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# Post-fire peatlands conditions based on soil resistivity and physical properties in Balangan County, Indonesia

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**Abstract**

Tropical peatlands are formed by the accumulation of organic matter under waterlogged conditions for thousands of years. Tropical peatlands are ecosystems that play an important role in global carbon storage and cycling. However, peatfires lead to a decline and insufficient soil quality. This study examines post-fires soil condition based on soil resistivity and physical properties in the peatland areas that burned in 2015 and reoccurred in 2019. This study was conducted in the peat hydrological unit of the Balangan River - Batangalai River in Balangan County, Indonesia. The study area included natural areas with no fires, areas burned in 2015, areas burned in 2019, and areas burned in 2015 and reoccurred in 2019. Field measurements of soil resistivity using the Wenner configuration geoelectric method with the smallest spacing of 10 cm to n = 12. The physical properties test of soil samples includes Bulk Density (BD), water content, fibre content, ash content and pH. This study was conducted during the dry season, so the condition of the area that experienced fires in 2015 and repeated in 2019 had only peat decomposition up to 10.0 cm thick, and the underlying layer was still bedrock. This research shows that the results of the physical and electrical properties of the soil indicate that the peatland that was burned in 2015 exhibited a recovery rate for eight years that was nearly identical to that of the unburned peatland. The peatland that was burned in 2019 and the peatland that was burned in 2015 and re-burned in 2019 exhibited a low recovery rate in comparison to the unburned peatland.

## 1. Introduction

Peatland is a wetland ecosystem where organic matter accumulates over a long period of time. Peat soils are usually waterlogged or flooded throughout the year. The process of decomposition of the organic matter accumulated over a long period of time with ash content ≥35%, depth ≥50 cm, and organic carbon content ≥12% (Lourenco et al., 2023; Osaki et al., 2016; Page and Baird, 2016). Peatlands are usually waterlogged or flooded throughout the year (Cole et al., 2022; Swails et al., 2018; Osaki and Tsuji, 2015). Tropical peatlands are ecosystems that play an important role in global carbon storage and cycling (Dadap et al., 2021; Cobb et al., 2020; Lawson et al., 2015). Tropical peatlands cover an estimated 441,025 km$^2$ (11%) of global peatland resources (Osaki and Tsuji, 2015; Kurnianto et al., 2015; Page et al., 2011).

The role of tropical peatlands in recent decades has been significantly reduced due to the experience of land use change, fires and the disruption of ecosystems and the global carbon cycle (Dadap et al., 2021; Vetrita and Cochrane, 2020; Page and Hooijer, 2016). Peatlands in Indonesia have been degraded by deforestation, drainage, fire and land conversion (Harrison et al., 2020; Dohong et al., 2018; Afriyanti et al., 2016). Degraded peatlands are more susceptible to fire (Kiely et al., 2021; Austin et al., 2019; Miettinen et al., 2016). Peatlands in Indonesia experienced severe fires in 2002 – 2018 caused by El Ninõ-Southern Oscillation (ENSO) and fires until 2019 were not influenced by El Ninõ (Hayasaka et al., 2020; Yulianti et al., 2020; Gaveau et al., 2014). Peatland conditions are also affected by global climate change related to greenhouse gas (GHG) emissions (Leng et al., 2019; Stockr et al., 2013). Fires on peatlands will result in reduced biodiversity (Syaufina and Hamzah, 2021; Agus et al., 2019; Glaves et al., 2013); carbon loss (Gray et al., 2021; Ingram et al., 2019; Kettridge et al., 2019; Uda et al., 2017); changes in soil physical and chemical properties (Wahyono et al., 2024; Wahyono et al., 2023; Arisanty et al., 2020; Agus et al., 2019); changes in hydrology (Thompson et al., 2019; Lukenbach et al., 2017; Brown et al., 2015) and resulting in more flammability (Noble et al., 2019).

The resistivity value of the subsurface layer can be estimated by measuring the potential difference value as geological parameters such as mineral and fluid content, porosity and water saturation in rocks. Geoelectric exploration techniques are widely used in environmental, engineering, hydrogeological and mining investigations (Loke et al., 2013; Loke et al., 2011; Telford et al., 1990). Geoelectric measurements based on the earth's resistivity value can describe lithological conditions, porosity, water content, mineral composition and type (Dahlin and Zhou, 2006); mineral composition, organic content and water conductivity in peat (Muhammad and Islami, 2020; Yusa et al., 2019; Kowalczyk et al., 2017). Research on subsurface structure and hydrology and hydrochemistry in peatland (Romero-Ruiz et al., 2022; Valois et al., 2021; Juandi and Islami, 2021); peat stratigraphy from probing, fluid chemistry and vegetation patterns in peatland (Nurmaisarah et al., 2023); and peat layer thickness (Zuhdi et al., 2019).

In this research, we aim to examine the peatland condition based on post-fires conditions in the areas that burned in 2015 and reoccurred in 2019 and compared with unburned condition. In particularly, we focused on the measurement of earth's electrical properties and soil physical properties in post-fire peatlands. The research location is in the Balangan River-Batangalai River KHG in Balangan County and conducted during the dry season. Measurement points in the area of no fire, fire in 2015, fire in 2019, and also fire in 2015 and fire again in 2019. Field measurements using the Wenner configuration geoelectric method with the smallest spacing of 10 cm to n = 12. Testing the physical properties of soil samples includes water content, Bulk Density (BD), fibre content, ash content and pH.

## 2. Materials and methods

This study was conducted in the peat hydrological unit of the Balangan River – Batangalai River in Balangan County, Indonesia. The study area consists of four conditions area that are natural areas with no fires, areas burned in 2015, areas burned in 2019 and lastly areas burned in 2015 and reoccurred in 2019 (Fig. 1).

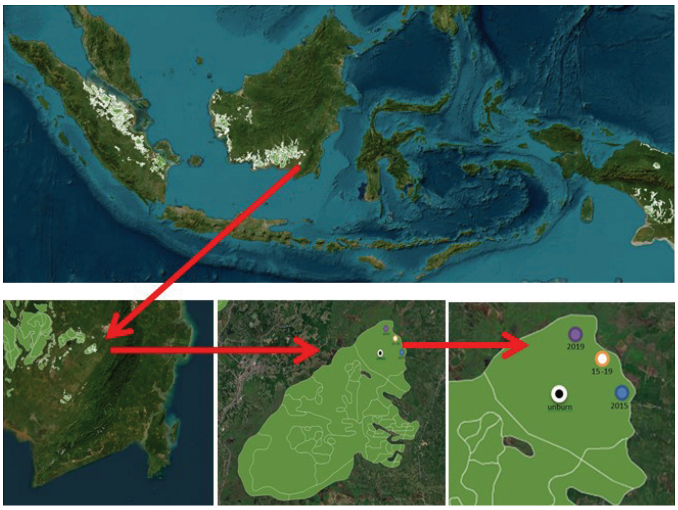


**Fig. 1.** Research location (BRGM RI, 2024)

Measurements and soil sampling from the research site in the dry season in September 2023. Starting from April-November 2023, Balangan County experienced low rainfall, because it was influenced by the strengthening of the La Nina phenomenon or cold phase, which is a phenomenon of cold sea surface temperatures above normal that occurs in the central Pacific Ocean, the opposite of El Nino (Arif, 2023). There is a negative anomaly in the southern part of Kalimantan, resulting in drier conditions (ASMC, 2023). The topography of the measurement area is at an altitude of 14–15 metres above sea level. The coordinates of the data collection site in the unburned area are –2.397336°S and 115.382125°E, the burned area in 2015 is –2.398951°S and 115.388029°E, the burned area in 2019 is –2.393788°S and 115.381203°E, and the burned area in 2015 and repeated in 2019 is –2.396386°S and 115.385059°E. The soil resistivity measurements carried out 2D subsurface mapping based on the electrical value of the earth and physical properties of soil samples. Soil samples were taken in each area at depths of 0–10, 10–20, 20–30, 30–40, and 40–50 cm. Soil physical properties tested included water content, BD, fibre content, ash content and pH.

Geo-electrical measurements used OYO McOHM 2119EL Resistivitimeter equipment and Wenner data collection configuration. Resistivity measurements with the smallest spacing of 5 cm, the largest spacing of 60 cm and a track length of 4 m. The geoelectric method studies the nature of electrical flow in the earth and detects it from the earth's surface.

The current flow pattern in the earth spreads in all directions in the form of a hemisphere that gets wider and deeper. The potential difference measured at the two MN points (Loke et al., 2011; Telford et al., 1990) is:

$$V_{MN} = \frac{i\rho}{2\pi}\left[\frac{1}{d_1} - \frac{1}{d_2} - \frac{1}{d_3} + \frac{1}{d_4}\right] \tag{1}$$

Where $V_{MN}$ = voltage between electrodes M and N (V)
$i$ = electric current (A)
$\rho$ = resistivity (Ωm)
$d_1$ = distance between electrodes A and M (m)
$d_2$ = distance between electrodes M and B (m)
$d_3$ = distance between electrodes N and B (m)
$d_4$ = distance between electrodes A and N (m)

The geometry factor for the Wenner electrode array (Fig. 2) is:

$$K_{wa} = 2\pi\left[\frac{1}{a} - \frac{1}{2a} - \frac{1}{2a} + \frac{1}{a}\right]^{-1} = 2\pi a \tag{2}$$

Where $K_{wa}$ = geometry factor for the Wenner electrode array (m)
$a$ = spacing between electrodes (m)

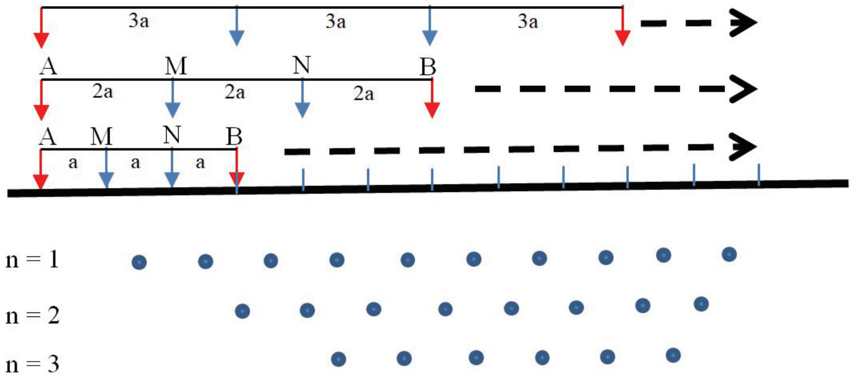


**Fig. 2.** Wenner 2D configuration data retrieval steps

So that the measured resistivity value is:

$$\rho = K_{wa}\frac{V}{i} \tag{3}$$

Where $\rho$ = apparent resistivity (Ωm)
$K_{wa}$ = geometry factor for the Wenner electrode array
$V$ = voltage between electrodes (V)
$i$ = electric current (A)

Equation (3) express the apparent resistivity, where the inversion of apparent resistivity is required to estimate the subsurface resistivity.

Physical properties such as BD, water content, fibre content and ash content based on American Standard Testing and Material (ASTM). BD testing is the weight of a mass of soil per unit volume (Walter et al., 2016; Hossain et al., 2015) with formulation (Antille et al., 2015; FAO, 2023):

$$BD = \frac{\text{dry soil mass (g)}}{\text{volume of cylinder (cm}^3)} \times 100 \tag{4}$$

Water content, the ratio between the weight of water and the weight of solid grains of the soil volume, calculation based on the formula (ASTM D 2216-98, 2019):

$$w = \left[\frac{(M_{CWS} - M_{CS})}{(M_{CS} - M_C)}\right] \times 100 = \frac{M_W}{M_S} \times 100 \tag{5}$$

with: $w$ : water content (%)
$M_{cws}$ : mass of container and wet specimen (g)
$M_{cs}$ : mass of container and oven dry specimen (g)
$M_c$ : mass of container (g)
$M_w$ : mass of water ($M_w = M_{cws} - M_{cs}$) (g)
$M_s$ : mass of solid particles ($M_s = M_{cs} - M_c$) (g)

The fibre content of peat soils is related to the compressibility of the soil. (Johari et al., 2016; ASTM D 1997-20, 2020). Fibre testing was done manually using a No.8 sieve (Khoerani et al., 2023).

Soil ash content is tested by gradually drying the soil sample by increasing the temperature to 440°C in an oven until the sample is completely reduced to ash. The formula for ash content is (ASTM D 2974-87, 2020):

$$Ash\ Content\ (\%) = \frac{(C \times 100)}{B} \tag{6}$$

with: $C$ : ash (g)
$B$ : oven-dried test specimen (g)

Testing the pH of soil suspended in water by dissolving 0.01 M calcium chloride, which is useful in determining the solubility of soil minerals and the mobility of ions in soil. The tests were carried out using pH sensitive paper in accordance with ASTM D 4972-19, 2021.

## 3. Results and discussion

The results of field measurement data processing the 2D geoelectric method Wenner configuration with the smallest spacing of 10 cm, 400 cm track length, and up to layer n = 12 in several conditions.

In Fig. 3, 2D cross-sectional model of soil resistivity value at the sampling point, the deeper the soil resistivity value gets smaller from 1244 Ωm to 329 Ωm, inversely proportional to the water content value from 142% to 215%. The data illustrates that the condition of the soil layer is wetter with decreasing resistivity value. This study was conducted during the dry season, so that

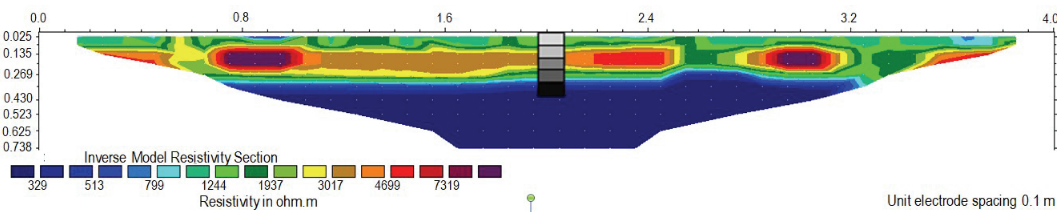


**Fig. 3.** 2D cross-sectional model based on resistivity values in peatland areas that did not experience fire

the conditions in areas that did not experience fires remained stable because the organic layer was still thick.

In Table 1, the BD value increases due to soil compaction, from 0.64 g cm$^{-3}$ to 1.35 g cm$^{-3}$. The fibre content value is getting smaller due to the change of fibre into soil; the fibre content value decreases from 7.74% to 6.33%. The ash content value decreases the deeper the value is because of the conversion of ash into soil; the ash content value decreases from 14.3% to 8.1%. Drainage of peatlands will cause the soil surface to subside and increase the ash content at the top caused by peat oxidation and $CO_2$ emissions (Krüger et al., 2015). The pH value decreases the deeper the value is due to the change of ash into soil, the pH value decreases from 5.6 to 4.5.

The Fig. 4 shows a 2D cross-sectional model of soil resistivity at the sampling point. The deeper the soil resistivity decreases from 1244 Ωm to 329 Ωm, inversely proportional to the water content, from 139% to 198%. The results demonstrate that the soil layer becomes wetter with decreasing resistivity. This research was conducted during the dry season so that the conditions in the areas that experienced fires in 2015 began to recover, but were not evenly distributed at every depth.

The Table 2 shows that BD increased due to soil compaction from 0.77 g cm$^{-3}$ to 1.41 g cm$^{-3}$. The fibre content lessens due to the change of fibre into soil, the fibre content decreased from 7.55% to 6.02%. The ash content value decreased due to the change of ash into soil, the ash content value decreases from 21.6% to 9.6%. The pH value reduced due to the conversion of ash into soil, the pH value decreases from 4.9 to 4.0.

In the post-fire area in 2015, the BD values were higher, the fibre content was lower, the ash content was greater, and the pH was smaller than in areas that did not experience fires.

The Fig. 5 demonstrates a 2D cross-sectional model of soil resistivity value at the sampling point. The figure indicates that soil resistivity value increase with depth from 1244 Ωm to 7319 Ωm and are inversely proportional to the water content value (from 138.62% to 82.84%). The data illustrates that the condition of the soil layer is becoming drier and denser, with reduced resistivity values. This research was conducted during the dry season; thus the condition of the area that experienced the 2019 fire was only 13.5 cm thick peat decomposition and the layer below was still bedrock.

The BD value in Table 3 increases with depth due to soil compaction from 0.81 g cm$^{-3}$ to 1.91 g cm$^{-3}$. The fibre content value is getting smaller due to the change of fibre into soil, the fibre content value decreases from 7.42% to 3.34%. The ash content value is decreasing due to the incorporation of ash into soil,

**Table 1**
Test results for resistivity value, water content, bulk density, fibre content, ash content and pH in peatland areas that did not experience fire

| Depth (cm) | Resistivity (Ω m) | Water Content (%) | Bulk Density (g cm$^{-3}$) | Fiber Content (%) | Ash Content (%) | pH |
|---|---|---|---|---|---|---|
| 0–10 | 1244 | 142 | 0.64 | 7.74 | 14.37 | 5.6 |
| 10–20 | 3017 | 156 | 1.13 | 7.22 | 11.2 | 5.6 |
| 20–30 | 1244 | 176 | 1.26 | 6.79 | 9.9 | 5.3 |
| 30–40 | 513 | 202 | 1.30 | 6.57 | 8.3 | 5.1 |
| 40–50 | 329 | 215 | 1.35 | 6.33 | 8.1 | 4.5 |

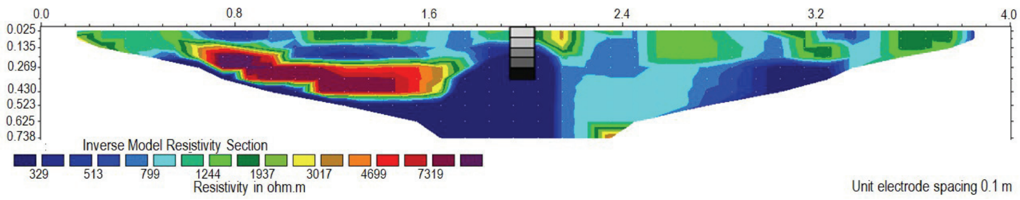


**Fig. 4.** 2D cross-sectional model based on resistivity values in peatland areas that experienced fires in 2015

**Table 2**
Test results for resistivity value, water content, bulk density, fibre content, ash content and pH in peatland areas that experienced fires in 2015

| Depth (cm) | Resistivity (Ω m) | Water Content (%) | Bulk Density (g cm$^{-3}$) | Fiber Content (%) | Ash Content (%) | pH |
|---|---|---|---|---|---|---|
| 0–10 | 1244 | 139 | 0.77 | 7.55 | 21.6 | 4.9 |
| 10–20 | 513 | 182 | 1.23 | 6.83 | 17.6 | 4.6 |
| 20–30 | 329 | 192 | 1.33 | 6.33 | 15.8 | 4.4 |
| 30–40 | 329 | 195 | 1.37 | 6.16 | 10.3 | 4.3 |
| 40–50 | 329 | 198 | 1.41 | 6.02 | 9.6 | 4.0 |

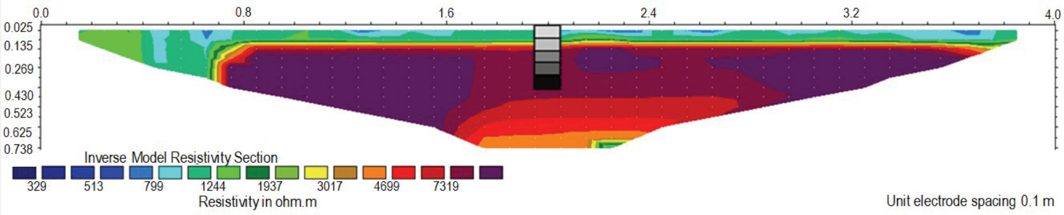


**Fig. 5.** 2D cross-sectional model based on resistivity values in peatland areas that experienced fires in 2019

**Table 3**
Test results for resistivity value, water content, bulk density, fibre content, ash content and pH of peatland areas that experienced fires in 2019

| Depth (cm) | Resistivity (Ω m) | Water Content (%) | Bulk Density (g cm⁻³) | Fiber Content (%) | Ash Content (%) | pH |
|---|---|---|---|---|---|---|
| 0–10 | 1244 | 138 | 0.81 | 7.42 | 30.4 | 4.7 |
| 10–20 | 4699 | 112 | 1.26 | 6.65 | 26.5 | 4.5 |
| 20–30 | 7319 | 92 | 1.55 | 4.38 | 21.2 | 4.3 |
| 30–40 | 7319 | 87 | 1.77 | 3.78 | 16.3 | 4.2 |
| 40–50 | 7319 | 82 | 1.91 | 3.34 | 11.7 | 3.6 |

falling from 30.4% to 11.7%. The pH value is getting smaller due to the introduction of ash into soil, where it has dropped from 4.7 to 3.6. The post-fire area in 2019 illustrates a higher BD value, less fibre content, more ash content and a lower pH than areas that did not experience fires and those that experienced fires in 2015.

The Fig. 6 is showing 2D cross-sectional model of the soil resistivity value at the sampling point. The deeper the soil resistivity value is the greater from 1244 Ωm to 7319 Ωm inversely proportional to the water content value 125% to 52%. The data illustrates that the condition of the soil layer becomes drier and denser with reduced resistivity values. This research was conducted during the dry season, so the condition of the area that experienced fires in 2015 and again in 2019 only had peat decomposition as thick as 10.0 cm and the layer below was still bedrock.

The Table 4 shows that the increased of BD value with depth due to soil compaction from 0.90 g $cm^{-3}$ to 1.98 g $cm^{-3}$. The fibre content value becomes smaller due to the change of fibre into soil, the fibre content value decreases from 7.21% to 2.88%. The

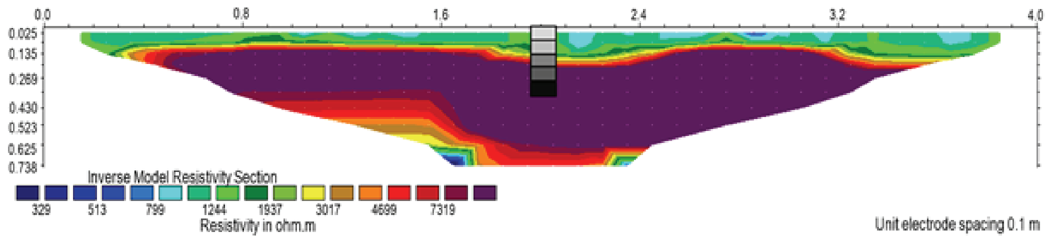


**Fig. 6.** 2D cross-sectional model based on resistivity values of peatland areas that experienced fires in 2015 and recurred in 2019

**Table 4**
Test results for resistivity value, water content, bulk density, fibre content, ash content and pH in peatland areas that experienced fires in 2015 and were repeated in 2019

| Depth (cm) | Resistivity (Ω m) | Water Content (%) | Bulk Density (g cm⁻³) | Fiber Content (%) | Ash Content (%) | pH |
|---|---|---|---|---|---|---|
| 0–10 | 1244 | 125 | 0.90 | 7.21 | 32.8 | 3.9 |
| 10–20 | 1987 | 98 | 1.35 | 6.48 | 28.9 | 3.8 |
| 20–30 | 7319 | 78 | 1.66 | 4.15 | 22.7 | 3.7 |
| 30–40 | 7319 | 65 | 1.80 | 3.33 | 19.1 | 3.7 |
| 40–50 | 7319 | 53 | 1.98 | 2.88 | 12.9 | 3.3 |

ash content value also decreases from 32.8% to 12.9% as ash is transformed into soil. Moreover, the pH value is decreasing due to the conversion of ash into soil, dropping from 3.9 to 3.3.

In the area (Fig. 6) after the 2015 fire and the 2019 reoccurrence, the BD value is larger, the fibre content is smaller, the ash content is larger, and the pH is smaller than in the unfire area, which was burned in 2015 and again in 2019.

The water content values in some conditions of the no-fire, post-fire in 2015, post-fire in 2019, and post-fire in 2015 and 2019 areas are shown in Fig. 7(a). The figure illustrates that the water content in the no-fire and post-fire areas in 2015 has increased at each depth, while the post-fire area in 2019 and post-fire areas in 2015 and 2019 areas have decreased. These conditions indicate that the organic matter content in the no-fire and post-fire in 2015 areas is thicker, allowing to maintain soil moisture levels during the dry season. In contrast, the organic matter content in the post-fire of 2019 and of 2015, and post-fire in 2019 areas remains thin, so the lower soil layer is dense mineral soil that is dry.

The Fig. 7(b) is a graph of BD values at each depth in the no-fire, post-fire in 2015, post-fire in 2019, and post-fire in both the 2015 and 2019 areas. The graph illustrates that the deeper the soil sample increases the BD value. The BD value in the no-fire and post-fire in 2015 areas increased less significantly than in the post-fire in 2019, and post fire in both 2015 and 2019 areas. Peat soils with higher BD values tend to behave like mineral soils. Non-degraded peat soils have BD values <0.1 g cm$^{-3}$, and will experience an increase in BD values after drought (Liu and Lennartz, 2019). BD values increase with depth and age due to decomposition and compression (Sandman, 2018).

The analysis of the relationship between water content and BD in the no-fire and post-fire in 2015 shows that water content increases along with BD. In the post-fire in 2019 and post-fire in both 2015 and 2019 areas, the water content decreased along with the increase in BD. According to Liu et al., (2022) the condition of good peatland is an increase in water content along with BD while the condition of degraded peatland is a decrease in water content along with an increase in BD.

The Fig. 7(c) illustrates the relationship graph of fibre content at each depth in the no-fire, post-fire in 2015, post-fire in 2019, and post-fire in both 2015 and 2019 areas. The figure illustrates that the deeper the soil sample, the lower the fibre content value. The fibre content value in the no-fire and post-fire in 2015 areas decreased less significantly than in the post-fire in 2019, and post-fire in the 2015 and 2019 areas. When compared to the soil/rock resistivity value, the post-fire in 2019 and post-fire in both 2015 and 2019 areas are bedrock/mineral soil, consequently the fibre content value is low. When compared to the BD value which increases with depth, the fibre content value is low in the post-fire in 2019 and post-fire in 2015 and 2019 areas. Older peat soils usually found in the lower layers tend to undergo further decay and have lower fibre content, smaller fibres and higher BD (Sandman, 2018).

The Fig. 7(d) illustrates the relationship graph of ash content at each depth in the no-fire, post-fire in 2015, post-fire in 2019 and post-fire in 2015 and 2019 areas which have decreased. The average ash content value in the post-fire in both the 2015 and 2019 regions is the highest, followed by post-fire in 2019, post-fire in 2015 and the lowest ash content value in the no-fire region. This shows that the post-fire in 2019 and post-fire in 2015 and 2019 areas still contain high ash content, indicating that the area is still degraded. A high ash content is an indication of degraded land. Ash content on land is influenced by current and past anthropogenic activities (Krüger et al., 2015). Peatlands are now in a worrying condition due to land use impacts, a suggested method of monitoring ash and carbon changes (Laiho and Pearson, 2016).

The Fig. 7(e) illustrates the pH relationship graph at each depth in the no-fire, post-fire in 2015, post-fire in 2019 and post-fire in 2015 and 2019 areas which have decreased. The average pH value in the post-fire in 2015 and in 2019 area is the lowest, followed by post-fire in 2019, post-fire in 2015 and the highest

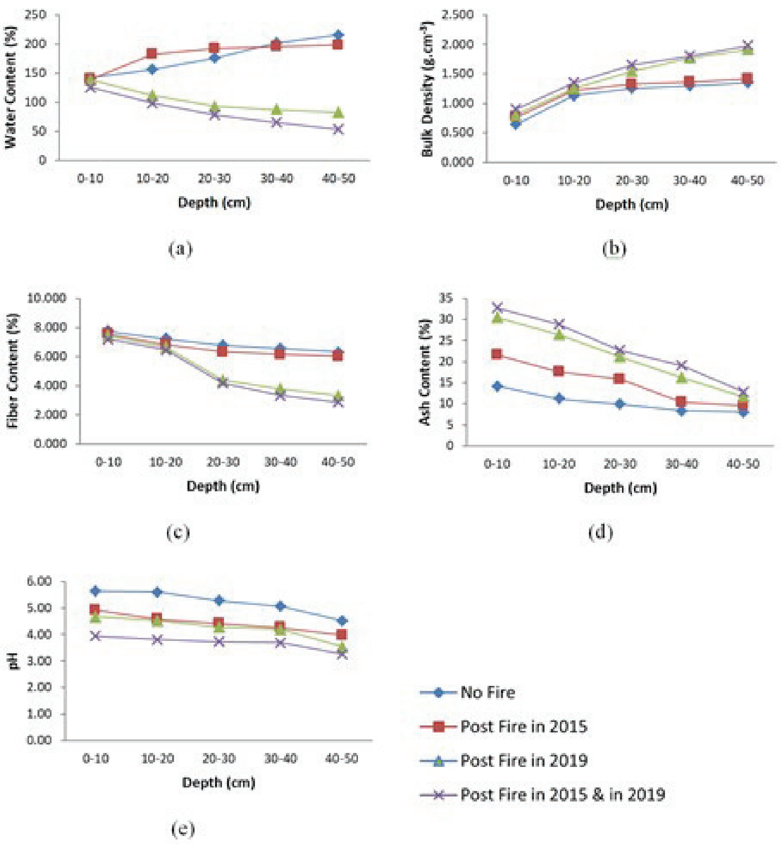


**Fig. 7.** (a) Graph of the relationship of water content versus depth, (b) Relationship graph of bulk density versus depth, (c) Relationship graph of fibre content versus depth, (d) Graph of ash content versus depth, (e) Graph of pH versus depth

pH value in the no-fire area. Natural peatlands are deposits of decomposed biomass. This situation inhibits the growth of decomposers due to poor nutrition and low pH (Anshari, 2010).

The identification results in the area not experiencing fires show that the soil resistivity value is getting smaller from 1244 Ωm to 329 Ωm inversely proportional to the water content value from 142% to 215%. The BD value from 0.64 g $cm^{-3}$ to 1.35 g $cm^{-3}$, fibre content value from 7.74% to 6.33%, ash content value from 14.3% to 8.1% and pH value decreased from 5.6 to 4.5. The data illustrates that the soil layer conditions are getting wetter with decreasing resistivity values. This condition indicates that the organic matter content is still thick, so that it can maintain soil moisture during the dry season.

In the burned area in 2015 the deeper soil is the smaller its soil resistivity value from 1244 Ωm to 329 Ωm and inversely proportional to the water content value from 139% to 198%. The BD value from 0.77 g $cm^{-3}$ to 1.41 g $cm^{-3}$, fibre content value from 7.55% to 6.02%, ash content value from 21.6% to 9.6% and pH value from 4.9 to 4.0. In the post-fire area in 2015, the values of BD were larger, fibre content was smaller, ash content was larger and pH was smaller compared to the area that did not experience fires. The data illustrates that the condition of the soil layer is getting wetter with reduced resistivity values. This research was conducted during the dry season, so the conditions in the area that experienced fires in 2015 have begun to recover, but they are still not evenly distributed at every depth.

In the 2019 burned area, the soil resistivity value at the sampling point, that the deeper the soil, the greater its resistivity value from 1244 Ωm to 7319 Ωm and inversely proportional to the water content value from 138.62% to 82.84%, BD value from 0.81 g $cm^{-3}$ to 1.91 g $cm^{-3}$, fibre content value from 7.42% to 3.34%, ash content value from 30.4% to 11.7% and pH value from 4.7 to 3.6. The data illustrates that the condition of the soil layer is getting drier and denser with decreasing resistivity value. This research was conducted during the dry season, so the condition of the area that experienced the 2019 fire was only 13.5 cm thick peat decomposition and the layer below was still bedrock. The post-fire area in 2019 showed greater BD, less fibre content, greater ash content and less pH than the area that did not experience fires and the area that experienced fires in 2015.

In the burned area in 2015 and repeated in 2019, the soil resistivity value at the sampling point was that the deeper the soil, the greater its resistivity value from 1244 Ωm to 7319 Ωm and inversely proportional to the water content value from 125% to 52%. The data illustrates that the condition of the soil layer is getting drier and denser with reduced resistivity values. This research was conducted during the dry season, so the condition of the area that experienced fires in 2015 and repeated in 2019 had only peat decomposition as thick as 10.0 cm and the layer below was still bedrock. BD value from 0.90 g $cm^{-3}$ to 1.98 g $cm^{-3}$, fibre content value from 7.21% to 2.88%, ash content value from 32.8% to 12.9% and pH value from 3.9 to 3.3. In this area, the BD value is larger, the fibre content is smaller, the ash content is larger and the pH is smaller compared to areas that did not experience fires, those that experienced fires in 2015 and fires in 2019.

Post-fire conditions will usually increase soil pH (Muqaddas et al., 2015), due to the high ash content of fire residues (Alcańiz et al., 2018), due to OH loss, complete oxidation of organic matter during fire, cation release and soil heating (Certini, 2005). The increase in soil pH values caused by residual fire ash is temporary (Marcotte et al., 2022). After rainfall, the nutrients will be dissolved through the canals around the peatland. The pH value of the soil 4 months after the fire will have decreased (Arisanty et al., 2020). For the post-fire condition of the study area after some time there will be rainfall, then the remaining ash and pyrite will be dissolved, resulting in a decrease in pH, ash content and fibre content.

Low soil/rock resistivity values indicate that the soil/rock layer has a higher water content (Hassan and Toll, 2015; Bhatt and Jain, 2014) which has a significant effect on soil BD (Liu, et al., 2022; Bertermann and Schwarz, 2018). The results of soil/rock electrical property measurements showed that the average rock resistivity value in the burned areas was higher than in the unburned areas. The test results of the BD parameter of the soil that experienced the fire had a higher value because the top layer of soil that was still in the process of decomposition was burned, so that the hard/dense soil layer occupied the top layer.

The analysis of variance (ANOVA) model for comparing soil sampling location and depth data with soil physical property test results uses the F-statistics (Chen et al., 2018) (Table 5 and Table 6). If the calculated F value of the sample is greater than the F distribution, it can be indicated that there is a difference between the two data being compared. If the p-value is less than alpha, it can also be known that there is a difference between the two data being compared. If the two compared data are different, then it is necessary to continue the test using the Tukey test, which represents data that are different (Nanda et al., 2021).

Statistical analysis of variance (ANOVA) was used to test the effect of site and soil depth on soil physical properties. Statistical analysis of resistivity and water content data between sites indicates that there is a significant difference with a p-value $<0.05$. Further Tukey's tests indicated that resistivity and water content values at unburned sites and sites burned in 2015 were statistically significantly different compared to sites burned in 2019 and sites burned in 2015 and burned again in 2019. Resistivity values at unburned sites and burned sites in 2015 show lower values and water content has a lower value, this statement means that the area is still in a wet condition, high nutrient content and describes a condition that is not degraded or has occurred land recovery. While statistical tests between depths show the resistivity and water content values tend to be the same.

Statistical analysis of BD data between depths showed significant differences with p-value $<0.05$. Further Tukey's test indicated that BD values at 0–10 and 10–20 cm depths were statistically significantly different from those at 20–30, 30–40, and 40–50 cm depths. BD values at 20–30, 30–40, and 40–50 cm showed higher values, indicating that the deeper the soil, the denser it is and the lower the porosity. Statistical tests of BD data between sites show the same trend.

The statistical analysis of the fibre content data against depth, it indicates the fibre content is significantly different between depths with a p-value $<0.05$. Further Tukey's tests showed that the fibre content at 0–10 cm depth was statistically significantly different from that at 10–20, 20–30, 30–40,

**Table 5**
ANOVA analysis variance

| Physical Property | Soil Sampling | df | F | p | |
|---|---|---|---|---|---|
| Resistivity | Location | 3 | 7.20961 | 0.00281 | ** |
| | Depth | 4 | 0.58117 | 0.68094 | |
| Water Content | Location | 3 | 17.90318 | 0.00002 | ** |
| | Depth | 4 | 0.00156 | 0.99999 | |
| Bulk Density | Location | 3 | 1.38731 | 0.28275 | |
| | Depth | 4 | 10.55199 | 0.00029 | ** |
| Fiber Content | Location | 3 | 2.86954 | 0.06908 | |
| | Depth | 4 | 3.82743 | 0.02449 | * |
| Ash Content | Location | 3 | 4.61328 | 0.01648 | * |
| | Depth | 4 | 3.21037 | 0.04313 | * |
| pH | Location | 3 | 14.82569 | 0.00007 | ** |
| | Depth | 4 | 1.20192 | 0.35054 | |

and 40–50 cm depths. The fibre content at 0–10 cm shows a higher value, indicating that the upper part is still in the process of decomposition of inorganic material. Statistical testing of the fibre content data between sites shows that the trend to be the same.

Meanwhile, based on the data of ash content versus location and depth, it can be concluded that ash content has a significant difference with p-value <0.05. Tukey's post hoc test indicates that ash content at unburned sites is statistically significantly different compared to sites burned in 2015, sites burned in 2019 and sites burned in 2015 and reburned in 2019. Further tests of ash content at a depth of 0–10 cm were statistically significantly different from those at depths of 10–20, 20–30, 30–40, and 40–50 cm. Ash content at the unburned site and at a depth of 0–10 cm showed a higher value, indicating that the upper part of the site is accumulating organic material.

Statistical data showed that pH values between locations had a significant difference with a p-value <0.05. Further tests using Tukey provided information that the pH value at the unburned site was statistically significantly different compared to the burned site in 2015, the burned site in 2019, and the burned site in 2015 and burned again in 2019. The pH value at the burned site shows a lower value, which means that the remaining ash from the burning has dissolved and the pyrite is getting closer to the soil surface.

The test results of peatlands soil resistivity and the physical properties of peatlands shows the condition of post-fire peatlands, whether they were burned in 2015, 2019 or burned in 2015 and repeated in 2019, compared to unburned peatlands. These results show the extent of recovery of post-burn peatlands compared to unburned peatlands.

The soil resistivity values show that in the unburned and burned peatlands in 2015, the thickness of the peat layer (low resistivity/weathered layer) reached a depth of >0.74 m, so the peat layer started to form as an accumulation of organic matter. For the peatland burned in 2019 and the peatland burned in 2015 and repeated in 2019, the depth of the peat layer based on the resistivity value is only 0.1 – 0.14 m, so the accumulation of nutrients is still shallow. From the soil electrical measurements, it can be assumed that the increase in resistivity is proportional to the decrease in moisture content.

The results of the moisture content test showed that the average moisture content of the unburned peatland was 178.2%, which was lower than the peatland that experienced fires in 2015, which was 181.2%. The average moisture content of the unburned peatland of 178.2% was higher than that of the peatland that burned in 2019, which was 102.2%, and the peatland that burned in 2019 and re-burned in 2019, which was 83.8%. These moisture levels indicate that the peatlands that were burned in 2015 have recovered to the same level as the unburned peatlands. The peatlands that burned in 2019 and the peatlands that burned in 2015 and reoccurred in 2019 are still degraded because the moisture content value is still low compared to the unburned peatlands.

The results of the mean BD test showed that the unburned peatland had a value of 1.14 g $cm^{-3}$, which was lower than the peatland that burned in 2015 with 1.22 g $cm^{-3}$, the peatland that burned in 2019 with 1.46 g $cm^{-3}$ and the peatland that burned in 2015 and reburned in 2019 with 1.54 g $cm^{-3}$. These BD values reflect soil porosity (Ezzati et al., 2012; Robinson et al., 2022), density (Reynolds et al., 2002; Ferreira et al., 2021) and strength (Kranz et al., 2020). Degraded peatlands after fire have low porosity, high density and high soil strength (Sinclair et al., 2020). This suggests that peatlands will recover with increasing moisture content and decreasing BD values (increasing porosity values), indicating that the nutrient layer is beginning to reform.

The results of the fibre content test showed that the average fibre content value of the unburned peatland was 6.93%, which was higher than the peatland that burned in 2015 (6.58%), the peatland that burned in 2019 (5.11%), and the peatland that burned in 2015 and burned again in 2019 (4.81%). The different fibre content values in each site show that the burned site has lower fibre content, reflecting the lower organic matter content and higher BD value.

**Table 6**
Multiple Comparisons

| Physical Property | Location | | Mean Difference | df | t | $p_{tukey}$ | |
|---|---|---|---|---|---|---|---|
| Resistivity | 1 | 2 | 720.6 | 16 | 0.53304 | 0.94973 | |
| | 1 | 3 | –4310.6 | 16 | –3.18861 | 0.02638 | * |
| | 1 | 4 | –3768.2 | 16 | –2.78739 | 0.05754 | |
| | 2 | 3 | –5031.2 | 16 | –3.72164 | 0.00903 | ** |
| | 2 | 4 | –4488.8 | 16 | –3.32042 | 0.02029 | * |
| | 3 | 4 | 542.4 | 16 | 0.40122 | 0.97739 | |
| Water Content | 1 | 2 | –3 | 16 | –0.17728 | 0.99794 | |
| | 1 | 3 | 76 | 16 | 4.49099 | 0.00189 | ** |
| | 1 | 4 | 94.4 | 16 | 5.57828 | 0.00022 | ** |
| | 2 | 3 | 79 | 16 | 4.66827 | 0.00132 | ** |
| | 2 | 4 | 97.4 | 16 | 5.75556 | 0.00016 | ** |
| | 3 | 4 | 18.4 | 16 | 1.08729 | 0.70198 | |
| Bulk Density | 1 | 2 | –0.4625 | 15 | –3.0427 | 0.05438 | |
| | 1 | 3 | –0.67 | 15 | –4.4078 | 0.00395 | ** |
| | 1 | 4 | –0.78 | 15 | –5.13147 | 0.00099 | ** |
| | 1 | 5 | –0.8825 | 15 | –5.8058 | 0.00029 | ** |
| | 2 | 3 | –0.2075 | 15 | –1.3651 | 0.65739 | |
| | 2 | 4 | –0.3175 | 15 | –2.08877 | 0.2745 | |
| | 2 | 5 | –0.42 | 15 | –2.7631 | 0.09045 | |
| | 3 | 4 | –0.11 | 15 | –0.72367 | 0.94766 | |
| | 3 | 5 | –0.2125 | 15 | –1.398 | 0.63804 | |
| | 4 | 5 | –0.1025 | 15 | –0.67433 | 0.95903 | |
| Fiber Content | 1 | 2 | 0.685 | 15 | 0.77429 | 0.93416 | |
| | 1 | 3 | 2.0675 | 15 | 2.337 | 0.18695 | |
| | 1 | 4 | 2.52 | 15 | 2.84848 | 0.0776 | |
| | 1 | 5 | 2.8375 | 15 | 3.20737 | 0.03997 | * |
| | 2 | 3 | 1.3825 | 15 | 1.56271 | 0.54097 | |
| | 2 | 4 | 1.835 | 15 | 2.07419 | 0.28046 | |
| | 2 | 5 | 2.1525 | 15 | 2.43308 | 0.15975 | |
| | 3 | 4 | 0.4525 | 15 | 0.51148 | 0.98489 | |
| | 3 | 5 | 0.77 | 15 | 0.87037 | 0.90334 | |
| | 4 | 5 | 0.3175 | 15 | 0.35889 | 0.99605 | |
| Ash Content | 1 | 2 | –4.606 | 16 | –1.186 | 0.64392 | |
| | 1 | 3 | –10.846 | 16 | –2.79273 | 0.05696 | |
| | 1 | 4 | –12.906 | 16 | –3.32316 | 0.02018 | * |
| | 2 | 3 | –6.24 | 16 | –1.60673 | 0.4027 | |
| | 2 | 4 | –8.3 | 16 | –2.13716 | 0.18362 | |
| | 3 | 4 | –2.06 | 16 | –0.53043 | 0.9504 | |
| pH | 1 | 2 | 0.78 | 16 | 3.34115 | 0.01946 | * |
| | 1 | 3 | 0.96 | 16 | 4.11219 | 0.00408 | ** |
| | 1 | 4 | 1.54 | 16 | 6.59664 | 0.00003 | ** |
| | 2 | 3 | 0.18 | 16 | 0.77104 | 0.86631 | |
| | 2 | 4 | 0.76 | 16 | 3.25548 | 0.0231 | * |
| | 3 | 4 | 0.58 | 16 | 2.48445 | 0.10084 | |

> 0.05 not significantly different
0.01 < p < 0.05 * significantly different
p < 0.01 ** very significantly different

The results of the ash content test showed that the average ash content value of the unburned peatland was 10.4%, which was lower than that of the peatland that was burned in 2015 (15.0%), the burned peatland in 2019 (21.2%), and the peatland that was burned in 2015 and reburned in 2019 (23.3%). Ash levels are higher in the burned sites than in the unburned sites, which is the residue of carbon released through the air and dissolved through groundwater and surface water from the decomposition of the burned peat.

The pH test results showed that the mean pH of the unburned peatland was 5.2, which was higher than the peatland burned in 2015 (4.4), the burned peatland in 2019 (4.3) and the peatland burned in 2015 and reburned in 2019 (3.7). The pH of peatlands decreases as the plant community changes from Sphagnum to shrubs due to the accumulation of sulphur and phenolics (Xue et al., 2023) and the post-fire pH is lower (Liu et al., 2023). In the case of fire, the plants are burned out, so the pH of the burned site is lower than that of the unburned peatland.

## 4. Conclusions

In 2015 and 2019, severe peatland fires occurred in the South Kalimantan region of Indonesia. The fires affected the physical condition of the soil. This study discusses the investigation of differences in soil conditions of natural areas that did not experience fires, burned areas in 2015, burned areas in 2019, and burned areas in 2015 and repeated in 2019. Soil resistivity, water content, BD, fibre content, ash content and pH were measured during the dry season. This study found that peatlands will recover with increasing moisture content and decreasing BD values (increasing porosity values), indicating that the nutrient layer is beginning to reform. From the results of the physical and electrical properties of the soil, it can be concluded that the peatland that was burned in 2015 had a recovery rate for 8 years that was almost similar to the unburned peatland. The peatland that was burned in 2019 and the peatland that was burned in 2015 and re-burned in 2019 still had a low recovery rate compared to the condition of the unburned peatland.

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## Author Contributions

**Sri Cahyo Wahyono** – Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Ahmad Kurnain** – Conceptualization, Data curation, Investigation, Methodology, Supervision, Validation, Visualization, Writing – review & editing. **Iryanti Fatyasari Nata** – Conceptualization, Investigation, Supervision, Validation, Visualization, Writing – review & editing. **Mufidah Asyari** – Data curation, Investigation, Methodology, Supervision, Validation, Visualization, Writing – review & editing.

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