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Peatland wetness as an indicator of fire occurrence in Forest and Land Fires (FLFs)

M. Bayu Rizky Prayoga[1], Mahawan Karuniasa[1], Evi Frimawaty[1*]
[1] *School of Environmental Science, University of Indonesia, Central Jakarta 10430, Indonesia.*
*Correspondence: evi.frimawaty11@ui.ac.id

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ABSTRACT

Background: Peatland ecosystems play an important role in the hydrological cycle and carbon cycling. In Indonesia, peatlands store about 28.6 gigatonnes of carbon which is equivalent to 10 years of global fossil fuel emissions. Peatlands act as a water storage during wet seasons and slowly release water during dry seasons to maintain river discharges and hydrological balance. However, climate change induced prolonged drought has increased peatland dryness in recent decades which elevate the risks of unwanted peatland fires. During El Nino-induced drought in 2015, over 2.6 million hectares of forest and land burned, emitting 0.81–1.4 gigatonnes of greenhouse gasses. The extreme fires damaged biodiversity, degraded water quality and displaced thousands of locals. This study aimed to analyze peatland wetness as an indicator of fire occurrences in forest and land fires (FLFs) in Riau, Indonesia by examining the relationship between degree of peatland wetness derived from satellite imagery and hotspots data. **Methods:** Peatland wetness was estimated from microwave backscattering coefficients at several RadarSat synthetic aperture radar (SAR) wavelengths and cross validated with water table depth measurements from 120 monitoring wells. Hotspots data between 2015-2020 were obtained from NASA's MODIS active fire product. **Findings:** Preliminary results showed significant negative correlations between peatland wetness and numbers of hotspots in peatlands, with more hotspots occurring in drier peatlands compared to wetter ones. This implies that maintaining peatland hydrological functions through continuous saturation is pivotal to prevent severe peatland wildfires under future climate change. **Conclusion:** Conservation efforts to restore hydrological balance in degraded peatlands through re-wetting strategies are recommended. Further research utilizing machine learning algorithms to produce high-resolution peatland wetness maps can improve fire risk monitoring in peatlands. **Novelty/Originality of this Study:** This study introduces the novel concept of utilizing peatland wetness as a key indicator for predicting and mitigating forest and land fires in Indonesia, particularly in Riau Province. By combining peatland moisture and temperature data, the research establishes threshold values to better predict fire risks and guide timely mitigation efforts, thereby enhancing the efficiency and effectiveness of FLF response activities.

KEYWORDS: early detection; forest land fires; hotspots; mitigation; peatland wetness.

1. Introduction

Indonesia is a country with extensive peatland areas, particularly in Sumatra and Kalimantan. These regions are prone to forest and land fires (FLFs), also known as karhutla (kebakaran hutan dan lahan). FLFs have become a recurring disaster in Indonesia, causing significant environmental, economic, and social impacts (Harrison et al., 2009; Purnomo et al., 2017). The primary contributors to FLFs in Indonesia are Sumatra and Kalimantan, where emissions of carbon and toxic gasses from haze originate (Huijnen et al., 2016).

FLFs frequently occur in provinces with vast peatland areas, such as Riau, Jambi, and South Sumatra in Sumatra, and West Kalimantan, Central Kalimantan, South Kalimantan, and East Kalimantan in Kalimantan (Glauber & Gunawan, 2015; Purnomo et al., 2017).

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Deforestation due to peatland burning contributes significantly to global greenhouse gas emissions, accounting for approximately 15% (Page et al., 2011; Austin et al., 2019). Despite recent efforts to reduce deforestation rates, the figures remain alarmingly high, positioning deforestation and peatland burning as the primary causes of greenhouse gas emissions in Indonesia (Palmer, 2001; Austin et al., 2019).

FLFs are highly dynamic disasters that can rapidly escalate and become challenging to control if mitigation actions are delayed. Widespread FLFs result in substantial material and environmental losses, including the destruction of forest and plantation ecosystems (Purnomo et al., 2017; Irfan et al., 2020). The haze generated from peatland fires has severe negative impacts on human health, economic activities, and transportation sectors, such as airport closures (Fujii et al., 2014; Tham et al., 2019; Lan et al., 2021).

Historical data from the National Disaster Management Agency (BNPB) indicates that Indonesia experiences at least 100 FLF incidents annually between 2014 and 2019 (BNPB, 2020). However, the frequency alone does not fully reflect the severity of the fires. The Ministry of Environment and Forestry/*Kementerian Lingkungan Hidup dan Kehutanan* (KLHK) calculates the extent of burned areas using satellite imagery analysis combined with hotspot data, ground-checking reports, and fire suppression efforts (Ministry of Environment and Forestry, 2020).

FLFs not only result in material and environmental losses but also contribute substantially to carbon dioxide emissions into the atmosphere. The Indonesian government reported losses of USD 5.2 billion due to FLFs in 2019 and USD 16.1 billion in 2015, which were the most significant FLF events in the last decade (BNPB, 2020). The direct impacts on communities include respiratory issues caused by haze, reduced mobility due to air pollution, and disruptions to economic activities. Additionally, FLFs lead to increased carbon emissions, vegetation destruction, and biodiversity loss, resulting in substantial environmental damage (Harrison et al., 2009; Glauber & Gunawan, 2015; Purnomo et al., 2017).

One of the Indonesian provinces routinely affected by FLFs is Riau, located on the island of Sumatra. Riau has the largest peatland area in Sumatra, covering 2.2 million hectares (CIFOR, 2020). In 2019, for example, 2,289 hotspots were detected in Riau, with an estimated burned area of 90,550 hectares (Ministry of Environment and Forestry, 2020). To address FLFs, the government has implemented various mitigation efforts, such as employing weather modification technology (TMC) to induce rainfall and water bombing. However, these efforts often face challenges due to the timing of implementation, which frequently occurs during peak dry seasons when hotspots and fire escalation are already high.

Effective FLF mitigation requires a comprehensive understanding of the physical characteristics of peatlands and their relationship with fire occurrence. One crucial factor is the wetness of peatlands, which can be measured through soil moisture and temperature (Huang & Rein, 2017; Restuccia et al., 2017; Stracher et al., 2015). Several studies have highlighted the importance of monitoring peatland wetness as an indicator of fire susceptibility (Wösten et al., 2008; Cochrane, 2015; Rein, 2016; Wilkinson et al., 2018; Goldstein et al., 2020). To address this issue, the government, in collaboration with private entities, has developed various instruments to monitor peatland conditions, such as the SIPALAGA system deployed by the Peatland Restoration and Mangrove Rehabilitation Agency in high-risk areas like Riau, Jambi, South Sumatra, West Kalimantan, Central Kalimantan, and South Kalimantan (BRGM, 2020).

Despite the availability of instruments for measuring weather and soil physical variables in peatlands, their use as decision-making tools for FLF mitigation remains suboptimal. One contributing factor is the lack of scientific references or threshold values for peatland wetness variables that indicate high fire risk. This limitation has led to delayed implementation of mitigation efforts, as evidenced by the significant FLF events in 2019, despite the availability of peatland monitoring data (BRGM, 2020). According to Carter (2008), effective disaster management involves three stages: pre-disaster, emergency, and post-disaster. The pre-disaster stage is crucial for successful mitigation efforts, as thorough planning can help reduce the adverse impacts of natural disasters. Therefore, studying the relationship between peatland wetness and fire occurrence is an important aspect of FLF pre-disaster mitigation.

By analyzing data from peatland monitoring instruments, including soil moisture, soil temperature, and rainfall, it is possible to establish threshold values that indicate when a peatland area is becoming dry and susceptible to fires. This information can guide decision-making processes and the determination of FLF emergency status, enabling more effective and efficient implementation of mitigation activities such as weather modification technology, water bombing, and other measures (BPPT, 2020). In this research, the author aims to investigate the relationship between peatland wetness and hotspot emergence, as well as stakeholders' perceptions regarding the utilization of peatland wetness monitoring data in FLF mitigation efforts. The findings can contribute to the development of a peatland wetness-based FLF mitigation concept, enhancing the efficiency and effectiveness of FLF response activities, particularly in determining the emergency status in Riau Province.

2. Methods

2.1 Research location and duration

The research area in this study is Riau Province, Indonesia. Riau Province is located in the central part of Sumatra Island, astronomically located at 100° - 104° East and 2° LU - 1°LS. Administratively, Riau Province borders the Strait of Malacca to the north, Riau Islands Province to the east, Jambi Province to the south, and West Sumatra and North Sumatra Provinces to the west. Riau Province has a fairly large peatland cover area of 2.2 million hectares (CIFOR, 2020).

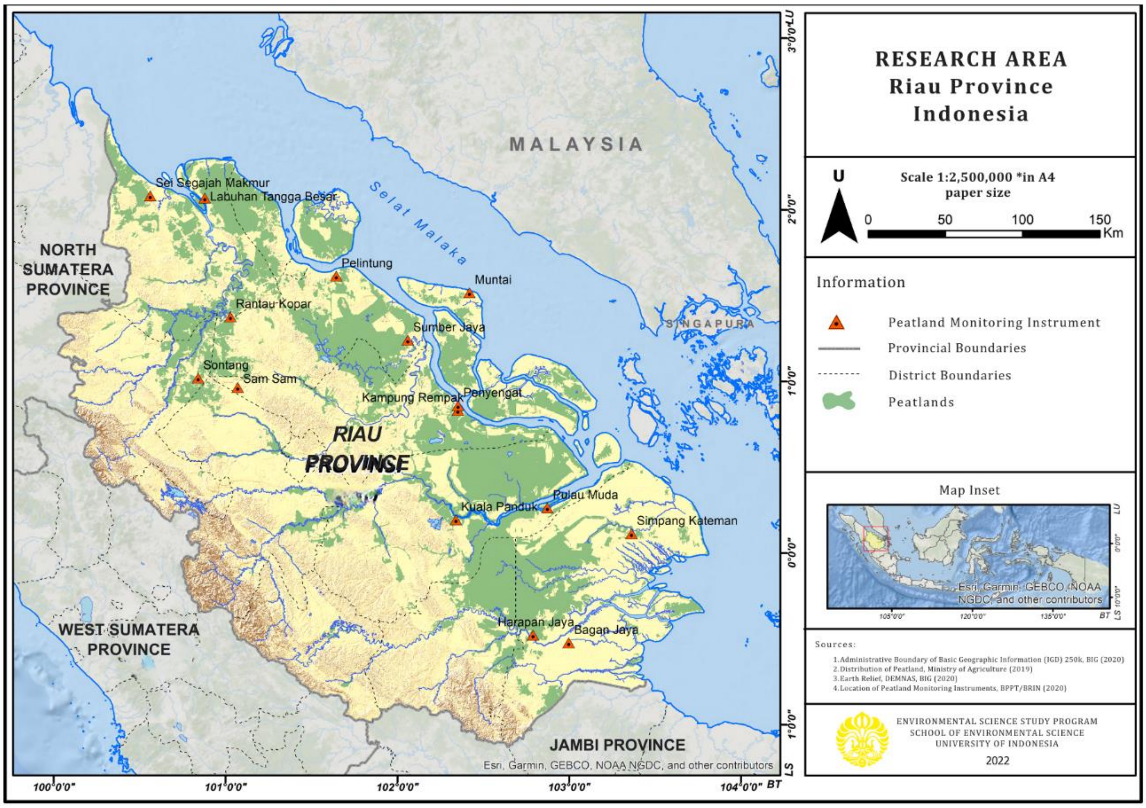

Fig. 1. Location map of the research area

The research area is one of the provinces in Indonesia that often experiences forest and land fires every year. Peatland cover in Riau Province is widely spread in the eastern coastal areas such as Rokan Hilir Regency, Bengkalis, Siak, Pelalawan, Indragiri Hilir, and parts of Dumai City. Forest fires that occur annually in Riau Province are however a major threat to the reduction of peatland cover in the region (Jefferson et al., 2020; Tacconi et al., 2019; Uda et al., 2020).

Based on terra/aqua MODIS satellite fire occurrence data, at least 2,289 hotspots were recorded in Riau Province in 2019 (Ministry of Environment and Forestry, 2020). Riau's position, which is relatively close to neighboring countries such as Malaysia and Singapore, allows forest fire smoke to be transported to these countries through wind factors (Wiggins et al., 2018; Tham et al., 2019). This makes Riau one of the most highlighted provinces in forest fire disaster mitigation efforts by the Indonesian government. As a form of early detection of forest and land fires, in recent years the Government has sought to further strengthen the monitoring aspects of peatlands in Riau Province. One of them is through the use of peatland physical monitoring instruments conducted by BRGM. The conditions in the research area represent the issues raised in this study. More details about the location of the research area are shown in Figure 1.

This research was conducted for 8 months, from January 2022 to August 2022. The stages carried out include collection, data collection in January-April 2022, data processing in May-June 2022, data analysis and interpretation in July-September 2022 as well as preparation into this research paper. This research uses a quantitative approach, quantitative methods are used to explain that peatland wetness can influence and be an indicator of the potential for forest and land fires. In general, the methods used in this research are statistical methods and spatial analysis, and are combined with qualitative methods to be able to conclude the results of data processing.

2.2 Research data and data analysis

The data used in this study are the results of measurements of research variables/sub-variables. The research data includes data on peatland wetness and hotspots. In general, research data undergoes stages of collection, processing, analysis, and interpretation to be able to help get research conclusions. Data collection on peatland wetness, which includes peatland moisture and temperature values, was obtained from the monitoring results of the Forest and Land Fire Management Information System/*Sistem Informasi Penanggulangan Kebakaran Lahan dan Hutan* (SIPALAGA) instrument in Riau Province during the 2019-2020 period. The SIPALAGA instrument used as a data source is an instrument that has been developed by BRGM and installed on peatlands in Riau Province. Peatland humidity and temperature are daily observation data at 15 points.

This study uses MODIS hotspot monitoring data for the 2019-2020 period in Riau Province which can be accessed on the Ministry of Environment and Forestry's Sipongi portal. Fire point data from the Terra/Aqua MODIS (Moderate Resolution Imaging Spectroradiometer) satellite has a confidence level that indicates the accuracy in comparison with fires in the field, namely: low confidence (<30%), medium confidence (30 - 80%), and high confidence (>80%) (Hantson et al., 2013). In order to get data that is closer to the actual fire occurrence, this research selects fire point data with high confidence. In order to obtain data that is closer to the actual fire occurrence, this research selects fire data with a degree of confidence ≥ 80%. There are many data sources that provide fire detection data from satellite monitoring. However, various data sources have their own limitations, especially if comparisons are made between fires detected by satellites and areas burned in actual conditions.

Several satellite fire detections such as AVHRR (Advanced Very High Resolution Radiometer), ATRS (Atmospheric Radiation Transfer Simulator), and TRMM VIRS (Tropical Rainfall Measuring Mission Visible and Infrared Scanner) have been described in several previous studies as having considerable bias in describing fire conditions on the ground (Nielsen et al., 2002; Amraoui et al., 2010; Arino et al., 2012). Apart from the algorithms used, the sensitivity of the thermal sensors from these satellites is also not very suitable for detecting fires that are close to reality (Hantson et al., 2015). By considering the results of several previous studies on the accuracy of fire detection, this study uses fire data sources observed by the Terra/Aqua MODIS satellite. The sensor design used by the Terra/Aqua MODIS satellite takes into account the experience of previous satellites by greatly increasing the number and sensitivity of thermal channels, which are currently the most widely used sensors for active fire detection (Krawchuk et al., 2009; Hantson et al., 2015; Kumari & Pandey, 2020). Validation of the accuracy of the Terra/Aqua MODIS satellite in detecting hotspots in various cases of forest fires in many regions of the world shows that fire observation data. MODIS can be relied upon to provide a picture of the presence and number of fires on the ground (Loepfe et al., 2012; Benali et al., 2016; Boschetti et al., 2016; Fusco et al., 2019).

Processing of observational data on rainfall, peatland moisture and temperature, and the number of hotspots in Riau Province was carried out using Microsoft Excel 365 and SPSS 26 software. Observational data on rainfall, peatland moisture and temperature are data in the order of hourly measurements. In this study, the peatland wetness observation data will be grouped into daily data, so that it has the same order as the hotspot data. The uniformity of the data order is done to help further data analysis. Analysis of the peatland wetness data is carried out by looking at how strong the relationship between rainfall and fluctuations in peatland moisture and temperature in Riau Province is through cross-correlation techniques to determine the time lag between these variables. Furthermore, the relationship between land wetness and the occurrence of hotspots will also be analyzed by looking at the statistical correlation results between peatland moisture and temperature on the number and distribution of hotspots in Riau Province. The results of the analysis will be visualized in the form of graphs, diagrams, and interpolated maps to assist in interpretation.

Correlation analysis of peatland wetness on the occurrence of hotspots a correlation test was conducted to determine the relationship between the level of peatland wetness and the escalation of the number of hotspots in Riau Province during the 2019-2020 period. The correlation test will be conducted using the Pearson correlation and cross-correlation test methods using SPSS 26 and Microsoft Excel 365 software. The results of the correlation test can show how much peatland wetness indicates the occurrence of hotspots and their time lag.

The spatial distribution of hotspots will be processed using the Kernel Point Density technique using ArcGIS 10.8 into a density map to facilitate descriptive analysis of the number and pattern of occurrence. Kernel Density is principally an interpolation technique that defines a constant smoothing parameter that remains the same throughout the study area and ensures equal weighting of observation points in areas with different degrees of density (Worton, 1989; Bajocco et al., 2017). Mathematically, the formula used to calculate density in the Kernel Density technique is shown in Equation 1, where n is number of points, h is smoothing parameter/bandwidth, K is Kernel density function, x is coordinate vector specifying the location where the function is estimated, and Xi is coordinate vector specifying each observation.

$$f(x) = \frac{1}{nh^2} \sum_{i=1}^{n} K \left\{ \frac{(x - X_i)}{h} \right\} \quad \text{(Eq. 1)}$$

The use of the Kernel Density technique has been widely used to visualize multi-scale spatial variations in the frequency of point-based observations, such as the distribution of hotspots in forest fires. In the study of forest fires, the Kernel Density technique has also been used to represent and obtain maps of fire ignition density. Knowing the fire density makes it easier to integrate it with other types of spatially explicit data, such as rainfall, to estimate drivers, geographic trends, and environmental effects (Amatulli et al., 2007; Gonzalez-Olabarria et al., 2012; Koutsias et al., 2016). In this study, the results of the fire density analysis will be further used to interpret its relationship with peatland wetness and formulate mitigation concepts.

3. Results and Discussion

3.1 Analysis of peatland wetness and fire occurrence

Before analyzing peatland wetness and fire occurrence, a weighting exercise was conducted to categorize the values of each of the peatland moisture and temperature sub-variables. Peatland wetness at each observation station was defined based on a combination of both values (humidity and temperature). The peatland moisture and temperature categories were divided based on fluctuations in values during the period 2019 to 2020. The division was also done by observing the difference in values during the dry and wet months.

Table 1. Peatland Moisture Categories

Humidity percentage	Category	Code
<25%	Not Humid	1
25-50%	Just Moist	2
>50%	Moist	3

Based on the monthly average value of peatland moisture, the author defines peatland moisture values into three categories. The three categories are divided based on fluctuations in moisture values during the dry months and wet months. The three classes of peatland moisture are not humid (humidity<25%), just moist (25-50%), and moist (>50%), as shown in Table 1 and Figure 2.

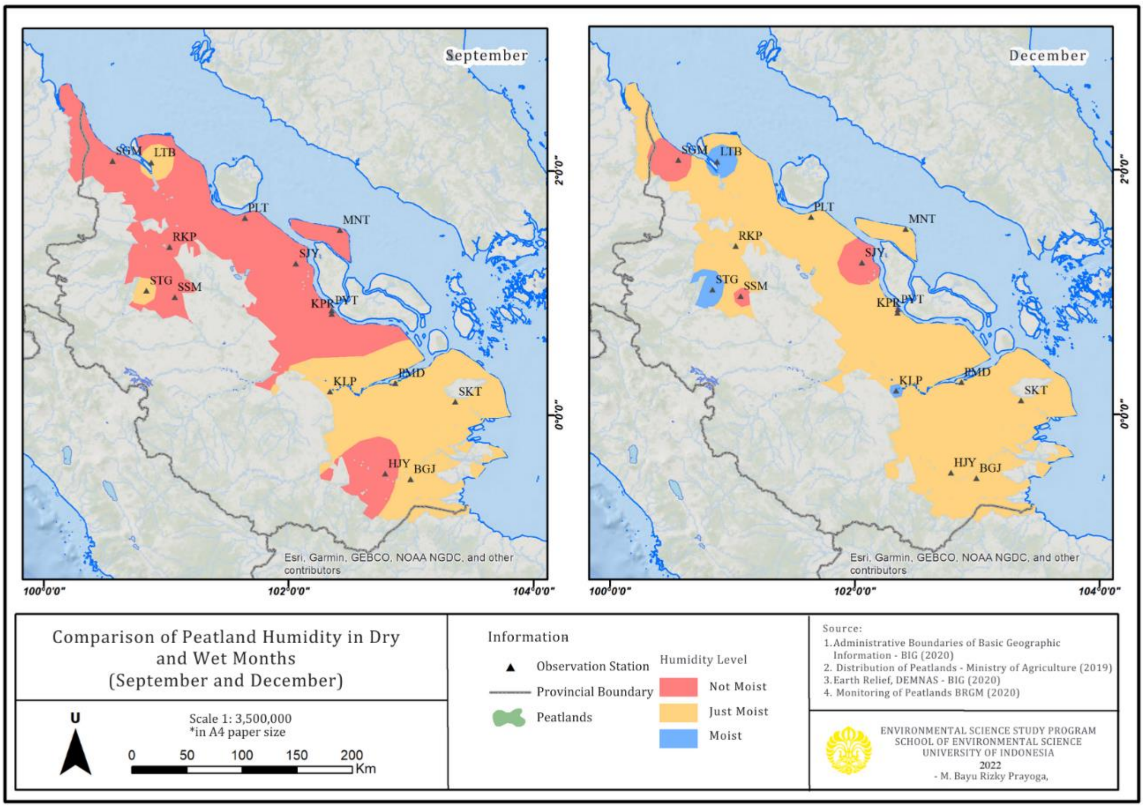

Fig. 2. Comparison of peatland humidity in dry and wet months

Similar categorization was also done for the peatland temperature data. Based on the monthly average values at all stations, the author defined the peatland temperature values into three categories. The three categories are divided based on fluctuations in peatland temperature values during the dry months and wet months. The three classes of peatland temperature are cold (<27.5°C), medium (27.5-29.5°C), and hot (>29.5°C), as shown in Table 2.

Table 2. Peatland Temperature Categories

Temperature value	Category	Code
<27,5 °C	Cold	3
27.5-29,5 °C	Medium	2
>29,5°C	Hot	1

To help see the differences in peatland temperature values spatially, Figure 3 is an example of the results of spatial analysis to compare peatland temperature values in the dry and wet month periods. In the dry month example, the peatland temperature category is dominated by the medium and hot categories. The hot peatland temperature category is generally distributed in the northern and eastern parts of the study area. Meanwhile, in the wet month, December, almost all areas in the study area fall into the medium peatland temperature category. In fact, some observation stations and surrounding areas show a temperature category in the cold category.

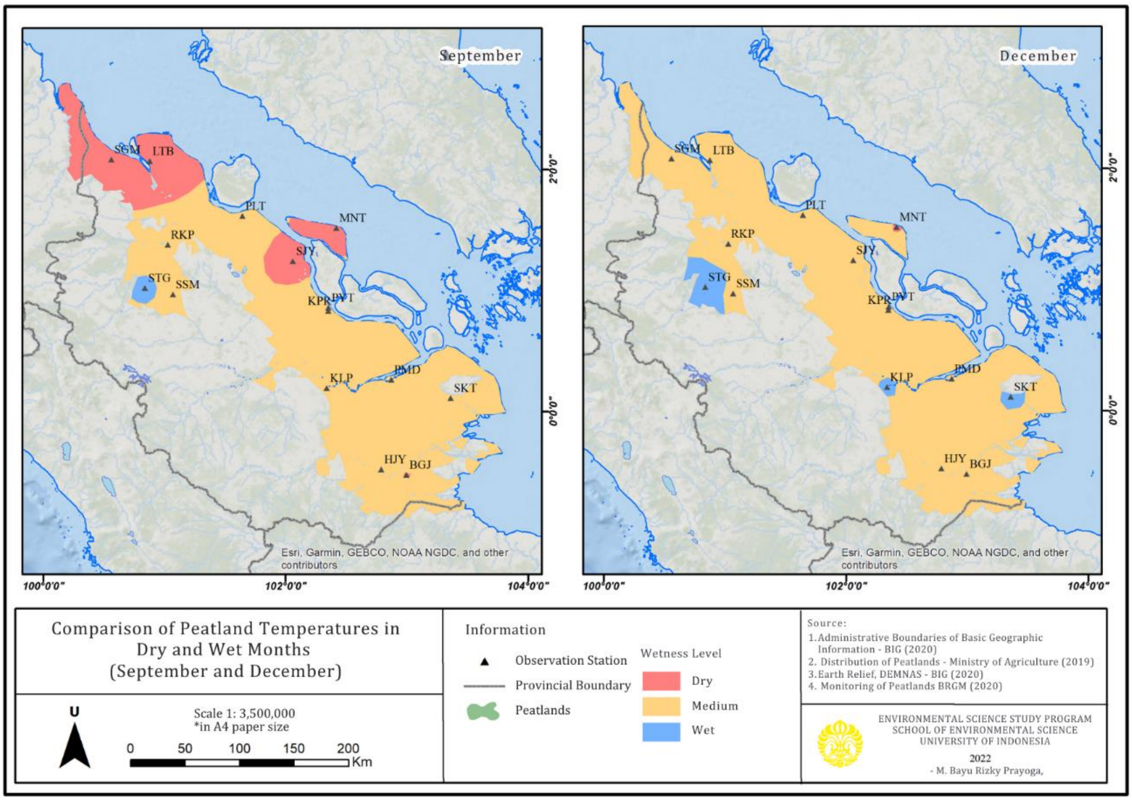

Fig. 3. Comparison of peatland temperatures in dry and wet months

Peatland wetness is defined by the combined values of the peatland moisture and temperature categories, as previously explained. The determination of the peatland wetness category value is derived from the sum of the peatland moisture and temperature values, as can be seen in Figure 4. The summation of these values was carried out through spatial analysis in ArcGIS 10.8 by calculating the total per-pixel value of the interpolated spatial data of the peatland moisture and temperature sub-variables in monthly time order and then overlapping them to obtain the spatial data of peatland wetness. Then, to facilitate interpretation and narration of the analysis results, the summed values of humidity and temperature were categorized into several classes. The peatland wetness category is divided into three classes, namely dry (values 2-3), moderate (value 4) and wet (values 5-6).

The analysis of peatland wetness and its relationship to the occurrence of fire hotspots in Riau Province, Indonesia, has been a crucial aspect of understanding the environmental dynamics of the region. In order to gain a comprehensive understanding of this relationship, a thorough examination of the tabular and spatial data of peatland wetness was conducted, followed by the selection of monthly hotspot data for the 2019-2020 period. The selection of hotspot data was a critical step in the analysis process, as it allowed for the isolation of fire hotspots that were specifically within the boundaries of the study area. This step was necessary due to the limited number and distribution of peatland monitoring observation stations used in the study, which meant that the interpolated area of the peatland physical data could not be generalized to all parts of Riau Province. By extracting the hotspots using the Clip method in ArcMap 10.8 software, a monthly distribution of hotspots within the study area was obtained, providing a focused dataset for further analysis.

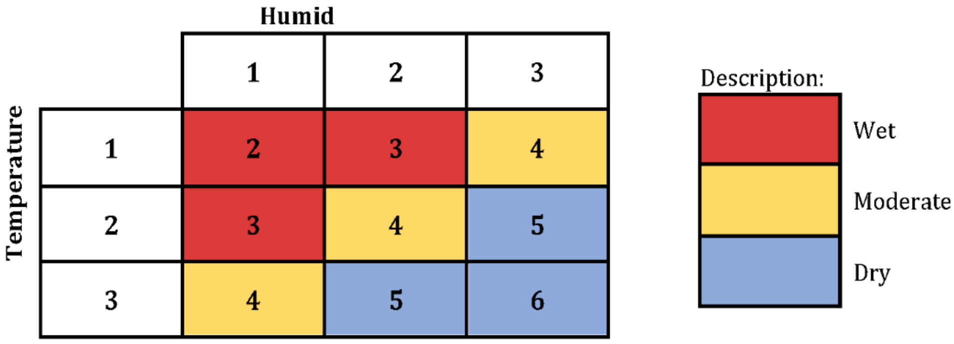

Fig. 4. Matrix for determining peatland wetness value

The interpretation of the processed spatial data was the foundation for the analysis of peatland wetness and its indication of hotspot occurrence. Figure 5, a map illustrating the peatland wetness and fire occurrence during the dry month period in 2019, provided a clear spatial representation of the relationship between these two factors. Upon examination, it became evident that areas with a high peatland wetness category (Dry) exhibited a more concentrated presence of hotspots compared to areas classified as Medium or Wet. This observation strongly suggests that the drier the peatland wetness in the study area, the higher the likelihood of hotspot occurrence.

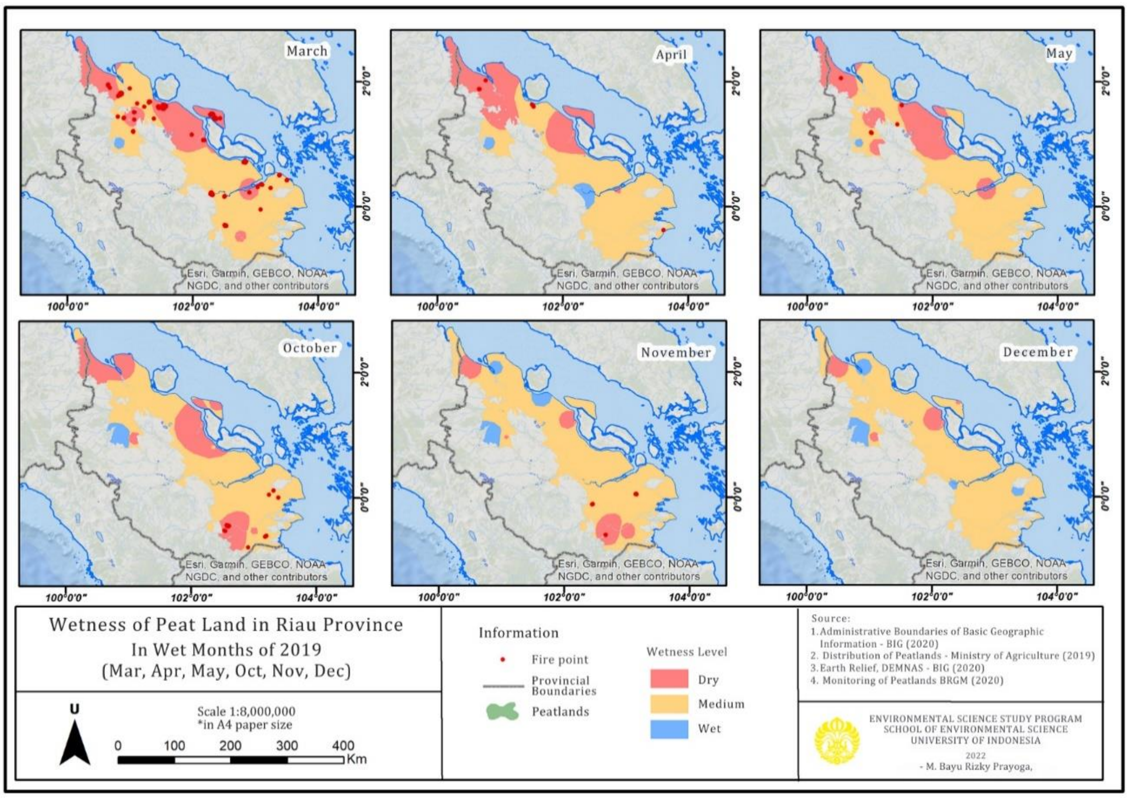

Fig. 5. Peatland wetness and fire spots distribution in the dry month period of 2019

The implications of this finding are significant, as it highlights the importance of monitoring and managing peatland wetness in order to mitigate the risk of fire outbreaks. Peatlands are known to be highly flammable when dry, and the accumulation of organic matter in these ecosystems can fuel intense and prolonged fires. The concentration of hotspots in areas with dry peatland wetness underscores the need for proactive measures to maintain adequate moisture levels and prevent the desiccation of these sensitive environments.

During the dry months of 2019, the number of hotspots tended to peak in August and September. This condition is associated with the wider distribution of peatland wetness category in the Dry category in these months compared to other months during the dry season in the study area. The results of the spatial analysis in Fig. 5 also indicate that although January and February are dry months, the escalation and distribution of hotspots are not as high as in the June-July-August-September period. August-September. In the June-July-August-September period, the direction of peatland wetness in the Dry category has a pattern of spreading from a small area in the north (in June), and then spreading to the south in a larger area in July-August-September.

Meanwhile, the results of the spatial analysis of peatland wetness during the wet months of 2019 show lower wetness values than during the dry months. During the March-April-May and October-November-December periods, which are synonymous with higher rainfall, the majority of areas in the study area were in the Medium category of peatland wetness. Even in October-November-December, some areas such as in the West and parts of the North show peatland wetness in the Wet category. This can be attributed to the minimal number of hotspots during these periods. In 2019, the highest concentration of hotspots during the wet months was in March, with the majority of hotspots concentrated in the North. This may be due to the fact that, given the rainfall pattern in the study area, March is a transitional period after experiencing dry conditions in January and February.

Meanwhile, during the wet month period in 2020, the level of peatland wetness in the Wet category is increasingly identified, especially in October-November-December. In addition, the number of hotspots also tends to be very minimal, and in some months such as May, November and December, no hotspots were identified in the study area. Although in March and April there were some areas that still showed a degree of peatland wetness in the Dry category, there were not as many hotspots as in 2019 during the same months. The dominance of areas with Wet peatland wetness categories was mostly distributed in the North and South in November-December, while other areas were in the Moderate category with a minimal number of hotspots.

3.2 Discussion

Peat ecosystems play an important role in ecology and are estimated to store carbon reserves of up to 104.7 gigatons (Dargie et al., 2017). In addition to environmental value, peatlands also have economic functions, as emphasized by Uda et al. (2017). The area of peatlands in Southeast Asia is a major asset, with an area of 247,778 km^2 storing around 68.5 gigatons of carbon (Page et al., 2011). However, forest and land fires have caused a very significant decrease in the area of peatlands in this region, including Indonesia. Miettinen et al. (2016) stated that one of the causes of the drastic decrease in the area of peatlands is the factor of forest and land fires. Other research by Miettinen & Liew (2010) identified that the main cause of fires on peatlands in Sumatra and Kalimantan was land clearing for use as Industrial Plantation Forest/Plantations. In addition to natural factors, the role of humans, both individually and collectively, also contributes to forest and land fires (Irfan et al., 2020; Purnomo et al., 2017).

The unique and different characteristics of peat from mineral soil make monitoring the physical parameters of peatlands very important. This research is supported by Verry et al. (2011), which states that peatlands can store water reaching 300-3,000% of their dry weight, a figure that far exceeds mineral soil in general. In Southeast Asia, including Indonesia, rainfall factors and subsurface conditions of peat (groundwater, humidity, and temperature) play an important role in changing the physical conditions of peatlands (Fahmi et al., 2015; Page et al., 2009). According to Field et al. (2016), forest and land fires in Indonesia have become increasingly concerning in the last three decades, and these fires have an impact on the carbon emissions produced. Huijnen et al. (2016) explained that Sumatra and Kalimantan are regions in Indonesia that contribute to carbon emissions and toxic gases from forest and land fire smoke. Agus et al. (2012) added that the loss of carbon content from peatlands is caused by the phenomenon of land subsidence and fires. Fires on peatlands also have long-term effects, where Masganti et al. (2014) explained that burning peatlands will accelerate the formation of mineral soil layers that are poor in nutrients, making it difficult to plant.

Fires that occur on peatlands have the potential to be difficult to extinguish due to the peat smouldering phenomenon. Cochrane (2015) explained that these fires can occur below the surface, making the spread of fire very difficult to detect. Rein (2016) further explained that peat smouldering is a slow, low-temperature, surface-free combustion of porous fuels, and is the most persistent combustion phenomenon. According to Wilkinson et al. (2018), fires that occur on the surface of peatlands can easily ignite fires in deeper layers of up to more than 50 cm, which is influenced by the level of peatland moisture. Goldstein et al. (2020) explained that peatland drought, both on the surface and deeper layers, greatly affects the peat smouldering phenomenon.

There is a change in fire patterns when viewed from the physical condition of the burned peatlands. Research by Usman et al. (2015) shows that peatland fires on the island of Sumatra during 2002-2013 occurred mostly on peatlands with a depth of 100-200 cm (moderate depth). However, starting in 2013, there has been a tendency for peatland fires to occur at depths in the very deep peat category (>400 cm). Riau Province is one of the provinces with a large peatland area. Yananto et al. (2017) through their research provides a spatial overview that areas with high levels of vulnerability to forest and land fires in Riau Province are concentrated in Bengkalis, Indragiri Hilir, and Pelalawan Regencies.

The analysis of how peatland wetness is an indicator of fire occurrence in this subchapter explains that there are differences that can be observed in the 2019 and 2020 conditions. This is due to the value of monthly rainfall in both years. As discussed in the previous section, monthly rainfall variations throughout 2019 are in the range of 57-273 mm/month, while 2020 has a range of 75-300 mm/month. Fluctuations in rainfall in both years contributed to the different conditions and patterns of peatland wetness, which have been discussed in this subchapter. However, through spatial analysis, it can be explained that at least in 2019 the pattern of peatland wetness can be an indicator of fire occurrence, through the spatial correspondence of fire concentrations and peatland wetness category classes, especially during the dry period.

Just like other disasters, forest and land fires in Indonesia are a challenge that must be addressed through various approaches. In sustainable development, the importance of disaster mitigation is seen as a form of protecting the survival of living things and the environment on this earth, especially since many disasters actually occur due to interventions from human activities (Goto & Picanço, 2021; Monte et al., 2021; Rana et al., 2021). Therefore, the importance of understanding disasters, including risk reduction, is important so that disaster risk prevention and management efforts, which are important points in the disaster mitigation framework, can be achieved (Kusumastuti et al., 2021; Ogra et al., 2021). This section explains the further elaboration of the findings of this research on previous studies as well as theoretical reflections. In addition, in this section the research results will be synthesized with the rules of Environmental Science.

This section explains the further elaboration of the findings of this research on previous studies as well as theoretical reflections. In addition, in this section, the research results will be synthesized with the principles of Environmental Science and aspects of sustainability in relation to the research theme. As a hydrometeorological disaster, forest and land fires have several variables that influence them. The characteristics of areas that often burn when forest and land fires occur in Indonesia are dominated by peatland cover, making it a threat to the ecological function of peat. In addition to damaging ecological functions, forest and land fires in peatlands also have an impact on socio-economic aspects considering that many human activities are empowered on peatlands (Dargie et al., 2017; Uda et al., 2017). The importance of observing peatland variables cannot be separated from the characteristics of peat soil itself. The porosity of peat and its ability to absorb water maximally in wet conditions and then release it in dry conditions make peat soil like a sponge. In addition, peat soil is formed due to the accumulation of organic matter, making it loaded with 'fuel' which will very easily spread fire. This phenomenon is often called peat smoldering, which is very difficult to extinguish once a fire below the peat surface has occurred (Cochrane, 2015; Goldstein et al., 2020). Therefore, in the context of mitigating forest and land fires, especially in peatlands, in addition to the importance of looking at historical weather parameters, it is also necessary to observe the physical conditions of the peat measured directly under the peat soil itself, such as humidity and temperature (Bonn et al., 2016; Wilkinson et al., 2018).

The results of the peatland wetness analysis in this study show that peatland wetness can be an indication of fire occurrence. This is shown by the tendency for the concentration of observed hotspots in Riau Province to be in peatland areas with a Dry peatland wetness category. Based on these findings, the second hypothesis of this research is also accepted. In disaster mitigation activities, the importance of early detection and preparedness is often the key to success in reducing potential disaster risks. Monitoring peatland wetness, which can be used as an indicator in early detection and strengthening disaster preparedness, is also in accordance with several previous studies (Miettinen et al., 2017; Evans et al., 2019). The results of this study are also in line with research conducted in Aguilera et al. (2016) which explains that wetness conditions in wetlands and peatlands can spatially indicate the potential for fire occurrence. In another study conducted by Yananto et al. (2022), also revealed that peatland wetness, one of which is measured through peatland moisture, is able to provide information on potential forest and land fire areas in Riau Province. The study also used satellite data to help complement the data from physical observations of peatlands measured directly. The results of the study, which show that peatland wetness as measured by peatland moisture and temperature can be used as an indicator of hotspots, can also be used as a complement in the review of peat ecosystem governance, especially in observing physical conditions other than only measured by groundwater level, as described in the Minister of Environment and Forestry Regulation 15/2017.

4. Conclusions

Based on the results and discussions conducted in this study, the conclusion that can be drawn is that the wetness of peatland can be represented by the values of moisture and temperature, which can be used to analyze the potential for forest and land fires. Peatland wetness can be used as an indicator in detecting the potential occurrence of fire hotspots. Peatland wetness in the Dry to Moderate categories is associated with high concentrations of fire hotspots in the study area spatially, especially during dry months. Further analysis is needed to distinguish peatland wetness in years with dry and wet rainfall characteristics. This is useful for studying how peatland wetness varies under different meteorological conditions influenced by regional phenomena, such as ENSO and IOD conditions. Peatland wetness in the Dry to Moderate categories is associated with high concentrations of fire hotspots in the study area spatially, especially during dry months.

A longer data set is needed to explain this study. Peatland wetness-based forest and land fire mitigation is an effort to reduce the risk of forest and land fires through the utilization of monitoring results that include peatland wetness values to enhance preparedness by involving relevant stakeholders, including government groups, the private sector, and the community. Analysis with a larger number of peatland observation stations will result in findings that can explain in more detail the spatial characteristics of peatland wetness.

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Author Contribution

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Biographies of Authors

M. Bayu Rizky Prayoga, Master student at Environmental Sciences, Universitas Indonesia.

- Email: prayoga.mbay@gmail.com
- ORCID: 0000-0002-5027-470X
- Web of Science ResearcherID: N/A
- Scopus Author ID: 57204825392
- Homepage: https://scholar.google.com/citations?user=n2xzuNMAAAAJ

Mahawan Karuniasa, Lecturer at School of Environmental Sciences, Universitas Indonesia.

- Email: mahawan.karuniasa11@ui.ac.id
- ORCID: 0000-0001-6444-6560
- Web of Science ResearcherID: N/A
- Scopus Author ID: 57205022900
- Homepage: https://scholar.ui.ac.id/en/persons/mahawan-karuniasa

Evi Frimawaty, Lecturer at School of Environmental Sciences, Universitas Indonesia.

- Email: evi.frimawaty11@ui.ac.id
- ORCID: 0000-0002-9016-4062
- Web of Science ResearcherID: N/A
- Scopus Author ID: 8128517300
- Homepage: https://scholar.ui.ac.id/en/persons/evi-frimawaty