resulted in the accumulation of recalcitrance organic materials (Cooper et al. 2019; Guillaume et al. 2015; Könönen et al. 2015; Ledger et al. 2023; Swails et al. 2017; Tonks et al. 2017). Deeper cores from spatially separated transects must be taken to prove this interpretation since peat physical properties exhibited contrasting significancies (Table 3), and similar trends were observed on other sites in the peatswamp forest. Weiss et al. (2002) found that the homogeneous condition due to thick accumulation of vegetation litter could reach over 150 – 200 cm.

As both areas are continuously limed and fertilized, it can be observed that the flooded area possessed significantly lower acidity, organic C, and C:N, as well as remarkably higher total N and available P compared to the unflooded area. This indicates that the intense decomposition process occurs in the flooded area, and the Leidong River deposits substantial amounts of nutrients after flooding. This process magnifies long-term amelioration (using lime/dolomite) and fertilization, especially for the immobile nutrients. However, for several macronutrient cations (K, Ca, and Mg; Figure 4), the flooding influence was attenuated ($P>0.1$; Table 3). These results suggested that the ion mobility and leaching masked both processes during the rainy season (Krarchler et al. 2018; Lampela et al. 2014; Marwanto et al. 2018; Tiemeyer et al. 2007).

The peat properties at the study site generally showed similar values to previous reports on other peats with different depths, formation types, and occupied with diverse land uses. Farther from the Leidong River (>0.9 km; Figure 2; Figure 4), peat BD and porosity were in accordance with peat occupied by shrub and secondary forest at South Sumatera and Central Kalimantan (Junedi et al. 2017; Sinclair et al. 2020). Contrastingly, BD at the closer distances were comparable to those recorded at ombrotrophic intact peatswamp forest at Central Kalimantan (Sinclair et al. 2020) and drained secondary peatswamp forest in Malaysia Peninsular (Tonks et al. 2020). Furthermore, BDs from all samples at both depths were in the range of those observed on peats under intermediate to mature (5-20 years old) oil palm plantation at Jambi (Couwenberg and Hooijer, 2013) and West Kalimantan (Anshari et al. 2010; Gusmayanti et al. 2019; Table 2). These patterns indicated that the land use effect on the peat's physical properties was strongly confounded at the local scale. Nevertheless, it also partially depicted the slower compaction and consolidation processes that occur at shallow GWL and periodical inundation near the Leidong river. In this area, water predominantly fills the macropores to maintain peat structural integrity, thus decelerating the consolidation and compaction processes. Owing to higher uplift pressure from the water, recent reports in OPP even pinpoint seasonal peat surface vertical oscillations following GWL dynamics (Chahyahusna et al. 2022; Evans et al. 2021; Ledger et al. 2023; Sulaeman et al. 2022). Higher air-filled pores and the loss of water's buoyant force due to the deepening of GWL and unfrequent flooding in farther areas, in contrast, reduce the structural integrity of peat materials and higher the desiccation intensity. This causes the pores to collapse and peat shrinkage (Brandyk 2002; Ledger et al. 2023; McLay et al. 1992; Oleszczuk et al. 2003; Sauerbrey and Zeitz 1999), consequently enhancing the subsidence rate and higher BD. Other contributing factors are the gaseous and fluvial carbon losses that resulted from biological decomposition (Cook et al. 2018; Guillaume et al. 2015; Wit et al. 2015), exacerbated by the extensive period of draining and cultivation.

Interestingly, the cut-off value (0.9 km distance from the Leidong River) estimated from peat physical properties overlaps with the potential decomposability of peat materials deduced from peat stoichiometry (Figures 2 and 5; Table 3) and the flooding limit during the rainy season (Figure 1). This study's results supported the previous findings that reported higher fertility and decomposability of peat materials in the periodically flooded area compared to ombrogeneous-formed peats, partially indicated by higher ash content (Page et al. 1999). Taking several stoichiometric parameters, *e.g.*, C:N as a proxy for organic material decomposability (Figure 5a; Springob and Kirchmann, 2003), our results suggested that C:N was observed across transect inside the cut-off value, significantly lower than those recorded outside (Figure 5; Table 3). Furthermore, we observed a significant but opposite pattern of C:K and N:K. Low C:N indicates a higher decomposition rate (Leifeld et al. 2020), which further explains the boundary of mineral nutrients deposited from periodical flood events.

Limited by the inclination of elevation gradient and peat thickness, as well as groundwater table soil pH and nutrient contents would decrease with the increasing distance from the river. Moreover, organic C and C:N would exhibit opposite patterns. These trends are observed among many sites at major rivers and coastal areas, harboring peatlands ecosystems at their backwamps (Lampela et al. 2014; Page et al. 1999; Page et al. 2006; Sjögersten et al. 2010). However, this study suggested that the natural distribution of several peat characteristics at the studied depth was altered by anthropogenic disturbance (in this case, converting to oil palm plantation). It was indicated by the contrasting deviation toward natural trends that were observed along our topo-hydrosequence transect (Figure 2). Total P and exchangeable Ca, Mg, and K tended to increase along with the increase of the distance from the Leidong River (Figure 2). All of the corresponding parameters were identified as mineral nutrients applied as fertilizers.

This study also found that the trends of some peat properties (i.e., pH H_2O, pH KCl, total C and N, and C:N; Figure 2) were seemingly unaffected by oil palm cultivation. As aforementioned before, their cut-off values of the distances from the Leidong River were concentrated around the boundary of the flooding area. Peat's bulk density and porosity recorded lower than 0.09 g/cm^3 and higher than 94%, respectively, at a distance closer to the Leidong River, with a cut-off value of approximately 1.9 km. Both parameters had opposite values at farther distances. Our study results suggested that the effect of peat compaction and consolidation process generated by artificial drainage and machinery were likely to have less effect on modulating natural variation induced by spatial differences of nutrients and mineral particle incorporation.

Besides the trend alteration modulated by cultivation at some peat properties, other parameters were partially changed. For instance, BS inclined over 0.8 km from the river, then showed a contrasting trend over farther distances. However, its values at the farthest distance were insignificantly higher than those observed at the nearest distance (Figure 2). Furthermore, it can be assumed that higher peat acidity can not be offset by currently available bases or lime addition, owing to an elevated level of organic acids. In tropical peat, the breakdown of organic material resulted in smaller particles and organic acid, which COOH groups dominate. Soil acidity/pH at the study transect (Figures 2, 3, and 7) were in the range of H^+ dissociation of COOH groups (Sabiham 2010; Siegel et al. 2006; Tan 1998).

CONCLUSIONS

This current study suggested that the long-term drainage and cultivation practices may partially alter the trends and patterns of peat's physicochemical properties in comparison to the natural patterns, with respect to the distance from the river and sampling depth. We found that flooding experience, followed by distance from the river had the strongest effect on all peat parameters, examined using the combination of analysis of variance, multivariate principal component analysis, and polynomial regression. Sampling depth had more profound effects on peat physical properties, while its influence on peat chemical properties was greatly reduced. The prominent properties and stoichiometry of the observed peat were bulk density, pH, total N, available P, C:N, and N:K. Distance from the river and flooding experience were the driving mechanisms controlling peat properties and stoichiometry at the study site. This study's results demonstrated peat physicochemical characteristics and stoichiometry trends that were observed at microtopographical features with a relatively small tributary may resemble those studies representing the extensive landscapes.

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