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How Do Groundwater Levels and Soil Moisture Influence the Peat Fire Vulnerability Index in Oil Palm Plantations?

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Abstract

Peatland fires are a significant environmental issue, impacting local ecosystems and contributing to global climate change. This study evaluates the Peat Fire Vulnerability Index (PFVI) for sapric and hemic maturity levels under oil palm plantations in Pangkalan Pisang Village, Riau Province. Data on groundwater level, soil moisture, rainfall, and maximum temperature were collected from December 2021 to December 2022. The PFVI, modified from the Keetch-Byram Drought Index (KBDI), was calculated and correlated with these variables. The groundwater level varied from 3 cm to 76 cm below the surface, with an average of 36.23 cm. In sapric blocks, 29% of the groundwater level was less than 40 cm, while 73% were deeper. In hemic blocks, 44% were less than 40 cm, and 56% were deeper. Soil moisture in the top 10 cm layer fluctuated between 32% and 55% (v/v) Results showed significant negative correlations between PFVI and groundwater levels (r = -0.173 to -0.889) and soil moisture (r = -0.835 to -0.808), indicating that lower groundwater levels and soil moisture increase fire risk. High PFVI values in July corresponded with the lowest rainfall (59 mm) and groundwater levels below 40 cm. The study highlights the importance of monitoring hydrometeorological conditions and soil properties to effectively predict and mitigate peatland fires. Our findings are crucial for developing strategies to manage peatland sustainability and reduce fire hazards, especially in tropical regions with prevalent oil palm cultivation.

Keywords: early warning system, fire mitigation, hydrological, hemic, sapric

Introduction

Peatland fires pose a major threat to people, ecosystems, and economies locally and globally, causing short-term impacts such as health issues and disrupted livelihoods (Putra et al., 2020; Yulianti et al., 2020). These fires result in the degradation of environmental resources and ecosystems, such as the loss of flora and fauna, decrease in microbial biomass and activity, fungi usually decline more; reduction in soil quality by reducing total nitrogen (6%), cation exchange capacity (8%) and soil organic carbon (2%), and alteration of hydrological functions such as decrease water retention capacity by 1 to 12 % (Certini et al., 2021; Saharjo and Wasis, 2019; Sulaeman et al., 2021; Waddington et al., 2015). Additionally, peatland fires contribute to severe economic losses and environmental pollution through haze, which causes a decrease in air quality which impacts both Indonesia and neighboring countries and also has an impact on health (Hein et al., 2022a; Kiely et al., 2021; Mulyasih et al., 2022; Saharjo and Wasis, 2019). The release of greenhouse gases and particulates from these fires exacerbates climate change and air pollution (Kiely et al., 2021). Indonesia experienced large forest and peatland fires in 2015, covering an area of 2.6 million hectares, and is estimated to have released 1.74 gt CO_2-eq and 95% matter (PM2.5) (Saharjo and Novita, 2022).

Despite these challenges, peatlands in Indonesia have substantial potential for agricultural development, particularly for oil palm plantations. Approximately 18% of oil palm plantations in Indonesia are located on peatlands (Mulyani et al., 2019). However, the drainage required for these plantations artificially lowers the water table, causes subsidence, increases greenhouse gas emissions, and increases the risk of fire during dry seasons (Dadap et al., 2021; Harris et

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al., 2020; Hein et al., 2022b; Nurhayati et al., 2020, 2021; Word et al., 2022). Climate change further increases the vulnerability of these areas to fires in the future (IPCC Task Force on National Greenhouse Gas Inventories, 2014).

In peatlands, the physicochemical properties of the surface peat layer are influenced by the depth of the water table and the associated hydrological response. Changes in the depth of the water table can alter peat transpiration, evaporation and decomposition, which contribute to the variability of the surface peat moisture (Waddington et al., 2015). Peat is susceptible to fire when daily rainfall reaches a minimum value and the depth of the water table decreases sharply and causing the surface soil moisture to decrease from 0.90 $cm^3.cm^{-3}$ to 0.50 $cm^3.cm^{-3}$ (Adesiji et al., 2014; Putra et al., 2018; Wösten et al., 2008).

Efforts to mitigate peatland fires in Indonesia have been implemented through various strategies, including rewetting, reforestation, and sustainable land management practices. These efforts focus on rewetting degraded peatlands to raise the groundwater level, thus reducing fire risk and promoting the recovery of native vegetation (Saharjo and Novita, 2022; Yuwati et al., 2021).

Recent studies emphasize the critical need to understand the interactions between soil moisture and water table depth in predicting peatland fire vulnerability (Wösten et al., 2008) These interactions are significant in tropical peatlands, where seasonal fluctuations significantly impact fire (Taufik et al., 2015, 2022). Advanced modeling approaches and the integration of remote sensing data have enhanced our ability to monitor and predict these parameters accurately (Gaveau et al., 2014; Page and Hooijer, 2016). Consequently, more comprehensive fire risk assessment tools are being developed to incorporate these hydrological variables, improving fire management strategies (Fanin and Van Der Werf, 2017).

Peatland fires can be predicted using drought indices, such as the Standard Precipitation Index (SPI) and the Keetch-Byram Drought Index (KBDI), which utilize meteorological data, soil moisture, hydrology, and remote sensing (Ariyanto et al., 2020; Novitasari et al., 2019; Putra et al., 2019; Taufik et al., 2019). However, the traditional KBDI primarily relies on weather information (air temperature and rainfall) and may not fully capture the complexities of peatland hydrology. Modifications to KBDI, incorporating groundwater and soil hydrology information, aim to improve early fire warning systems for tropical peatlands(Taufik et al., 2022). This modified index, known as the Peat Fire Vulnerability Index (PFVI), has been tested in Jambi and West Kalimantan, yielding promising results (Lisnawati et al., 2022).

The primary objective of this study will be to assess the Peat Fire Vulnerability Index in capric and hemic maturity levels of peatlands under an oil palm plantation. Thus, it would help better understand peatland fire risk by estimating the correlation of PFVI with groundwater level and soil moisture. This research aims to fill the gap in informing and enhancing fire risk prediction and mitigation strategies concerning the role of hydro-meteorological factors in peatland vulnerability.

Material and Methods

Study Site

This study was conducted on a private oil palm plantation in Pangkalan Pisang Village, Koto Gasib Subdistrict, Siak Regency, Riau Province, located at 0°43’34.10” N and 101°45’33.40” E (Figure 1). The plantation covers an area of approximately 6,599 hectares, divided into 10 divisions and 247 blocks. Each block measures 300 × 1,000 meters with a planting density of 136 trees per hectare. Observations were made on two blocks representing sapric peat maturity and two blocks representing hemic peat maturity. The ecosystem studied is an oil palm plantation of the Tenera variety with various plant ages of 16 - 23 years.

Sampling Methods

The oil palm trees at the study site were planted in 2002. The site experiences an annual average temperature range of 24°C to 32°C and an annual average rainfall of 2000 to 3000 mm. The peak rainy season typically occurs in November and December, while the dry season spans from May to September and is characterized by lower but still significant rainfall.

Data collected from each research block included groundwater level, soil moisture, rainfall, and maximum temperature from December 2021 to December 2022. The instruments used were: 1) Water Level Logger (WLL) (HOBO U20L-40, USA), to measure and record changes in the Groundwater Table (GWT), 2) Micro Station (Hobo H21-002, USA), which is integrated with soil moisture and soil temperature sensors (Hobo S-SMC-005) to measure and record changes in soil moisture content, and 3) Automatic Weather Station (AWS) to measures and records microclimatic conditions (rainfall and

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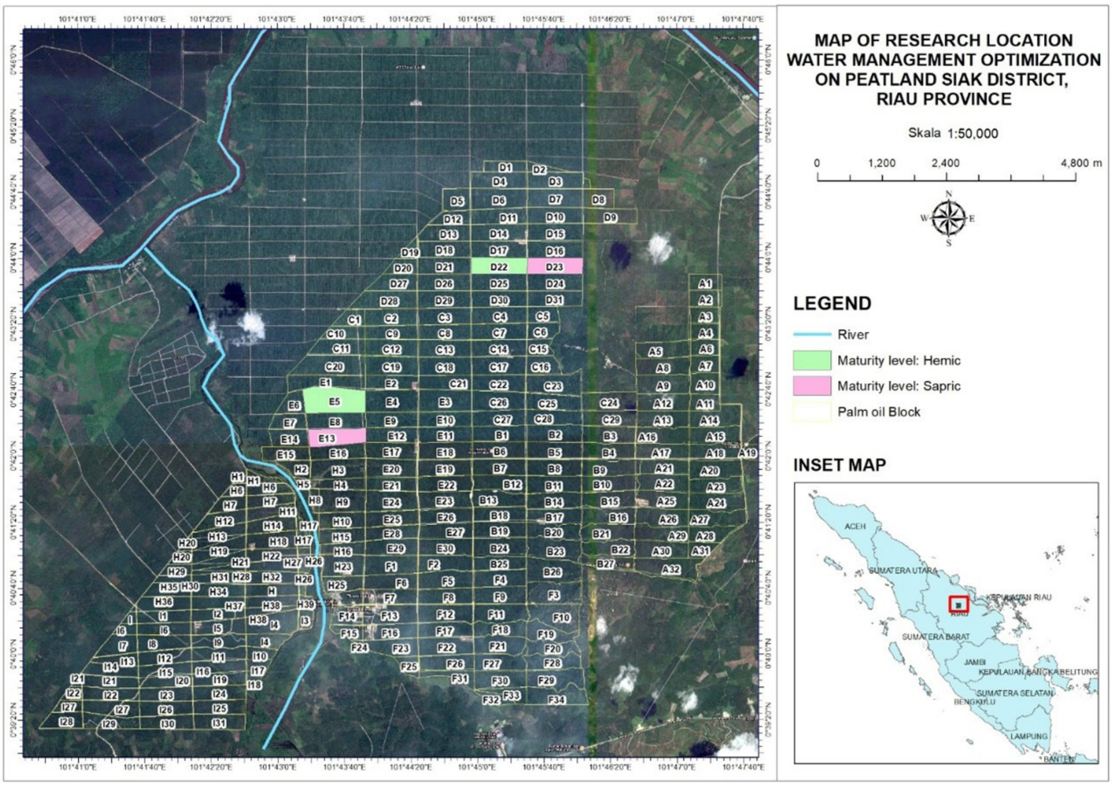

Figure 1. The research location at Pangkalan Pisang Village, Koto Gasib Sub District, Siak District Riau Province.

maximum temperature) at the research site. The AWS was located at 0°42›59.67»N and 101°45›21.05»E in the plantation.

Data for groundwater level, soil moisture, and microclimatic conditions were recorded every 30 minutes daily. Analysis of fire risk indicators required microclimatic data (rainfall and temperature) obtained from AWS recordings. Secondary data include peat characteristics, climate and oil palm productivity to describe the existing condition of oil palm plantation.

Statistical Analysis

Daily average groundwater level, soil moisture, and rainfall were calculated. Maximum temperature data were also collected daily. The Peat Fire Vulnerability Index (PFVI), a modification of the mKBDI (Taufik et al., 2022), was computed using the following equations:

$$\mathrm{PFVIt} = \mathrm{PFVIt} - 1 + \mathrm{DFt} - \mathrm{RFt} - \mathrm{WTFt} \qquad (1)$$

$$\mathrm{WTFt} = \mathrm{aH} - \mathrm{bH} \times [(1 - \theta(\mathrm{h})\mathrm{t}) \times 300] \qquad (2)$$

$$DF^{t}_{adj(Ro,ET)} = (300 - PFVI^{t-1})\frac{(0.4982\, e^{0.0905\, x\, Tm+1.6096}}{1+10.88\, e^{(-0,001736\, x\, R0)}} - 4{,}268)\, x10^{-3} \qquad (3)$$

where:
PFVIt is the vulnerable index value on day t
PFVIt−1 is the vulnerable index value on day t-1,
DFt is the drought factor
RFt is the rainfall on day t
WTFt is the groundwater level factor
aH is the maximum groundwater level factor
bH is the correction factor

PFVI values were categorized into four fire hazard levels as shown in Table 2 (Taufik et al., 2022). The collected data on rainfall, groundwater table depth, soil moisture, and PFVI values were visualized in graphs linking these variables.

Table 2. The percentage of vulnerability index criteria correlation and regression analyses, as well as t-tests, were conducted to examine the relationships between PFVI values and rainfall, groundwater table depth, and soil moisture using the following equations (Irfan et al., 2020):

$$\mathrm{Y} = \mathrm{a} + \mathrm{bx} \qquad (4)$$

$$a = \frac{(\Sigma y \Sigma x^2) - (\Sigma x \Sigma xy)}{N(\Sigma x^2)(\Sigma x)^2} \qquad (5)$$

$$b = \frac{N(\Sigma xy) - (\Sigma x \Sigma y)}{N(\Sigma x^2)(\Sigma x)^2} \qquad (6)$$

Where y is the dependent variable, x is the independent variable, a is the intercept, and b is the slope.
The correlation coefficient (r) was calculated using:

$$R_{xy} \frac{1}{N-1} \sum_{i=1} N \frac{(xi-x)-(yi-y)}{S_x S_y} \qquad (7)$$

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Where s_x and s_y are the standard deviation for each variable of (x,y), respectively

Results dan Discussions

Peatland Characteristics

Based on the Peat Soil Map at a 1:50,000 scale (BBSDLP, 2018), the research block representing the hemic maturity level is located on backswamp landforms or peat domes with flat relief (slope 0-1%). The soil-forming materials consist of organic matter and sediment deposits, such as clay, silt, and sand, creating peat soils with medium maturity and very deep depths ranging between 500 and less than 700 cm. In contrast, the research block representing the capric maturity level is situated on similar landforms with flat relief (slope 0-1%). It comprises identical soil-forming materials, producing sapric (mature) peat soils with medium depths between 100 and less than 200 cm.

Observation results indicate that the western side of the hemic peat representative block consists of very deep peat with depths greater than 400 cm, characterized by hemic (semi-mature) maturity and classified as Typic Haplohemists. In the central to eastern parts, the peat depth ranges from 218 to 236 cm, also showing hemic maturity and classified as Typic Haplohemists.

The southwestern sapric block has a maturity level classified as Typic Haplosaprist. The northeastern part features medium-depth peat with a depth of 108 cm and sapric maturity, also classified as Typic Haplosaprists. The western, central, and southeastern parts contain very deep peat with depths greater than 400 cm, characterized by semi-mature hemic maturity and classified as Typic Haplohemists. This block predominantly exhibits sapric maturity levels.

The physical characteristics of the soil show bulk density ranging from 0.09 to 0.15 g.cm^{-3}. Soil moisture content (w/w) at depths of 0-30 cm ranges from 205 to 405%, and at depths of 30-50 cm, it ranges from 461 to 474%. This density variation in the surface layer depends on the peat maturity level, ranging from 0.1 to 0.2 g.cm^{-3}.

Oil Palm Productivity

The productivity of oil palm plantations from 2015-2022 is presented in Figure 2. Oil palm Tenera variety productivity in the observed blocks was planted in 2000-2004. Productivity appears to be stable throughout the year without significant fluctuations. Productivity ranges between 20-22 tons.ha^{-1} per year for sapric maturity levels, while for hemic, productivity tends to be slightly higher, around 21-23 tons.ha^{-1} per year. Each year, hemic peatlands have higher productivity than sapric peatlands, with an average difference in productivity between sapric and hemic of around 1-2 tons.ha^{-1} per year. In 2016-2017, there was a decrease in productivity compared to 2015. It is suspected that this was due to the impact of El Niño in 2015. The impact of the El Nino event on palm oil production does not occur immediately but is visible 12-24 months later after drought stress occurs (Holepa and Safriyani, 2024). A strong El Nino event caused a decline in oil palm plantation productivity with a variation of 6-60. As a result, FFB productivity decreased by 11-16%, and CPO production decreased by 8-14% (Azlan et al., 2016; Darlan et al., 2016) Peak productivity occurred in 2018 when the plants were around 14 to 18 years old. In 2021-2022, productivity declined again as the plants were>20 years old.

Hydrometeorological Dynamics

From December 2021 to December 2022, the study area experienced 207 rainy days, with a total

Table 1. Peat fire vulnerability index (PFVI) value range based on fire hazard level

Fire hazard Level	PFVI value range
Low	0 -75
Moderate	76 -150
High	151 – 225
Extreme	225 – 300

Table 2. The percentage of vulnerability index criteria

Maturity Level	Low (%)	Moderate (%)	High (%)
Sapric	56.12	25.80	18.09
Hemic	56.38	26.06	17.55

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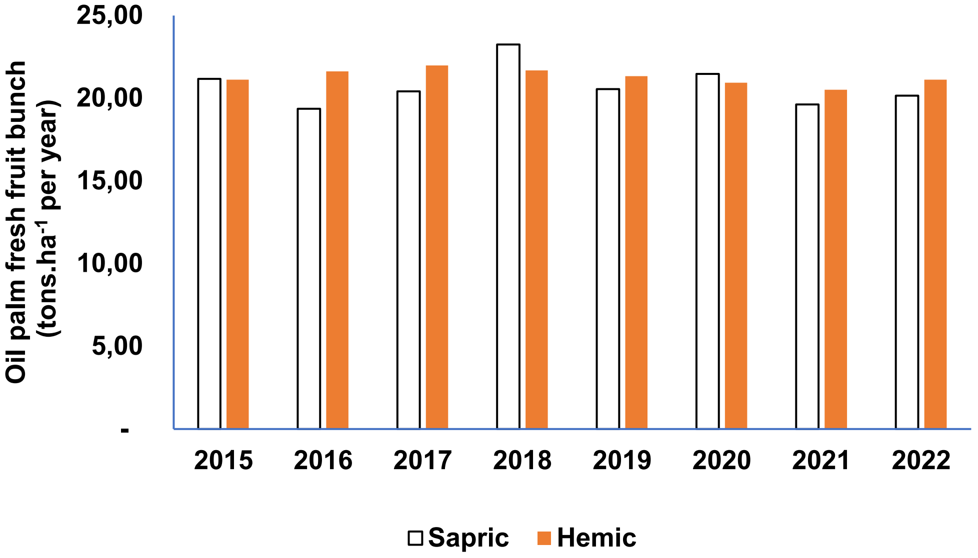

Figure 2. The yield of oil palm plantations in the research locations from 2015-2022.

rainfall of 2119.40 mm, averaging 5.92 mm per day. Throughout this period, all months were classified as wet months, except for July, which recorded a rainfall of 59 mm. The highest rainfall was recorded in October 2022, amounting to 369.80 mm. Based on average rainfall data from 115 BMKG stations across Indonesia, 2022 ranked as the second-wettest year since 1985. Nationally, the annual rainfall in 2022 was 122% of the normal level. Although the 2022 La Niña was of moderate intensity, its combination with various factors resulted in higher rainfall compared to 2010, which experienced a weak to moderate La Niña. The high rainfall throughout 2022 led to a generally shorter dry season compared to normal. Some regions, such as parts of Riau, Jambi, South Sumatra, and most of Kalimantan, did not experience a dry season due to consistently high monthly rainfall. The daily air temperature fluctuated between 23°C and 30°C, with an average of 27°C during observation. Even in the absence of rain, the average temperature was 27.69°C. Temperatures above 30°C were recorded only for 2 days in May throughout the year. According to the Köppen climate classification (Kottek et al., 2006), the study location, with a minimum temperature above 18°C and rainfall over 60 mm per month, falls under the Af climate type.

Groundwater levels varied during the observation period, ranging from near the surface (3 cm) to significantly below the surface (76 cm), with an average depth of 36.23 cm below the surface. In the research block with sapric maturity levels, only 29% of the groundwater level was less than 40 cm, while 73% of the depths were more than 40 cm. In the block with hemic maturity levels, 44% of the groundwater level was less than 40 cm, whereas 56% was more than 40 cm (Figure 3). Previous studies have suggested a critical groundwater level of 40 cm below the peat surface to prevent fires in already degraded drylands (Nugraha et al., 2017; Putra et al., 2016; Wösten et al., 2008). In an agricultural peatland with artificial drainage networks, the highly fluctuated water level dynamic was influenced by water loss due to seepage and groundwater flow rather than evapotranspiration (Kartiwa et al., 2023).

Peat soil moisture (volume/volume) monitored in the top 10 cm soil layer fluctuated from 32% to 55% (Figure 3). The lowest moisture level occurred during 13 days without rain. Soil moisture reached its highest condition above 55% in October, with the highest accumulated rainfall during the observation period. Soil water content is influenced by peat-forming material, peat maturity, and groundwater level (Nurzakiah et al., 2020)

Peat Fire Vulnerability Index (PFVI)

Figure 3 shows a graph of the relationship between rainfall, groundwater level, soil moisture, and PFVI during the observation blocks with sapric and hemic maturity levels. In general, the PFVI values during the observation period showed that from December 2021 to April 2022, it was in the low category, May – June 2022 was in the medium category, July - Early October 2022 was in the high category, and November-December2022 returned to the low category. A similar pattern was observed in both sapric and hemic peat, attributed to the similar physical characteristics of these peat types. PFVI tended to increase on average after 12 rain-free days or when rainfall was below 5 mm per day, with soil moisture reaching 46% - 48% (v/v). Peatland's vulnerability increased in July, with the lowest rainfall (59 mm) and a groundwater

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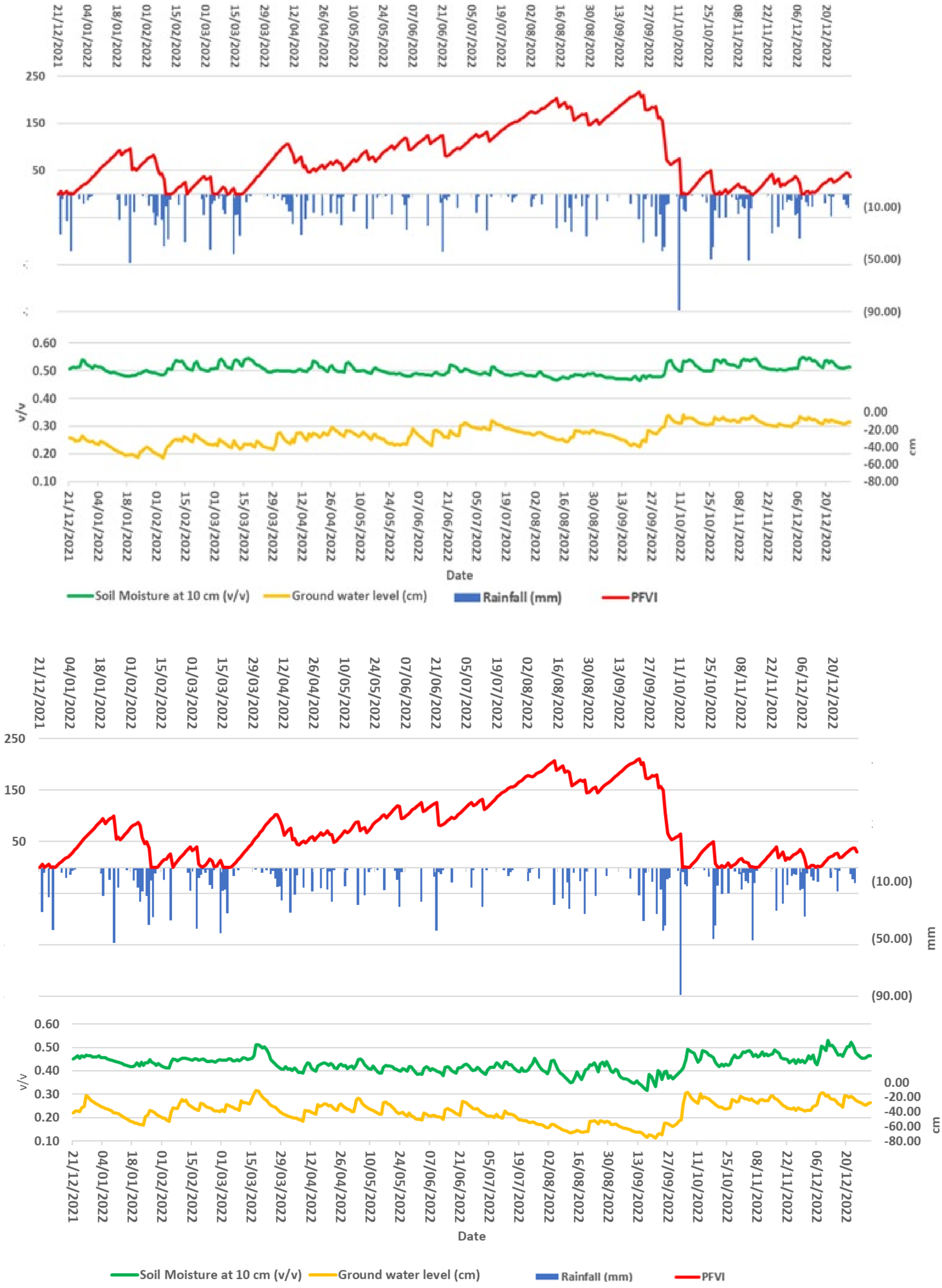

Figure 3. Rainfall, soil moisture, ground water level againts PFVI from Deember 2021 to December 2022 at sapric and hemic maturity levels.

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level below 40 cm. A shallow groundwater level can supply sufficient water to the surface layer, as high soil moisture indicates. This finding aligns with the research that found that a groundwater table near the soil surface enhances soil moisture in the root zone (Adesiji et al., 2014).

A deeper groundwater level in August and September 2022 contributed to the highest PFVI values observed during the study period. This was observed in both sapric and hemic peat blocks, although the groundwater level in the hemic peat block was lower than in the sapric block. Soil moisture in the hemic peat block fluctuated with the groundwater level, while in the sapric block, soil moisture was more stable. Sapric peat was better able to maintain groundwater level than hemic peat, which nearly reached a depth of 80 cm with the same rainfall volume. The capillary rise can supply water to the surface layer, playing a crucial role in maintaining the upper layer's moisture and preventing fires, including smoldering combustion (Taufik et al., 2022). Fire risk prediction cannot rely solely on groundwater level. Soil moisture may not necessarily be lower or drier at greater depths.

Deep groundwater levels are still correlated with high PFVI during the dry season. In March and October-December, when the groundwater level was near the surface (approximately 20 cm) and soil moisture was stable, low PFVI values were found. September exhibited a trend of deep groundwater levels due to low rainfall, with water lost to evaporation or drainage discharge, contributing little to raising the water table (Tarigan, 2011). In January-February, groundwater levels were below 40 cm, yet soil moisture remained around 50 % (v/v) for sapric and lower for hemic peat. PFVI values remained low despite the groundwater level exceeding 40 cm. This indicates that although the groundwater level fluctuates, soil moisture remains stable, keeping PFVI low. This stability is likely due to capillary water and root water uptake, which help to moisten the soil. The capillary water in the oil palm plantation could rise from about 50 - 76 cm (Adhi et al., 2020; Nugraha et al., 2017). Evapotranspiration, driven by maximum temperature, also influences capillarity. If surface soil moisture decreases due to evaporative water loss, it is replenished by capillaries. Groundcover plants and surface mulch can also maintain soil moisture.

In the sapric block, groundwater level and soil moisture were more stable despite fluctuating rainfall, whereas in the hemic block, these parameters were more variable. This is due to hemic peat's higher fiber content than capric peat, resulting in larger pores that cause faster water loss and lower groundwater levels. (Nugraha et al., 2017; Wösten et al., 2008).

During the observation period, the percentage of PFVI criteria is presented in Table 2. There was no significant difference between sapric and hemic maturity levels. This is because the characteristics of sapric and hemic in peatlands are not significantly different. There were 11 wet months during the observation period, so the peat vulnerability index was in the low to medium category. A high level of vulnerability was found in July, which had the lowest monthly CH accumulation during the observation period.

Significant negative correlations existed between PFVI, groundwater level, and soil moisture (Table 3). This means that increases in groundwater depth or soil moisture are associated with decreases in PFVI. The correlations are stronger in Hemic soils than sapric soils, indicating that changes in groundwater depth or soil moisture have a greater impact on PFVI in Hemic soils. The analysis of sapric peat maturity levels reveals that the correlation between the mean annual temperature (MAT) and the Peat Fire Vulnerability Index (PFVI) is notably weak. Consequently, the established MAT threshold of 40 cm as an indicator of peat fire vulnerability may not be reliable. In contrast, the correlation between soil moisture and PFVI is stronger, indicating that soil moisture thresholds should also be considered critical indicators of peat fire vulnerability.

It is essential to understand the critical groundwater level point where it can no longer sustain soil moisture through capillarity. Preventing peatland fires can be achieved by measuring a vulnerability index using parameters such as precipitation, groundwater level, soil moisture, and the duration of dry periods. Based

Table 3. Correlation analysis between groundwater depth and soil moisture with PFVI

Maturity Level	Variable 1	Variable 2	Correlation	P-value
Sapric	Groundwater level	PFVI	-0.173	0.001*
	Soil moisture	PFVI	-0.835	0.000*
Hemic	Groundwater level	PFVI	-0.889	0.000*
	Soil moisture	PFVI	-0.808	0.000*

Notes: * = significant according to t-test at α=0.05.

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on remote sensing, the variables that cause fires are successfully identified: the level of vegetation at the fire location, groundwater level, temperature, maturity of peat type, bulk rain, and fire duration (Kusuma et al., 2021.) Regular monitoring of precipitation, groundwater level, and their relationship to the groundwater level in channels is crucial. The depth of the groundwater level is particularly important as its critical threshold, beyond which it cannot supply surface soil moisture, can serve as a vital measure for peatland fire prevention (Kettridge et al., 2015; Page and Hooijer, 2016).

Conclusions

PFVI values show strong negative correlations with groundwater levels and soil moisture. Lower groundwater levels and reduced soil moisture significantly increase peatland fire risk. Seasonal variations in PFVI indicate higher fire risk during low rainfall and deep groundwater periods. Hemic peatlands, with higher fiber content and larger pores, exhibit more significant groundwater and soil moisture variability than sapric peatlands, making them more fire prone. This highlights the need for continuous monitoring, adaptive management, and soil-specific fire management practices.

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