Celebes Agricultural 3(1): 1 - 19 August (2022)

Research Article

Evaluating the Effect of Fire on Cultivated Tropical Peat Properties: Lessons Learned from Observation in East Kutai Peatlands

Mengevaluasi Pengaruh Api terhadap Karakteristik Gambut Tropika yang Dibudidayakan: Pembelajaran dari Pengamatan pada Wilayah Gambut Kutai Timur

Heru Bagus Pulunggono[1]*, Moh Zulfajrin[2], Nabila Hanifah[2], Lina Lathifah Nurazizah[3]

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

*email:
heruipb@yahoo.co.id

Received: July 2022
Accepted: August 2022
Published: August 2022

p-ISSN: 2723-7974
e-ISSN: 2723-7966
doi: 10.52045/jca.v3i1.351

Website:
https://ojs.untika.ac.id/index.php/faperta

Abstract: Fire and its associated impact highly affect peatland, particularly the peat properties, the plant cultivated above it, and its surrounding environment. Despite much research focused on fire monitoring or susceptibility assessments, peat consumption during fire occurrence, emissions from burned peat, and rehabilitation or restoration of burned peat, little attention is given to studying the changes of peat bio-physicochemical after burning. This small-scale study aims to examine the fire' effect on the upper 30 cm of peat's bio-physicochemical properties two months after being burned, using unburned peat as a reference. The result of this study indicated that fire-affected peat at all of our sampling depths. The impacted changes on peat chemical variables were varied. This study also found that sampling methods, fire magnitude and severity, peat physicochemical properties, laboratory determination, and statistical analyses were paramount in examining the fire effect on peat properties. This study also promotes the combination approach that represents both local and global phenomena to analyze and interpret the change of burned peat properties from its initial unburned state. More efforts are required to verify the initial results reported in this study and to gain in-depth information concerning the intricate relationships of organic materials, climate, hydrology, and vegetation across spatial and temporal scales in cultivated tropical peat as affected by fire events.

Keywords: burned peat, multivariate analysis, soil bio-physicochemical properties

Abstrak: Kebakaran dan dampak terkaitnya sangat mempengaruhi lahan gambut, secara khusus karakteristik dari tanah gambut, tanaman yang dibudidayakan di atasnya, maupun lingkungan sekitarnya. Meskipun banyak penelitian yang berfokus pada pemantauan atau penilaian kerentanan kebakaran, konsumsi gambut selama terjadinya kebakaran, emisi dari gambut yang terbakar dan rehabilitasi dan/atau restorasi gambut yang terbakar, hanya sedikit perhatian yang diberikan untuk mempelajari perubahan bio-fisikokimia gambut setelah dibakar. Studi skala kecil ini bertujuan untuk mengkaji pengaruh api terhadap sifat biofisikokimia pada 30 cm teratas gambut dua bulan setelah dibakar, menggunakan gambut yang tidak terbakar sebagai referensi. Hasil penelitian ini menunjukkan bahwa kebakaran mempengaruhi gambut di semua kedalaman pengambilan sampel. Terjadi variasi pada perubahan variabel kimia gambut. Studi ini juga menemukan bahwa metode pengambilan sampel, besaran dan keparahan kebakaran, sifat fisikokimia gambut, penetapan di laboratorium, dan analisis statistik merupakan faktor terpenting dalam menguji efek kebakaran pada sifat gambut. Studi ini juga mempromosikan pendekatan kombinasi yang mewakili fenomena lokal dan global untuk menganalisis dan menginterpretasikan perubahan sifat gambut yang terbakar dari kondisi awalnya. Diperlukan lebih banyak upaya untuk memverifikasi hasil awal yang dilaporkan dalam penelitian ini, serta untuk mendapatkan informasi mendalam sehubungan dengan hubungan rumit antara bahan organik, iklim, hidrologi, dan vegetasi baik secara spasial maupun temporal di gambut tropika yang dibudidayakan yang terkena dampak kebakaran.

Kata kunci: gambut yang terbakar, analisis multivariat, sifat bio-fisikokimia tanah

Citation:
Pulunggono HB, Zulfajrin M, Hanifah N & Lathifah LL. 2022. Determining the effect of fire on cultivated tropical peat properties: Lessons learned from observation in East Kutai Peatlands. *Celebes Agricultural*, 3(1): 1-19. doi: 10.52045/jca.v3i1.351

INTRODUCTION

Tropical peatlands are one of the critical ecosystems on earth, containing very dense C, estimated at about 100 Pg C, and considered a pivotal constituent of the global C cycle. Around 35-50% of the world's tropical peatlands are found in Southeast Asia, which covers its coastal and sub-coastal lowlands (Page et al., 2011; Page and Hooijer, 2016; Dargie et al., 2017; Gumbricht et al., 2017; Mishra et al., 2021). Tropical peatlands also harbor remarkably rich and highly specialized biodiversity (Posa et al., 2011; Rieley, 2016; Husson et al., 2018; Harrison et al., 2019). In terms of ecosystem services, peatlands exert principal contributors to sustaining the livelihoods of local, regional, and global communities (Dohong et al., 2017; Thornton et al., 2020; Miller et al., 2021; Terzano et al., 2022).

Nowadays, tropical peatlands are extensively impacted by anthropogenic disturbance, as shown by a rapid expansion of artificial drainage across large peatland areas and land-use change at a dramatic rate. This consequently destabilizes their long-term C storage capacity (Dadap et al., 2021; Page et al., 2022; *e.g.,* Ramdani & Hino, 2013; Adrianto et al., 2020; Hoyt et al., 2020). As a result of high organic materials and their location in the landscape, peat naturally had high moisture content or even was waterlogged for an extended period, which prevented them from being quickly burned or oxidized. This condition hence is considered suboptimal for plant growth and development. The development of drainage canals makes peatland possible to cultivate by deepening groundwater level/GWL below the active plant root system. However, it also increases peat's vulnerability to fire. During the dry season, GWL drawdown generates inadequate water content of organic materials on the surface of drained peat, which becomes dryer and highly combustible (Siegert, 2001; Page et al., 2009; Page and Hooijer, 2016). The associated risk is also aggravated by prolonged drought due to extreme weather linked to El Niño southern oscillation and Indian Ocean Dipole (Field et al., 2009; Putra et al., 2019; Nurdiati et al., 2022).

Many research and reviews put pressure on tropical peat fire monitoring or susceptibility assessments (Vetrita et al., 2021; Prasetyo et al., 2022; Taufik et al., 2022), peat consumption during fire occurrence (Che Azmi et al., 2021; Volkova et al., 2021), gas and particulate emissions from burned peat (Hirano et al., 2013; Crippa et al., 2016) and rehabilitation or restoration of burned peat (Scheper et al., 2021; Yuwati et al., 2021). However, little attention has been paid to the bio-physicochemical changes of peat after being burned.

Peat combustion not only emits diverse gasses and particulates but also leaves the solid pyrogenic products that are thereby mixed with unburned peat particles (Bodi et al., 2014). Several researchers reported that the fire could affect peat materials at the subsurface layer, which can be more than 30 cm in depth (Usup et al., 2004; Zaccone et al., 2014; Sazawa et al., 2018). This condition is attractive since unburned subsurface peat materials were considered slightly different (depending on the burned thickness) than the exposed peat at the surface. Moreover, the fire-related product on peat could be sustained for more than 24 months until it reverses to the initial pre-fire condition (Sazawa et al., 2018).

The condition had found contrasting results regarding the magnitude of the effect of fire on soil physicochemical properties. Dhandapani and Evers (2020) reported very high nutrient contents in the dry season 1 month after burning. Their results during the wet season five months after being burned were lower. However, the entire Dhandapani and Evers (2020)' results, either in dry or wet seasons, were remarkably higher than those reported by Sulaeman et al (2021), who collected peat one month after the fire occurrence. Marcotte et al. (2022) also found a lower ability of peat ash to significantly decrease peat acidity, indicating the transient effect of elevated peat pH after burning. Reviewing previous authors' sampling designs dan methodologies, both sampling depth and time, as well as fire magnitude or severity about the mobility difference of the nutrient ions in peat, were likely crucial in investigating the effect of fire on peat properties.

Here, we presented a small-scale study of burned and cultivated Bornean Peatlands, examining the changes in fire-affected peat properties with the framework of sampling methods, fire magnitude and severity, peat physicochemical properties, and statistical analysis.

MATERIALS AND METHODS

Soil Sampling

The sampling site is located on oil palm cultivated peatland, East Kutai Regency, East Kalimantan Province, Indonesia, as shown in Figure 1. Burned peats site had undergone fires around two months before the campaign was conducted. At this location, six peat samples were compositely collected from three burned blocks representing two sampling depths, namely 0-15 and 15-30 cm, for peat chemical analysis and biological analyses. In addition, twelve undisturbed peat samples for peat physical analysis were collected using a ring sampler at similar sites and depths of peat chemical analysis. Unburned peats as reference were also collected at the adjacent block on the east side of the burned peats, consisting of 2, 4, and 2 peat samples for chemical, physical, and biological analyses, respectively.

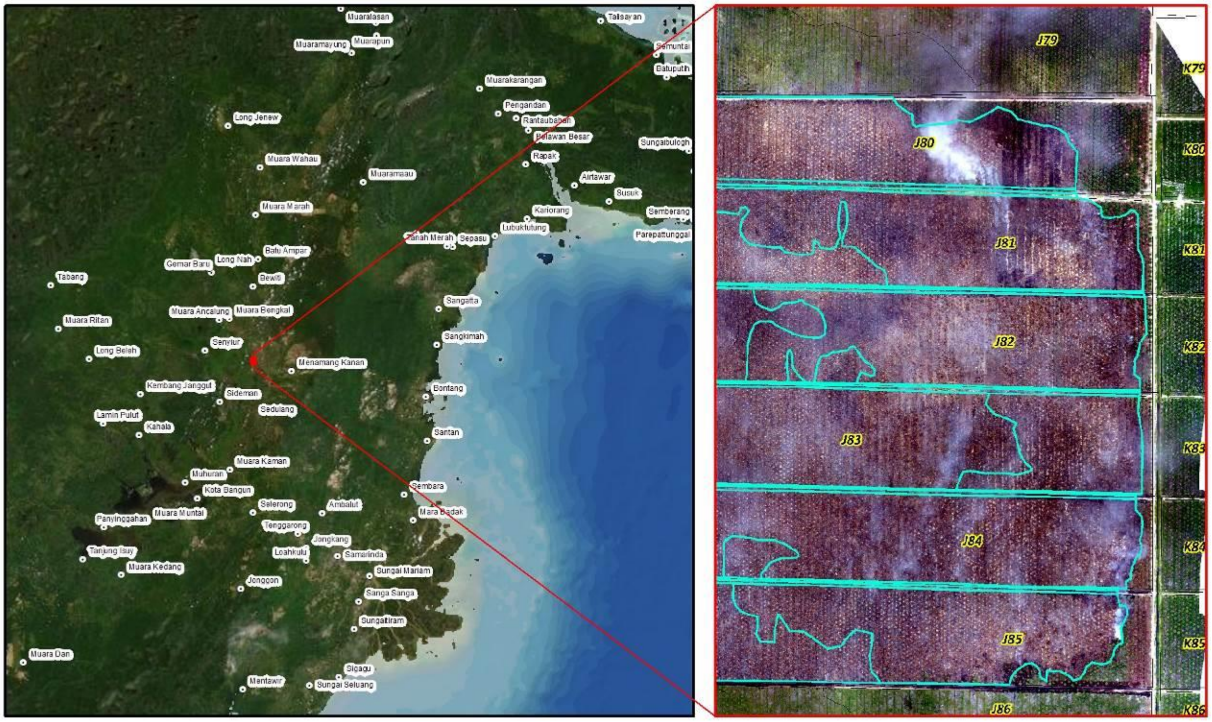


Figure 1. The map of the research site

Laboratory Analysis

After being sampled, the peat samples for chemical analysis were packed using a sack. In contrast, the peat samples for biological analysis were loaded into a cooler box. Moreover, ring samplers containing peat were put into a ring sampler box. All of the materials were then transported to the Laboratory of Soil Chemistry and Fertility, Department of Soil Science and Land Resources, Faculty of Agriculture, IPB University. The entire samples for chemical analysis were air-dried, then ground and sieved using a 2 mm sieve before analysis.

Peat chemical analyses were carried out to determine peat acidity and macro-and micronutrients. Peat pH was determined using a pH meter at the peat-to-water ratio of 1:5. Organic-C was determined using two approaches, dichromate-based extraction of WB (Walkley and Black) and gravimetric-based extraction of LoI (loss on ignition) methods. Kjeldahl method (distillation+titration) was carried out to determine total N. Phosphorus were determined for their total using HCl 25% and available using Bray1. Exchangeable macronutrients (Ca, Mg, K, and Na) were extracted using NH_4OAc 1 N pH 7. Available peat micronutrients (Fe, Cu, Zn, and Mn) were determined using DTPA-TEA (diethyl triamine penta-acetic acid-triethanolamine) extractant. The concentration of Bray1- and HCl-extracted P, exchangeable Ca and Mg, and available micronutrients were then measured using atomic absorption spectrophotometer (Shimadzu AA-6300). Meanwhile, exchangeable K and Na were measured by a flame emission spectrophotometer (Jenway PFP7).

Peat physical analyses were comprised of ash content, bulk density, and porosity determination. Ash content of the sampled peats was determined using the LoI method. Meanwhile, peat bulk density and porosity were measured using the equations below:

$$\text{BD (g cm}^{-3}\text{)} = \text{DW/V} \qquad \text{[eq 1]}$$
$$\text{Porosity (\%)} = (1 - (\text{BD/PD})) \times 100\% \qquad \text{[eq 2]}$$

BD, DW, V, and PD are bulk density, dry weight, ring volume, and particle density, respectively. DW was the weight of peat inside the ring sampler after being heated at 105 ^{o}C for 48 hours. Peat PD was set to a common value of 1.4 g cm^{-3}. To avoid high variability that emerged on peat physical data, the entire data of each observation unit were then averaged to obtain their means.

Furthermore, peat biological analyses were conducted to determine total microbes and fungi. Both parameters employed the most probable number/MPN approach based on colony-forming units/CFU. CFU measurements were selectively finalized after several dilution series with positively grown colonies, consisting of 10^{-5} and 10^{-3} dilutions for microbes and fungi, respectively.

Statistical Analyses

All statistical analyses were conducted using Minitab 19 software, except for PCA. Graphical boxplot was supplied by `ggplot2` in the R environment (R Core Team, 2022; Wickham, 2022). To interpret fires' effect on peat chemical, physical, and biological properties at the study site, several statistical methods consisting of local and global/general approaches were used. Firstly, the local approach comprised the differences between burned and unburned peats (using all sampling depths), which were assessed using analysis of variance with an unbalanced design (ANOVA type 3), continued with Tukey's honestly significant difference/HSD as a posthoc test. Secondly (also considered a local approach), an equivalence test was employed to test whether the means of peat parameters in each sampling depth at burned peats are equivalent to their referenced values in unburned peat. Concerning the limitation of observation number and common consideration of high variability of peat properties, the entire variance analysis and equivalence test were conducted entirely at 90% confidence intervals.

The correlation analyses based on Pearson product-moment test were also used to quantify the magnitude and direction of relationships among sampling depth and all peat chemical properties with a 90% confidence interval. The correlation analyses were carried out twice using the entire data (burned+unburned; representing general relationships) and specifically for burned data only. To avoid interpreting the relationships of every variable, we develop classification based on the differences/changes between general correlation as the initial condition and burned-only correlation as observed impact. The intensifying and diminishing trends in both directions (positive and negative) exceeding the magnitude of 0.1 were considered significant and classified as increasing and decreasing changes, respectively. Contrasting/drastic differences in the direction (positive to negative and vice versa) with magnitudes above 0.1, were classified as contrasting changes. The differences below 0.1 were classified as insignificant changes.

In order to gain a generalized interpretation of the fire on studied peats, this study performed a multivariate analysis in the form of principal component analysis/PCA. The combined chemical-physical data were then pooled with biological data, dropping their sampling depth differences. All significant PCs were selected based on their eigenvalue exceeding 1. PCA was executed using `FactoMineR` (Husson et al., 2020) and visualized using `factoextra` (Kassambara and Mundt, 2020) in the R environment (R Core Team). This study also modeled several peat properties as a function of sampling depth and WB-extracted organic-C, projecting them onto three-dimensional surfaces through the distance method.

RESULTS

The analysis of variances of the entire peat' chemical, physical, and biological properties, as well as their posthoc tests, were presented in Figure 2. According to the figure, burned peats exhibited remarkably higher only exchangeable Ca and Mg, as well as Mn-DTPA compared to unburned peat. Both sites' chemicals, physicals, and biological properties were not significantly different. pH, P-Bray1, P-HCl, exchangeable K and Na, DTPA-extracted Fe and Zn, and ash content increased when peats are burned. In contrast, LoI-extracted organic-C and bulk density, as well as total microbe and fungi, seemingly exhibited opposite trends. Ignoring their skewness, similar means were shown by WB-extracted organic-C, total N, and DTPA-extracted Cu in burned and unburned peats.

The results of the equivalence test of burned and unburned peats in both sampling depths were shown in Table 1. The equivalence test results denoted that on the peat surface (0-15 cm), pH, Bray1 and HCl-extracted P, exchangeable Ca and Mg, DTPA-extracted Fe, Zn, and Mn, and ash content at the burned peat surface were significantly higher than their reference values located in the unburned site. In similar depth, organic C (LoI) and total N were notably lower than their reference values. Contrastingly, WB-extracted organic-C, exchangeable K and Na, DTPA-extracted Cu, BD, porosity, and the entire biological parameters were not significantly different than their reference value at the peat surface.

In the higher depth (15-30 cm; Table 1), the entire macronutrients collected in the burned sites were markedly higher than their reference value in the unburned site, except for LoI-extracted organic-C. pH, DTPA-extracted Fe, Cu, and Mn, and porosity also exhibited similar results, whereas BD and total fungi showed an opposite direction of significance. However, DTPA-extracted Zn, ash content, and total microbe were insignificantly different compared to their reference value.

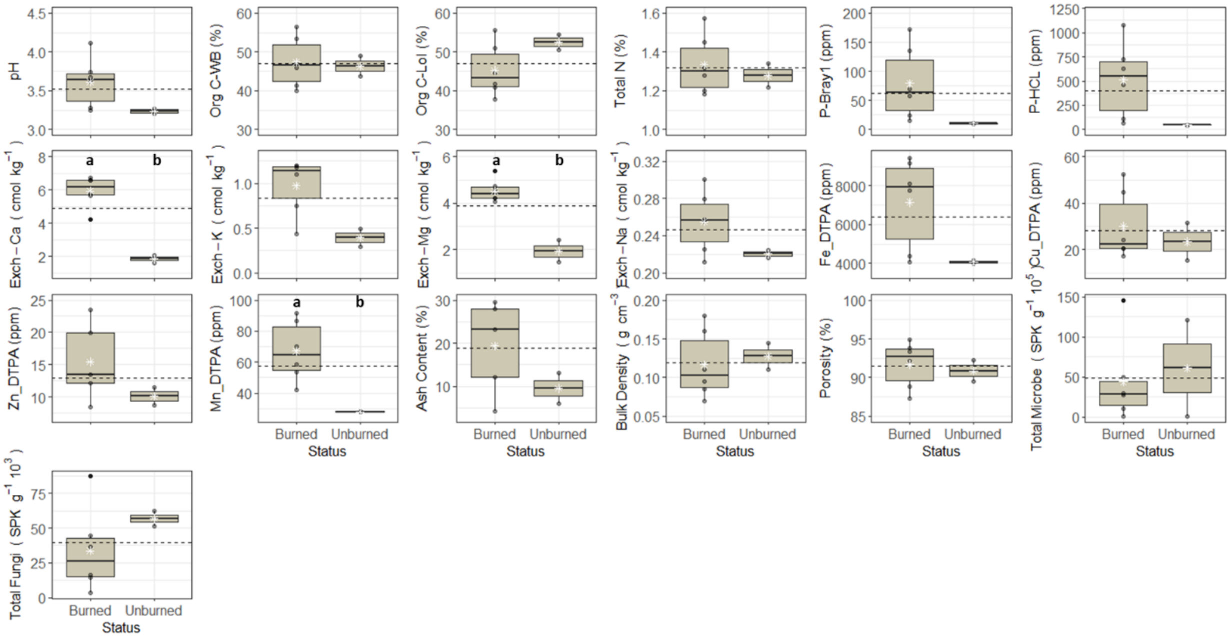


Figure 2. The effect of fire on peat chemical and physical properties at the study site. The letter above the boxplots denoted significant differences that are the results of Tukey HSD's posthoc test. The white asterisk and black horizontal line inside the boxplot indicate mean and median values, respectively; the black dashed line indicates means from the entire y-axis data.

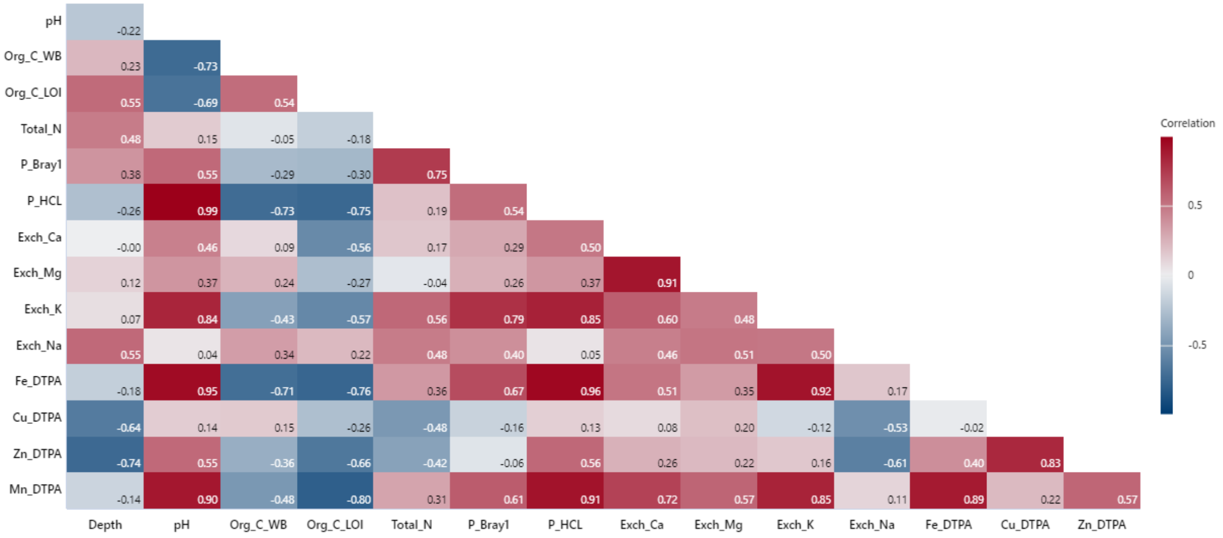
Table 1. Equivalence test results for peat chemical, physical, and biological properties, grouped by two sampling depths.

Variables	Means ± SE		Target References (Unburned Values)		P-Values (> and < Target References)	
	Depth 0–15 cm	Depth 15–30 cm	Depth 0–15 cm	Depth 15–30 cm	Depth 0–15 cm	Depth 15–30 cm
Peat Chemical Properties						
pH	3.71±0.24	3.51±0.13	3.20	3.27	**0.08**; 0.92	**0.10**; 0.90
Org-C_WB	44.85±4.2	49.86±3.33	48.95	43.65	0.78; 0.22	**0.10**; 0.90
Org-C_LoI	41.36±1.97	49.16±4.32	50.46	54.52	0.98; **0.02**	0.83; 0.17
Total N	1.33±0.06	1.43±0.09	1.34	1.22	0.93; **0.07**	**0.07**; 0.93
P-Bray1	50.26±13.69	107.71±47.76	9.22	11.39	**0.05;** 0.95	**0.09**; 0.91
P-HCl	636.79±282.92	385.93±165.92	47.33	41.47	**0.09**; 0.91	**0.09**; 0.91
Exch-Ca	6.00±0.30	5.84±0.82	1.61	2.08	**0.002**; 0.99	**0.02**; 0.98
Exch-Mg	5.00±0.15	4.55±0.42	1.45	2.42	**0.001**; 0.99	**0.02**; 0.98
Exch-K	0.91±0.24	1.04±0.15	0.49	0.30	0.11; 0.89	**0.02**; 0.98
Exch-Na	0.23±0.01	0.28±0.01	0.22	0.22	0.24; 0.76	**0.02**; 0.98
Fe_DTPA	7.65±1.64×10^3	6.63±1.29×10^3	4.12×10^3	3.95×10^3	**0.08**; 0.92	**0.09**; 0.91
Cu_DTPA	38.20±10.73	21.72±4.21	31.39	15.34	0.30; 0.71	**0.02**; 0.98
Zn_DTPA	18.90±2.94	8.92±1.70	11.47	8.74	**0.06**; 0.94	0.46; 0.54
Mn_DTPA	71.57±10.91	62.59±13.01	27.61	28.17	**0.03**; 0.97	**0.06**; 0.94

Variables	Means ± SE		Target References (Unburned Values)		P-Values (> and < Target References)	
	Depth 0–15 cm	Depth 15–30 cm	Depth 0–15 cm	Depth 15–30 cm	Depth 0–15 cm	Depth 15–30 cm
Peat Physical Properties						
Ash Content	28.69±3.40	15.24±7.45	13.00	6.00	**0.02**; 0.98	0.17; 0.83
BD	0.15±0.02	0.08±0.01	0.15	0.26	0.50; 0.50	0.97; **0.03**
Porosity	89.42±1.41	93.98±0.45	89.56	81.83	0.54; 0.46	**0.001**;0.99
Peat Biological Properties						
Total Microbe	75.17±35.77	13.08±7.74	121.00	1.25	0.84; 0.16	0.13; 0.87
Total Fungi	56.00±15.81	11.42±3.98	62.25	51.50	0.64; 0.36	0.99; **0.01**

Note: SE, Org-C, WB, LoI, BD, and Exch means standard errors, organic-C, Walkley and Black, loss on ignition, bulk density, and exchangeable, respectively. Org-C, ash content, and porosity metrics are percent (%). Total N, P-Bray1, P-HCl, and DTPA-extracted micronutrients are quantified by ppm. All exchangeable bases and BD had metrics of cmol^{+} kg^{-1} and g cm^{-3}, respectively. Total microbe and fungi were quantified by CFU (colony-forming units). P-value in bold style indicates significance at a 90% confidence interval.

Table 2 and Figures 3 and 4 showed the fire effect on the interrelationships between several peat properties, assessed on a two-dimensional axis using Pearson correlation and on a three-dimensional surface using the distance method. According to Figure 3 and Table 2, fire occurrence diversely impacted the relationships among peat chemical properties and other factors, such as depth, as shown by contrasting, increasing, decreasing, and insignificant changes. Profound fire impacts were exhibited mainly by the relationships of the depth, Bray1-extracted P, and exchangeable Ca and Mg with other variables, as shown by the highest changes (contrasting+increasing+decreasing changes; totaling 12 changes) from the total of 14 correlation instances (Figure 3) or had a maximum significant to the insignificant ratio (6.00). A relatively less impact of the fire was denoted by the relationships of pH, total N, HCl-extracted P, and DTPA-extracted Mn with other variables, as shown by the lowest significant to the insignificant ratio (1.00; Table 2).



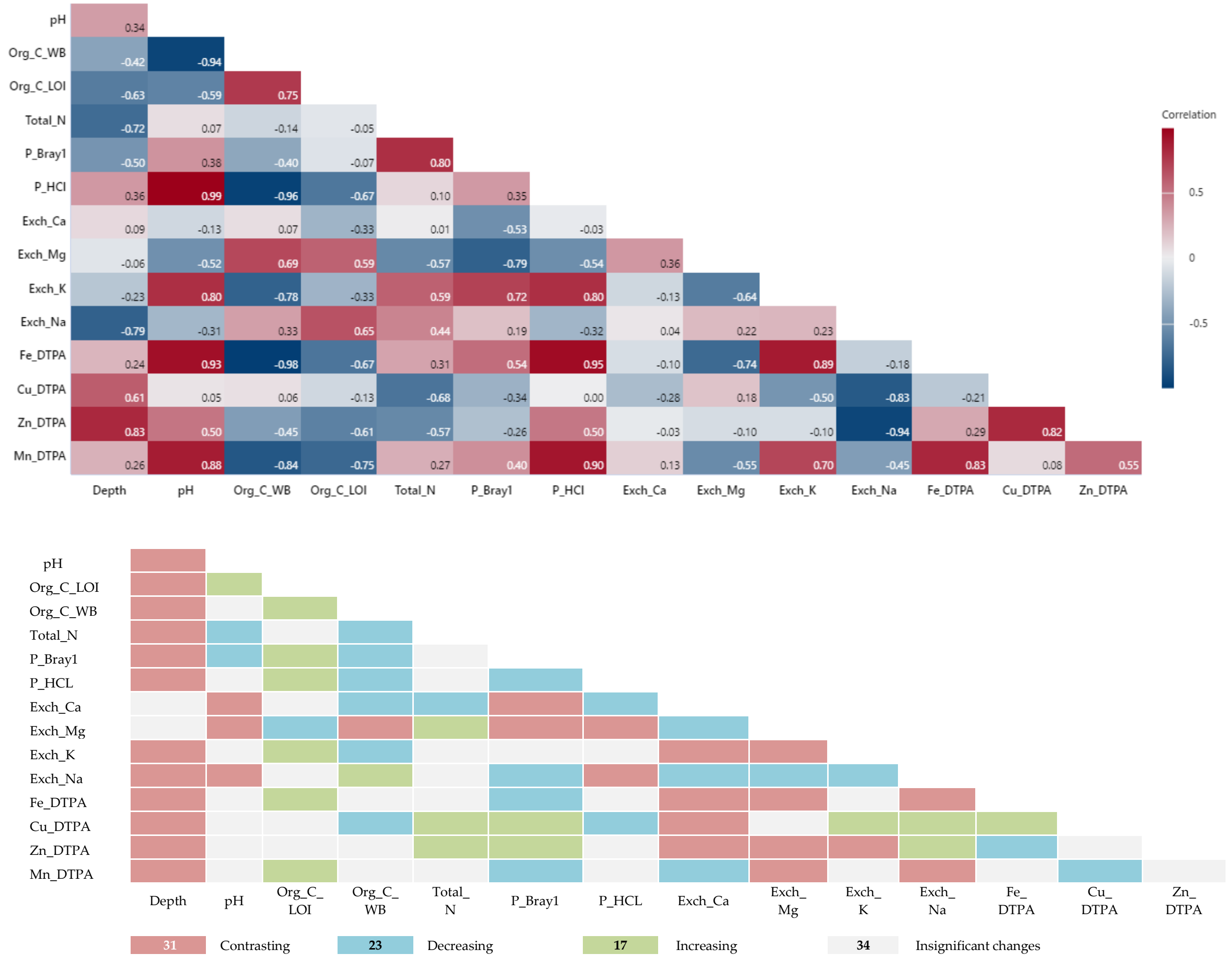


Figure 3. Correlation diagrams among sampling depth and peat chemical properties using the entire data (burned+unburned; upper graph) and burned-only data (middle graph). Their differences are presented in the lower graph representing contrasting, increasing, decreasing, and insignificant changes. The changes are considered significant if exceeding the magnitude of 0.1.

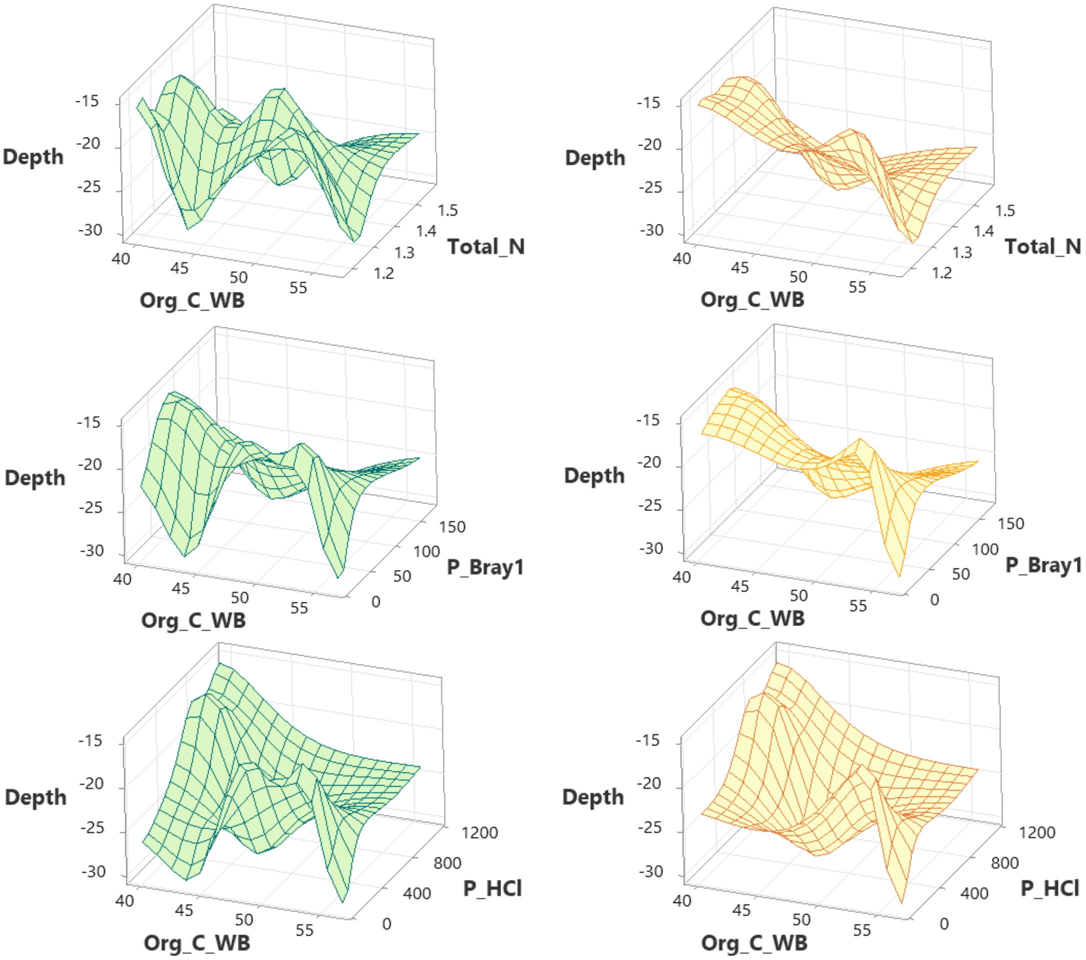
Table 2. Comparisonal information regarding the correlation among sampling depth and peat chemical properties

Variables	Total Significant Changes	Total Insignificant Changes	Significant Insignificant Ratio
Depth	12	2	6.00
pH	7	7	1.00
Org_C_LOI	9	5	1.80
Org_C_WB	10	4	2.50
Total_N	7	7	1.00
P_Bray1	12	2	6.00
P_HCL	7	7	1.00
Exch_Ca	12	2	6.00
Exch_Mg	12	2	6.00
Exch_K	8	6	1.33

Variables	Total Significant Changes	Total Insignificant Changes	Significant Insignificant Ratio
Exch_Na	12	2	6.00
Fe_DTPA	8	6	1.33
Cu_DTPA	10	4	2.50
Zn_DTPA	8	6	1.33
Mn_DTPA	7	7	1.00

Note: Significant changes were summed from contrasting, increasing, and decreasing changes (differences exceed 0.1).

Figure 4 projected three-dimensional surfaces of the peat properties as a function of sampling depth and WB-extracted organic-C. Mixing burned with unburned peats data (left) exhibited patterns differently than their counterparts that only consisted of burned peats (right). According to the figure, total N and exchangeable Mg underwent a relatively drastic change concerning peat depth and WB-extracted organic C. Relatively mild changing patterns were shown by Bray1 and HCl-extracted P, as well as exchangeable Ca and K.



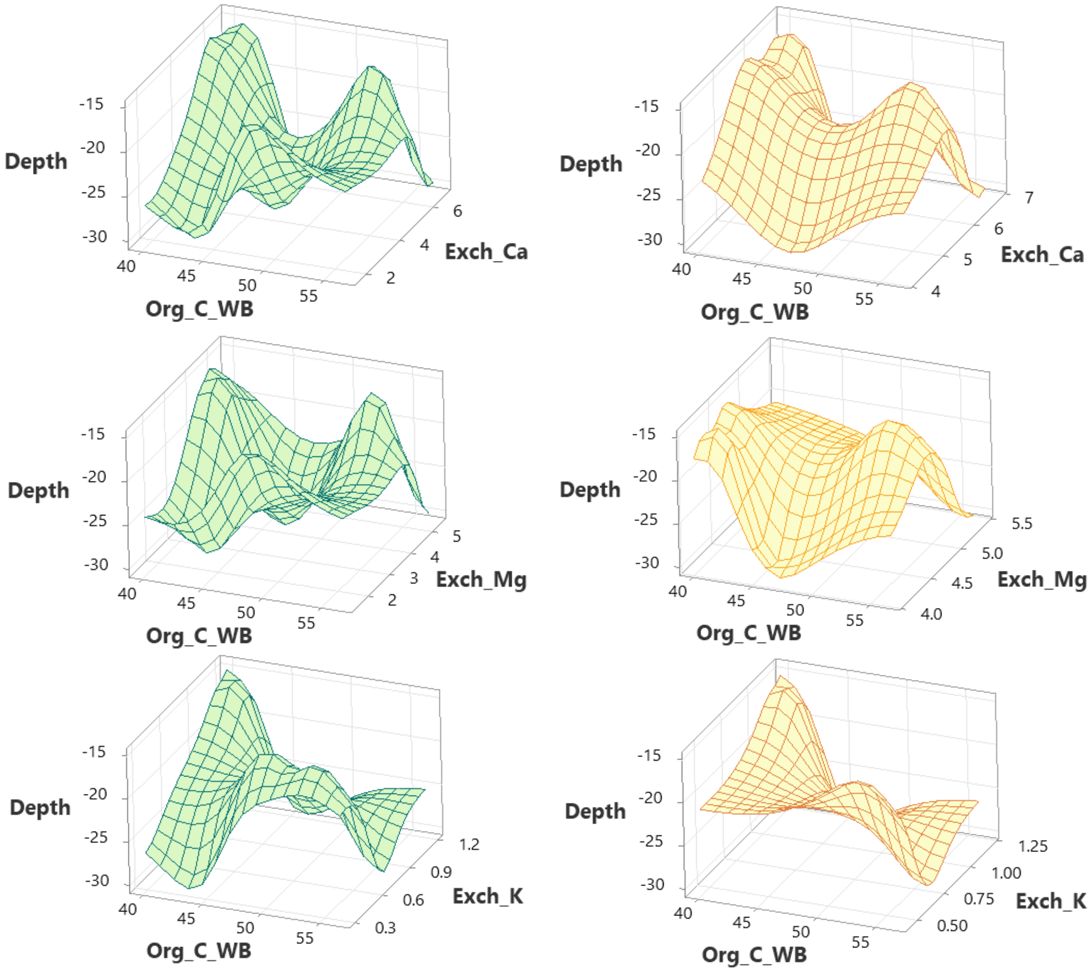


Figure 4. Three-dimensional surface of several peat properties projected through distance method. Left: using burned+unburned data, right: using only burned data. Note that all of the metrics for every variable used in this figure are referenced to those in Table 1.

The results of multivariate PCA are presented in Figure 5. Based on the elbow point in the scree plot, the first four principal components (PCs 1-4; eigenvalue >1) were selected to be further analyzed, cumulatively representing 91.70% of the variances. The first PC explained 41.25% of the total dataset variance and was loaded primarily with soil chemical variables, such as DTPA-extracted Fe and Mn, HCl-extracted P, pH, and LoI-extracted organic C, and exchangeable K and Ca. Moreover, ash content was the only physical variable that contributed to PC1. The second PC (explained 32.27% of the total variance) had relatively diverse significant contributors, consisting of peat chemical (exchangeable Na, DTPA-extracted Cu and Zn, and total N), physical (porosity and BD), and biological (total fungi) properties. Soil chemical and biological properties predominantly composed the PC3 (explained for 12.04% of the total variance). Their significant contributors were exchangeable Mg and Ca, Walkley and Black-extracted organic C, and DTPA-extracted Cu for peat chemical variables and total microbe for peat biological variables. PC4 explained 6.14% of the total variance and solely amounted to the total microbe, Bray1-extracted P, exchangeable Ca, ash content, and LoI-extracted organic C.

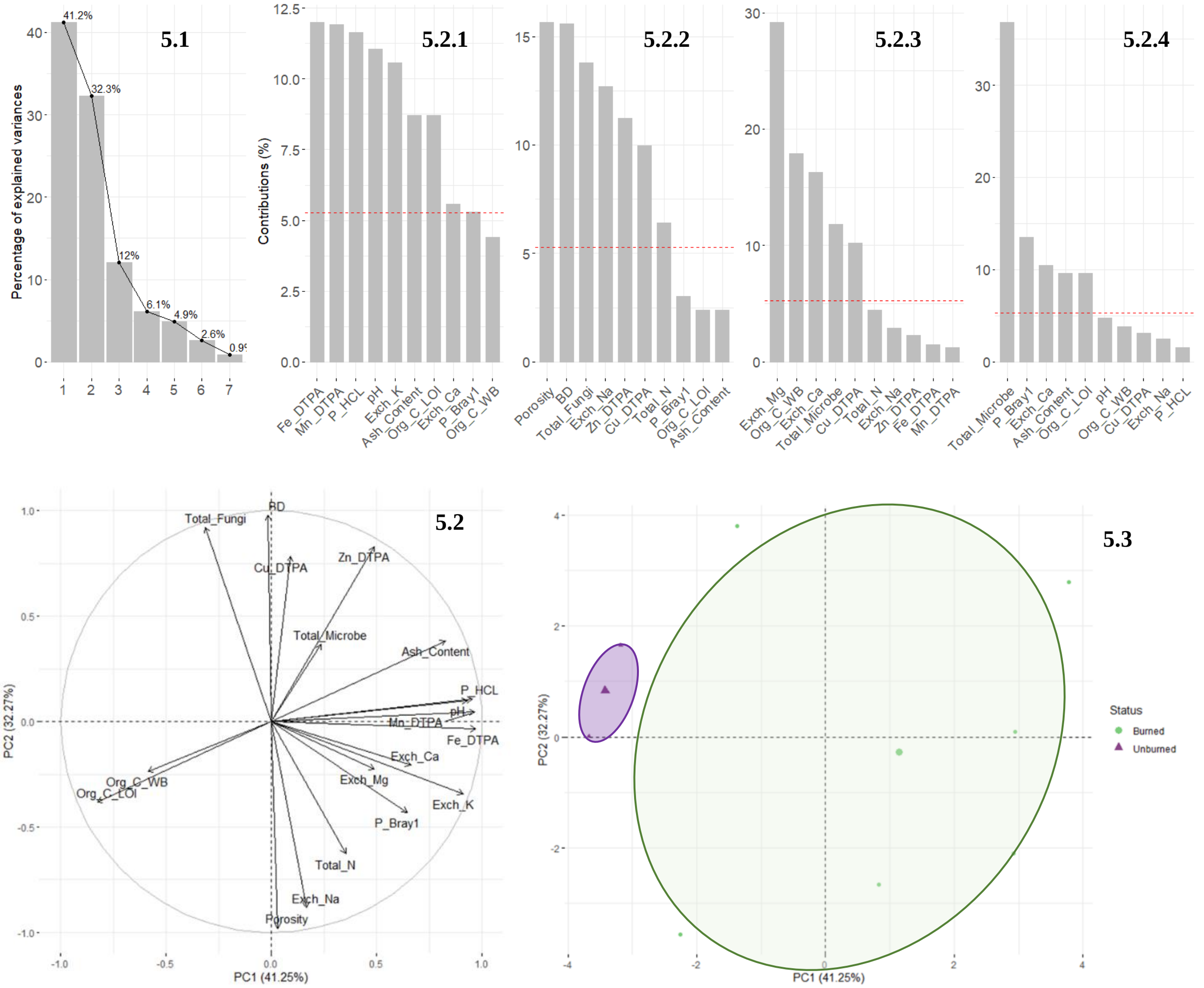


Figure 5. Principal component analysis/PCA. (5.1) scree plot showed the explained variances of every PC, (5.2.1-5.2.4) graphs representing the contribution and their significance (red dashed line) to first four PCs, (5.3) loading plot showed the correlation of peat properties observed in this study, projected at PCs 1 and 2, and (5.4) observation plot showed the grouping based on burned and unburned sampling sites, projected at PCs 1 and 2.

The observation plot showed grouping based on the fire occurrence status with clear separation. Connecting the grouping information to the loading plot using visual observation found that unburned peats were characterized by their higher organic C content, either extracted by titrimetric (Walkley and Black) or gravimetric (LoI) methods. Furthermore, higher pH, ash content, and most macro-and micronutrients constituted burned peat samples.

DISCUSSION

This study evaluated the fire effects on peat properties and its degraded impact, outlining the crucial role of sampling methods, fire magnitude and severity, peat physicochemical properties, laboratory determination, and statistical analyses throughout the discussion.

However, the entire arguments were not presented in a similar arrangement due to the importance of the highlighted contexts.

This study indicated that using a single standard or classical method (*e.g.,* only using ANOVA or paired t-test) in interpreting a small subset of fire-affected peat data may suffer unclear or spurious results. Our study's reason is a highly unbalanced design and inadequate observation. Nevertheless, the approach used in this study combined a local perspective as presented by variance, equivalence, and correlation analyses and a more flexible and global perspective as shown by three-dimensional surface models and multivariate PCA, seemingly successfully obtaining the required information. The choice of sampling site and determination methods concerning the type of sampled peat materials, the physicochemical transformation of burned organic materials, and the fire magnitudes that had undergone in peat are also vital to be thought about before carrying out a field survey to attain unbiased comparison. Besides the inevitable limitation, this study corroborates other findings. It provides valuable information and interpretation regarding peat chemical, physical, and biological properties two months after burned with an unburned peat site as a reference. Further studies are needed to examine the effect of fire on peat properties in more convenient ways as well as verify our results and findings, accounting for complex interrelationships among peat's organic materials, climate, hydrology, vegetation, and fire across spatial (space: horizontal and vertical) and temporal scales.

This study's results indicated that the pivotal effect of fire in governing peat chemical, physical, and biological properties substantially deteriorated over a short period when pooled and examined with single method, as shown in Figure 2. The variance analysis and Tukey HSD tests in Figure 2 indicated that after two months of fire occurrence, the differences in many peat properties using pooled data were not significant as expected. Only three variables denoted significant differences, while others exhibited no significance. Eight variables showed the inclination tendencies when peats are burned, whereas four variables presented opposite trends. Through visual observation, the other four variables showed no differences in their means. However, a significant effect of fire in regulating peat properties was found when the depth was separated and assessed using an equivalence test, as shown in Table 1. The prominent effect of fire seemingly achieved its most vital control over most peat chemical properties at higher depth (12 of 14 variables) compared to their counterpart on the surface (10 of 14 variables). The previous experiment found that our sampling depth for subsurface peats (15-30 cm) in burned sites was in the range of fire influence (Usup et al., 2004; Zaccone et al., 2014; Sazawa et al., 2018). These results may also confirm that a higher amount of soil nutrients had been transported vertically to the peat layer below the surface, as shown by significantly higher pH and most micro-and macronutrients in 15-30 cm unburned peats compared to their reference value. Sazawa et al. (2018) reported that the thermal product could be found in subsurface peat over two years after fire events.

From the soil science perspective, meaningful fire' impact was undergone on the N, P, and base cations, as shown by their huge content/concentrations after being burned compared to unburned peat, in agreement with other reports (Dhandapani & Evers, 2020), except for organic C and N contents. Meanwhile, pH increments in both depths at burned peat were not as high as hypothesized, similarly to the findings in subtropical (Marcotte et al., 2022) and tropical (Sulaeman et al., 2021) peatlands. However, the pH ranges at the burned sites presented in this study were much lower than those reported in burned Malayan peatland, North Selangor, either when peat was sampled in the wet or dry season (Dhandapani & Evers, 2020). It can be explained that the differences occur due to the variation in sampling strategies. Dhandapani &

Evers (2020) collected peat at 0-5 cm depth, whereas Sulaeman et al. (2021) conducted at 0-30 cm depth. Our sampling depths were in the middle (0-15 and 15-30 cm); moreover, the pooled means (representing 0-30 cm) resulted likely similar to Sulaeman et al. (2021) in terms of pH and total N ranges. Dhandapani and Evers (2020) might collect peats dominated by ash and other components of the 'pyrogenic C continuum' (sensu: Bodi et al., 2014) since they sampled the upper parts of burned peat materials. Even though the peat was sampled five months after being burned in the wet season, their sampling methods caused a higher observed pH and other nutrient concentration, as well as lowered organic C and N contents. Along with the increase in sampling depth, the proportion of intact organic materials was higher than the thermal products, resulting contrasting trends and ranges that could be observed one or two months after fire events (Sulaeman et al., 2021; Figure 2; Table 1).

The differences in fire magnitude and severity also impacted the proportion of organic materials with other thermal products in the sampled peat. For instance, the resemblance of our pooled results (Figure 2) with those reported in a relatively close sampling time to the fire event (*e.g.*, Sulaeman et al., 2021) suggested the similarity of the fire magnitude of both reports. However, using surface burned data (Table 1), our results should be in the range of Dhandapani and Evers (2020)'s findings in the wet season five months after burning, owing to the deteriorating effects of high precipitation, nutrient leaching, and longer sampling period from fire occurrence. Therefore, we speculated that their study was conducted in the peat area that experienced a relatively immense magnitude and more severe fire than both Sulaeman et al., 2021 and our sites. In addition, a high temperature was observed during peat combustion (~400 to 600°oC), causing the smoldering process and resulting in ash with higher pH (Quintana et al., 2007; Rein et al., 2008; Úbeda et al., 2009; Marcotte et al., 2022). We believe that the combination of the sampling method with the smoldering effect and higher ash' pH was why more burned-aged surface peat from Dhandapani and Evers (2020)' site had extremely high pH and soil nutrients concentration compared to our results.

Oppositely to our assumption and previous findings (Könönen et al., 2015; Sinclair et al., 2020; Sulaeman et al., 2021), the physical properties shown in Figure 2 exhibited contrasting patterns, particularly for bulk density dan porosity. The fire could induce the breakdown process of peat organic materials, causing them to become smaller particles that could fill the peat micropores (Könönen et al., 2015; Wijedasa et al., 2016). According to Sinclair et al. (2020) reports, the bulk density of peat sites that experienced fire was generally higher than those of peat sites that did not experience a fire. Interestingly, they also reported the possibility of other factors governing the higher magnitude of peat bulk density in the unburned and degraded peats outside of the oil palm plantation area, which gave them relatively similar results to this study. They suggested that the sampling site decision was important, accounting for the combination of hydrology, vegetation, and fire, in relation to the distance from the canal and GWL-based depth zonation (acrotelm-catotelm). In addition, we argued that besides all of the factors mentioned by previous authors, the magnitude of bulk density and porosity recorded in unburned sites reflected peat with a much higher decomposition degree compared to the burned sites.

Besides being affected by the above reasons, the attenuation of the effect of fires on peat properties recorded in this study might have occurred due to high precipitation before the sampling campaign; however, the magnitudes were different and distinct in every observed variable. Previous authors reported low pH and nutrients concentration in burned peat during wet season, highlighting the effect of precipitation and dilution on the nutrients ions in peat column after burn (Dhandapani and Evers, 2020; Marcotte et al., 2022). A typical case for the this argument could be observed on the concentration of the macronutrients in the surface of the burned peats, which exhibited no statistical significance and their value were close to those observed in the unburned site (Table 1). As the organic materials burn, they emit CO_2 and other aerosols particulate, thus leaving their macro-and micronutrient loadings as oxides or carbonates which were dependent on the combustion temperature (Usup et al., 2004; Bodi et al., 2014, Hu et al., 2018; Sazawa et al., 2018). These oxides or carbonates are highly dissolvable in water, which allows them to be leached down following the deepening of groundwater level or out from the soil system during high rainfall events (Bodí et al., 2014; Marcotte et al., 2022). Monovalent cations, such as K and Na, were reported to be highly mobile in soil, easily transported following the groundwater dynamics. Contrasting with that, bivalent cations (Ca and Mg) mobilities were relatively slower and more persistent in peats, since they had higher ionic strength which can replace the previous monovalent cations and bond tighter in organic exchange site (Sparks, 2003; Tipping, 2004; *e.g.*, Kalinichev & Kirkpatrick, 2007; Hakim et al., 2019).

Another reason was the pooled means that included subsurface data in the analysis. In several cases, the peat material from the subsurface layer had slightly different properties (*e.g.*, protected from immense combustion, less decomposed, more water content, less oxidative) that can possibly generate higher variance and tend to be similar to unburned peat. However, our equivalence test resulted in a potentially more significant fire effect on the peat properties below the surface (Table 1), as well as other research reported (Usup et al., 2004; Sazawa et al., 2018), providing partial support for their inclusion, thereby strengthening our third argument.

This study also promotes the collective usage of correlation and three-dimensional surface analyses to study the effect of fire on how peat chemical variables relate to each other, mainly while other statistical analyses resulted in dubious results. Both analyses revealed that after two months, fire residues were still capable of modifying the relationships between depth and all chemical variables observed in this study, as demonstrated in Figures 3 and 4. The impact of the fire was recorded as changes from the initial state (using the entire data) to burned state (only using burned data) that can be diminishing, amplifying, contrasting, or insignificant to the relationships of peat chemical variables with depth and each other (Figure 3; Table 2). The fire seems remarkably impacted most of the chemical variables' relationships with depth, neglecting how its forms. A similar effect also impacted Bray1-extracted P, and exchangeable Ca and Mg relationships with other chemical variables. Furthermore, the effect of fire could emerge from other chemical variables when visually compared using three-dimensional interrelationships, as shown by relatively drastic changes in the 3D surface of total N in Figure 4. Notwithstanding these above findings, our results must be clarified and reproduced, incorporating more observation in both peat sites, and covering more expansive areas.

A general grouping of the peat according to its fire occurrence status using multivariate PCA also corroborated with most of the local phenomena observed previously. The grouping was also intricately connected with some key variables that undergo chemical reactions during the fire occurrence, concerning the chemical and physical determination methods. In the observation plot in Figure 5, two groups are separated between burned (green points and circle) and unburn (violet points and circle) peats. Utilizing the loading plot, unburned peats were likely linked to the higher organic-C content, regardless of their extraction methods. On the other hand, burned peats were characterized by their high pH, ash content, and macro-and micronutrient concentration. Peat fire occurs if dry organic material exothermically react with oxygen. Organic material served as the fuel for the combustion reaction, volatilizing most of its C and N content and leaving ash as residues. Hence, the peat sampled at the surface of burned sites contained organic materials from subsurface layer mixed with ash and other residuals from burned peat. The subsurface peat might be less decomposed than the surface peat, containing lower solid particles, and higher pores and water content. However, their pores might be filled with combustion residues that could heighten the bulk density (Könönen et al., 2015; Wijedasa et al., 2016). Meanwhile, the unburned peat samples may contains more decomposed organic materials since they directly and continuously exposed to the dynamic environments (*e.g.,* weather change, GWL drawdown) and anthropogenic disturbance (*e.g.*, amelioration, fertilization, tillages, human footprints) for an extended period since the forest cover was cleared. This condition consequently generates an ideal condition for an enhanced decomposition process and higher bulk density. Both sampling sites potentially had bulk density boosting agents, likewise, consisting of very different materials. Walkley and Black method separated the organic materials from ash via dichromate reaction. Small interferences could emerge from ferrous iron and higher oxides of manganese (Nelson & Somners, 1996) that were possibly derived from ash, whereas this condition might be minimal at unburned peat. However, ash particles were accounted for while estimating ash content and LoI-extracted organic C, resulting in overestimated results composed of furnace-heated ash and additional previously burned ash. The above explanation might explain why organic C and ash content differences were not significant in Figure 2. In contrast, they were exhibited as salient features of unburned and burned peats in Figure 5.

CONCLUSIONS

This study demonstrated the importance of sampling methods, fire magnitude and severity, peat physicochemical properties, laboratory determination, and statistical analyses in examining the fire effect on peat properties. This study suggested that the effect of fire on peat after its occurrence could be interpreted as declining or even disappearing if assessed with only a single method. Coupling local and global-based statistical approaches, this study found that fire impacted peat properties over 30 cm depth, with diverse effects concerning their interrelationships (diminishing, amplifying, contrasting, and insignificant effects) two months after the events. This study also indicated the different rates of nutrient transportation vertically, enriching the fertility of the subsurface layer. A combination approach must be conducted to obtain more information, representing both local and global phenomena regarding the change of burned peat properties from its initial unburned state. More efforts are required to verify the initial results reported in this study, and to gain in-depth information regarding the intricate relationships of organic materials, climate, hydrology, and vegetation across spatial and temporal scales in cultivated tropical peat as affected by fire events.

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