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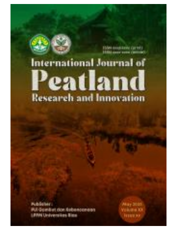

Spatio-Temporal Analysis of Meteorological Drought Index and Peat Fires Using Google Earth Engine (GEE) in Pelalawan Regency, Riau

Enji Wijaya Sukma[1], Rinaldi[1], Sigit Sutikno[1,2*]

1. Department of Civil Engineering, Faculty of Engineering, Universitas Riau, Indonesia
2. Center for Peatland and Disaster Studies (CPDS), Universitas Riau, Indonesia

Corresponding author: *sigit.sutikno@lecturer.unri.ac.id*

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ABSTRACT

Peatland ecosystems in Indonesia, particularly in Riau Province, are highly vulnerable to meteorological drought, which exacerbates the frequency and severity of peat fires. This study employs the Standardized Precipitation Index (SPI) to assess drought conditions in Pelalawan Regency (Riau Province) over 2012–2023 and examines their relationship with peatland fire occurrences. Google Earth Engine (GEE) was utilized for large-scale analysis, integrating high-resolution precipitation datasets from TRMM/GPM and fire hotspot data from NASA's FIRMS to evaluate drought trends over different timescales. SPI values were calculated on a monthly scale and correlated with the distribution and timing of fire hotspots. The results revealed a strong inverse relationship (r = -0.75) between SPI values and fire occurrences, indicating that severe drought episodes (SPI < -1.5) often precede major fire events by approximately 1–2 months. Fire hotspots were spatially clustered in peat-dominated areas with recurrent drought conditions, particularly in degraded peatlands and plantation zones, highlighting these regions' heightened vulnerability. By leveraging cloud-based geospatial analysis, this research demonstrates an enhanced capacity for real-time drought monitoring and early fire risk warning.

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1. Introduction

Peatlands are vital carbon sinks and hydrological regulators, storing approximately 30–40% of global soil organic carbon while covering only around 3% of the Earth's land surface [1]. However, these ecosystems are highly sensitive to climate variability and human-induced disturbances. Climate-driven drought events can desiccate peat soils and increase wildfire frequency [2], and anthropogenic pressures such as deforestation, peatland drainage, and land conversion have greatly exacerbated peat fire susceptibility in Southeast Asia [3]. Meteorological drought, defined as a prolonged precipitation deficit, lowers peatland water tables and dries out the peat profile, thereby significantly increasing the likelihood of peat fire occurrences [4]. In tropical regions like Indonesia, severe and extended dry spells (often associated with El Niño events) have contributed to massive peatland fires, leading to widespread environmental degradation, transboundary haze pollution, and substantial economic losses [5].

Drought indices are essential tools for quantifying precipitation anomalies and monitoring drought conditions. The Standardized Precipitation Index (SPI) has emerged as a widely accepted metric due to its robust, multiscalar nature, allowing it to characterize droughts over various timescales[6], [7], [8]. The SPI's flexibility across short to long accumulation periods makes it suitable for diverse climatic regions and applications [9]. It has been effectively utilized for drought detection globally and is commonly employed in Southeast Asian countries for drought monitoring and early warning [10]. Previous studies have also demonstrated a strong negative correlation between SPI values and fire activity, with more fire incidents occurring during periods of below-normal SPI (indicating drought) in fire-prone landscapes [11]. Despite these insights, there remains a research gap in integrating SPI-based drought analysis with real-time geospatial platforms – such as Google Earth Engine (GEE) – to enhance drought–fire risk assessments in peatland regions.

This study aims to address this gap by analyzing meteorological drought in Pelalawan Regency, Riau Province (Indonesia) using SPI and examining its spatio-temporal correlation with peatland fire occurrences. The specific objectives are: (1) to compute SPI at multiple timescales (1-month, 3-month, and 6-month) using TRMM/GPM precipitation data within GEE; (2) to analyze the spatio-temporal distribution of fire hotspots derived from MODIS and VIIRS satellite observations; and (3) to evaluate the statistical relationships (including any time lags) between SPI variations and peatland fire occurrence. By leveraging GEE's cloud-based computational capabilities, this work contributes to improved drought monitoring and early fire warning systems, which are crucial for sustainable peatland management and fire mitigation strategies.

2. Research Significance

This research is significant as it advances drought monitoring techniques by utilizing Google Earth Engine, providing an efficient, scalable, cloud-based approach to assessing meteorological drought via the SPI. Near real-time drought monitoring is particularly important for regions like Riau that are frequently affected by climate anomalies and recurring fires. By linking drought severity with fire occurrence, the study helps in predicting high-risk periods and developing more effective fire management strategies.

From a policy perspective, our findings offer scientific evidence to guide policymakers, conservationists, and land-use planners in implementing sustainable peatland management. Identifying drought-prone areas and their overlap with fire hotspots yields valuable insights for environmental conservation and fire mitigation efforts. Given the increasing frequency of extreme drought events due to climate change, this study also supports broader climate adaptation strategies by elucidating the role of meteorological drought in driving fire dynamics within vulnerable peatland ecosystems.

Moreover, the research contributes to the field of remote sensing applications by integrating multiple satellite-derived datasets within GEE, demonstrating its potential for large-scale climate monitoring and fire risk assessment. The results underscore the importance of combining advanced geospatial analytics with traditional drought indices to enhance environmental monitoring and proactive disaster risk reduction.

3. Methods

3.1 Study Area

The study was conducted in Pelalawan Regency, located in Riau Province, Sumatra, Indonesia as shown in Fig 1. Pelalawan Regency is located in Riau Province, Indonesia, and is characterized by extensive peatland ecosystems and a tropical rainforest climate. The region experiences distinct wet and dry seasons, with a pronounced dry season typically occurring around June to October, which makes it highly susceptible to meteorological droughts and peat fire occurrences. Peatlands cover a substantial portion (approximately more than half) of Pelalawan’s area, including parts of the carbon-rich Kampar Peninsula peat swamp. These peat soils, which store large amounts of organic carbon, become very fire-prone when dried. The combination of climate variability and wide peatland distribution makes Pelalawan an ideal case study for investigating the interactions between drought and peat fires. In this study, the period 2012–2023 was selected to capture recent climate extremes and fire events, allowing drought indices and fire occurrences in the regency to be analyzed.

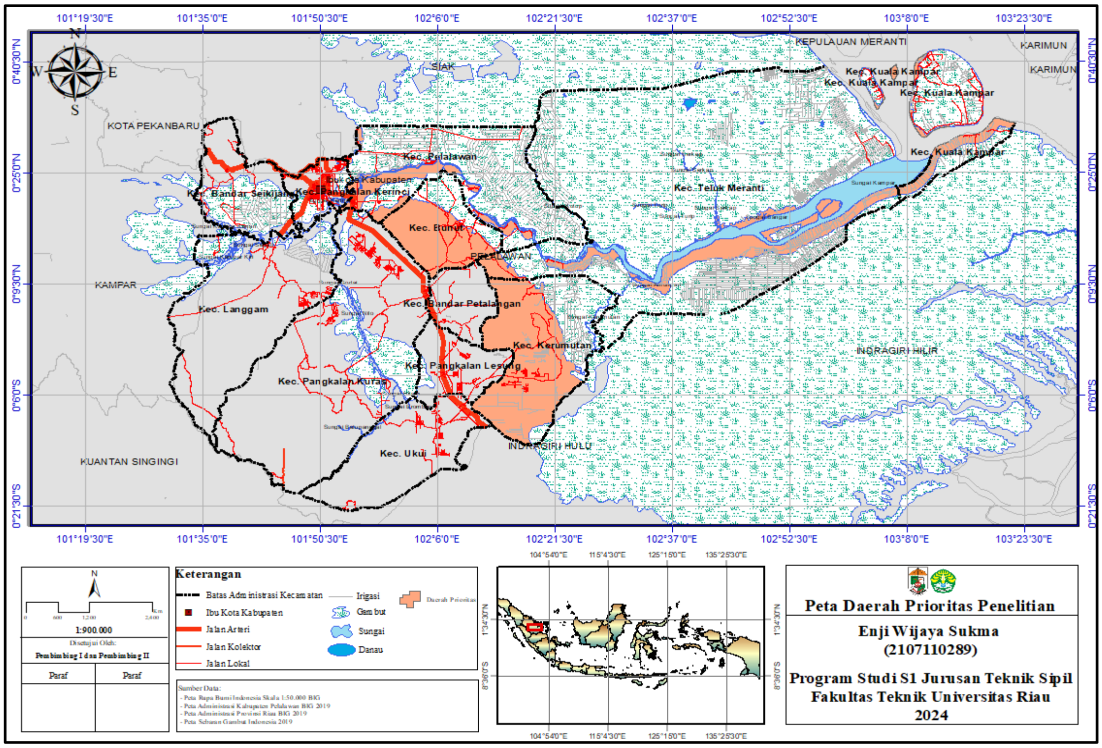

Fig 1. Study area of this research at Pelalawan Regency, Province of Riau, Indonesia

3.2 Data Sources

To conduct this study, we utilized several geospatial datasets and resources within the Google Earth Engine (GEE) platform:

1) **Precipitation Data: TRMM** (Tropical Rainfall Measuring Mission) satellite rainfall data was used as the basis for drought index calculation. The monthly precipitation product (0.25° \~27 km spatial resolution) was accessed via Google Earth Engine (GEE), which provides consistent precipitation estimates for tropical regions. For our analysis, TRMM data from **2012 to 2023** were extracted over Pelalawan Regency to capture the rainfall variability during the study period.

2) **Fire Hotspot Data:** Active fire location data were obtained from NASA's Fire Information for Resource Management System (FIRMS), which integrates thermal anomaly detections from the MODIS (Moderate Resolution Imaging Spectroradiometer) and VIIRS (Visible Infrared Imaging Radiometer Suite) satellite sensors. Both MODIS (available since 2001, \~1 km resolution) and VIIRS (available since 2012, \~375 m resolution) hotspot datasets were used. To ensure reliability, only fire hotspot detections with high confidence (e.g., confidence level >70%) were included. Each hotspot record contains the date, location, and confidence level of a detected fire.

3) **Administrative Boundaries:** A geospatial boundary of **Pelalawan Regency** was used to delineate the study area. This administrative boundary polygon (obtained from official

Indonesian mapping agencies) was applied in GEE to mask and extract data (precipitation and fire points) only within Pelalawan's extents.

4) **Peatland Distribution Map:** A **peat soil map** of Riau Province was used to identify and focus on peatland areas within Pelalawan. This dataset (sourced from national peatland inventories and soil maps) delineates the extent of peat soil coverage across the region. It allowed us to overlay fire and drought data specifically on peatland areas, distinguishing peat fires from those on mineral soil. The peatland map was especially important for interpreting results in the context of peat ecosystem vulnerability.

3.3 Data Processing and Analysis

All data processing and analyses were performed using Google Earth Engine for efficient computation and spatial analysis. The methodology involved several key steps, as outlined below:

1) **SPI Calculation using TRMM Data:** We calculated the Standardized Precipitation Index (SPI) to quantify meteorological drought conditions in Pelalawan. Monthly precipitation totals from the TRMM dataset (2012–2023) were extracted for all grid cells covering the regency. Using these data, SPI was computed at multiple timescales: 1-month (SPI-1), 3-month (SPI-3), and 6-month (SPI-6). Calculation of SPI followed the standard procedure of fitting the long-term precipitation record to a gamma probability distribution for each pixel and timescale, then transforming it to a standard normal distribution. This produces SPI values where negative values indicate below-normal rainfall (drought) and positive values indicate above-normal rainfall (wet conditions). Monthly SPI maps were generated in GEE for each timescale, allowing both short-term and longer-term drought patterns to be identified across space and time. For subsequent analysis, SPI values were also categorized into qualitative drought classes (e.g., near normal, moderate drought, severe drought) based on conventional SPI thresholds, to facilitate comparison with fire occurrence data.

2) **Fire Hotspot Filtering and Aggregation:** We processed the MODIS and VIIRS fire hotspot data to analyze spatio-temporal fire patterns. First, all fire hotspot points within Pelalawan Regency (using the administrative boundary mask) were collected for the years 2012–2023. Low-confidence detections were filtered out, and only hotspots flagged above the 70% confidence threshold were retained to minimize false alarms. The remaining high-confidence fire points from MODIS and VIIRS were combined into a unified dataset of monthly fire occurrences. Hotspot counts were aggregated by month and year to determine temporal trends in fire frequency, allowing the identification of peak fire months and particularly active fire years. Fire occurrence data were also summarized within each peatland sub-region to examine which peat areas experienced the most fires.

3) **Spatial Overlay of Drought and Fire Data:** To examine the spatial relationship between drought severity and peat fire occurrences, we performed an overlay analysis between SPI maps and fire hotspot locations. For each time step, the SPI class maps (e.g., showing areas under moderate or severe drought) were overlaid with the corresponding fire hotspots in that month. The peatland distribution map was used as a mask to focus the analysis on

hotspots occurring on peat soils. Through this spatial comparison, it was determined whether fire incidents were concentrated in areas experiencing drought at the corresponding time. Patterns were analyzed based on the proportion of fire hotspots located within areas classified as severe drought (as indicated by low SPI values) compared to areas with normal moisture conditions. Fire points were mapped onto SPI class maps within Google Earth Engine (GEE), allowing both visual and quantitative assessments of the spatial coincidence between drought conditions and fire events. This overlay approach also enabled the identification of specific peatland areas that consistently experienced both low SPI and high fire activity, thereby indicating critical hotspots for peat fire risk.

4) **Correlation and Lag Analysis:** In order to quantify the relationship between meteorological drought and fire activity, we conducted statistical correlation analyses on the time-series of SPI and fire occurrences. The Pearson correlation coefficient was computed between monthly SPI values and monthly fire hotspot counts over the 2012–2023 period. This analysis was conducted across various SPI timescales (e.g., SPI-1, SPI-3, etc.) to determine which drought index scale exhibited the strongest correlation with fire incidence. A negative correlation was anticipated, as lower SPI values (indicating drier conditions) are hypothesized to correspond with increased fire occurrences. In addition to the direct (concurrent) correlation, a lag analysis was performed to investigate the delayed effects of drought on fire activity. Specifically, correlations were tested between SPI values from preceding months and fire hotspot counts from subsequent months. For instance, it was examined whether SPI values one or two months prior had a significant correlation with fire hotspot counts in the target month. This approach was used to identify lag intervals (e.g., 1-month or 2-month lag) during which drought conditions most strongly influenced fire outbreaks. All correlation results were evaluated for statistical significance at the 95% confidence level ($p < 0.05$) to ensure reliability. Through this analysis, the strength and timing of the impact of drought conditions on peat fire frequency in the study area were quantified.

5) **Trend Analysis and Visualization:** We employed several visualization techniques to interpret the spatio-temporal trends of drought and fire in Pelalawan. Time-series graphs were generated to plot the SPI values alongside fire hotspot counts through the study period. These trend graphs (for SPI-1, SPI-3, SPI-6 and monthly fire counts) help in identifying synchronous patterns, seasonal cycles, and anomalies (for instance, years where SPI drops markedly below zero corresponding to spikes in fire activity). The time series was also decomposed into seasonal and residual components to better discern long-term trends versus seasonal variability in drought conditions. For spatial trends, we produced composite maps and overlays: for instance, heatmaps of average SPI values over the period and cumulative fire density were compared to show overlap between chronically dry areas and frequently burning areas. All maps and figures were created within the GEE environment or using GIS software for high-quality visualization. These visual analyses, including maps of drought-fire overlap and temporal trend graphs, provided intuitive insights into the data and supported the quantitative findings.

By integrating these methods, this study offers a comprehensive assessment of the relationship between meteorological drought and peat fires in Pelalawan Regency. The use of GEE allowed efficient processing of the large geospatial datasets and enabled dynamic mapping of drought indices and fire occurrences. The resulting analysis not only elucidates how and where drought conditions correlate with peat fire events, but also yields practical information (such as hotspot clustering in drought-prone peat areas and the critical drought lead times before fires) that can inform early warning systems and peatland fire management strategies.

4. Results and Discussion

SPI Trends and Drought Patterns

Figure 1 illustrates the monthly Standardized Precipitation Index (SPI) values alongside the number of fire hotspots in Pelalawan's peatland areas from 2012 through 2014. Periods of negative SPI (meteorological drought) clearly coincide with spikes in hotspot counts. For example, in February 2014 the SPI plummeted to -2.04 ("Very Dry"), and that same month recorded 849 hotspots, the highest monthly fire count in the study period. This extreme drought-fire concurrence is evident throughout the time series. In 2013, SPI reached -1.45 in June with 635 hotspots, and August 2013 saw SPI around -1.07 with 599 hotspots – both significant droughts followed by intense peat fire occurrences. Similarly, August 2012 (SPI ≈ -1.22) experienced 175 hotspots, marking the peak for that year. Overall, drier months (SPI < -1.0) consistently correspond to elevated fire activity, whereas months with positive or near-normal SPI show little to no fire incidence. Notably, during wetter conditions such as October 2022 (SPI ≈ +1.46) and January 2023 (SPI ≈ +1.60), zero hotspots were detected, underscoring that sufficient rainfall suppresses peat fires. These findings confirm a strong inverse relationship between rainfall-derived drought index and peat fire frequency: when meteorological drought intensifies, peatland fires escalate dramatically. This temporal pattern suggests that extreme drought conditions not only facilitate ignition but also promote the spread of peat fires, owing to the desiccation of peat (which once dried is difficult to re-wet).

Another important observation is the lagged effect – severe drought in one month often precedes peak fire counts in the following month(s). For instance, the severe dryness in June 2013 was followed by the highest fire counts in August 2013, indicating a short lag as dry peat accumulated and then ignited in subsequent weeks. This aligns with similar studies that found major fire outbreaks occur 1–2 months after the onset of a severe drought, highlighting a critical window for early.

Despite some inter-annual variability, the overall trend from 2012–2023 reinforces that **more severe meteorological droughts tend to result in more numerous peat fires**. Conversely, in years or periods with predominantly normal SPI values (e.g. much of 2016 and 2021), fire activity was relatively subdued. For instance, 2016 had many months with SPI in the normal range and consequently low hotspot counts, and 2021 exhibited almost no correlation between SPI and fire occurrences (Table 1), likely because that year's climate was wetter and few fires ignited. These temporal analyses suggest that meteorological drought is a primary driver of peat fire incidence in Pelalawan Regency.

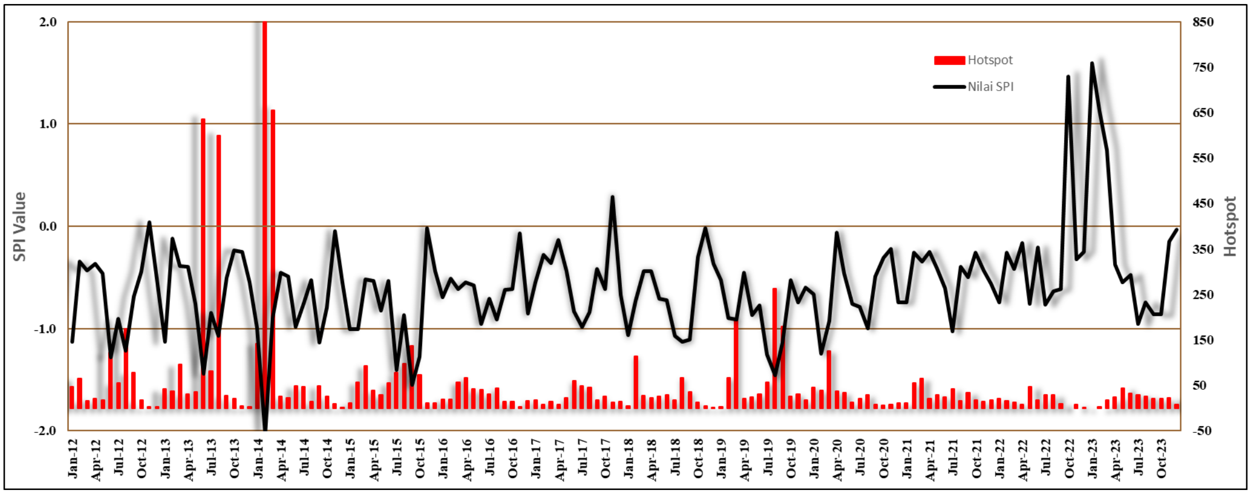

Fig 1. monthly Standardized Precipitation Index (SPI) values alongside the number of fire hotspots in Pelalawan's peatland areas from 2012 through 2014

4.2 Fire Occurrences and Spatial Distribution

Spatially, the distribution of drought severity across Pelalawan's peatlands further corroborates the drought-fire link. **Figure 2** presents the spatial classification of SPI and the overlay of fire hotspots for a representative severe drought year (2014). The map delineates areas under **"Very** Dry" (SPI ≤ –2), "Moderately Dry" (–1 to –1.9), and "Normal" conditions, along with the locations of detected fire hotspots. A pronounced cluster of Very Dry conditions in 2014 appears in the Teluk Meranti sub-district, which corresponds to a dense concentration of hotspots in that area. This indicates that Teluk Meranti experienced the most severe moisture deficit and, consequently, rampant peat fires. In Kerumutan sub-district, the map shows a mix of very dry and normal patches. Hotspot data reveal that even within this subdistrict, fires predominantly ignited in the pockets that were classified as drought-stricken. Meanwhile, areas like Kuala Kampar were split between moderately dry and normal conditions; accordingly, Kuala Kampar saw some fire activity in its drier zone, whereas the portions with normal moisture remained largely fire-free. In contrast, Bunut and central Pelalawan areas largely retained normal SPI levels throughout 2014, and these areas registered few to no hotspots, reflecting relative ecosystem stability under adequate moisture.

The spatial alignment between drought and fires is clear evidence that peat fire risk is highest in the regions undergoing meteorological drought. The 2014 drought map is a stark example: it shows that the most fire-prone zones are those with significant rainfall deficits. These spatial findings are consistent with multi-year observations that fire hotspots cluster in peat-dominated zones experiencing recurrent drought. Such maps are invaluable for land managers, as they highlight vulnerable hotspots where resources for fire prevention and peatland water management should be focused. By overlaying drought severity with fire occurrence, one can identify critical areas (for example, southern and central Pelalawan peatlands) that require improved water retention or fire patrols during dry spells.

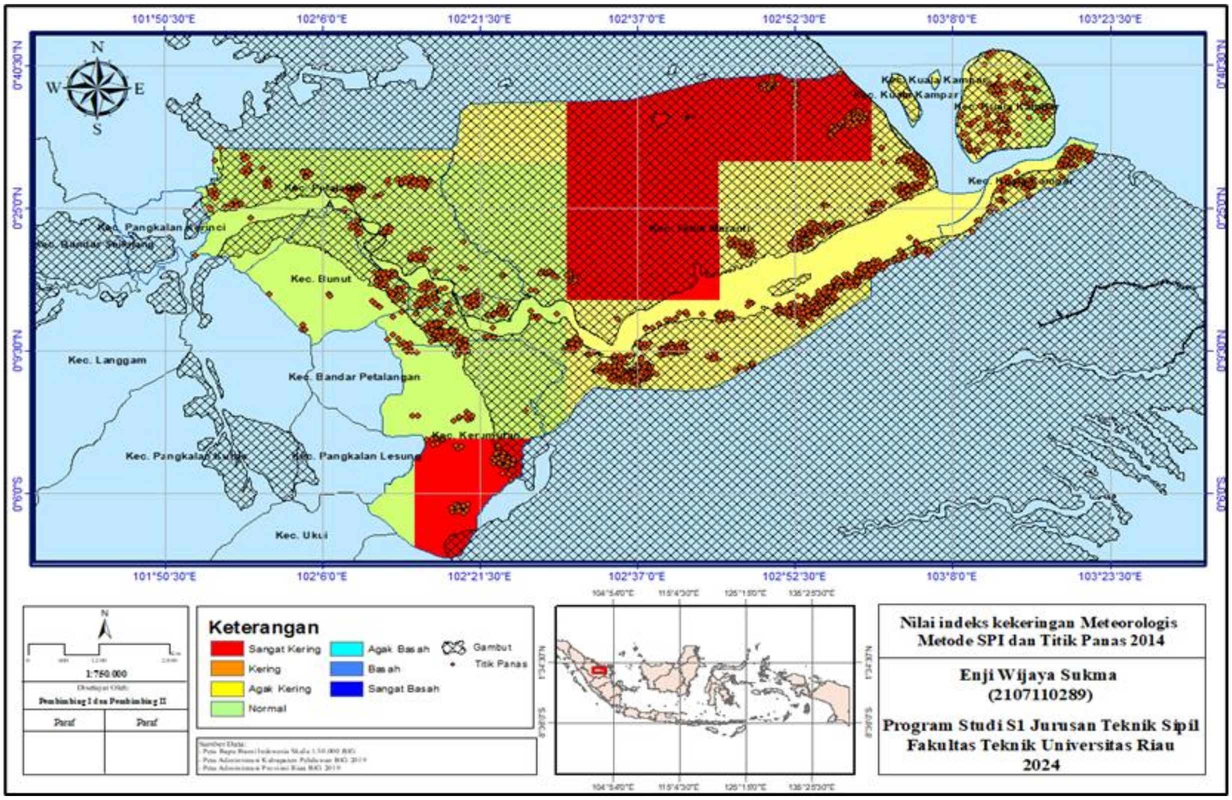

Fig 2 spatial classification of SPI and the overlay of fire hotspots for a representative severe drought year (2014).

4.3 Correlation Between SPI and Fire Events

To quantify the relationship between meteorological drought and peat fires, a Pearson correlation analysis was conducted for each year of the study. Table 1 summarizes the correlation coefficient (r) between monthly SPI values and monthly hotspot counts from 2012 to 2023, as derived from the data. The coefficients are uniformly negative, reinforcing that lower SPI (drier conditions) is associated with higher fire incidence. In most years the correlation is strong (|r| ≈ 0.6–0.8), and in several years it is very strong. For example, 2013 shows *r* ≈ –0.84, indicating an extremely tight inverse relationship between SPI and hotspot frequency that year. Years like 2012, 2014, 2017, 2019, and 2023 also exhibit strong negative correlations (r from –0.75 to –0.77). These correspond to years in which at least one major drought episode led to an outbreak of fires (e.g., the severe mid-2013 and early-2014 droughts discussed above). In contrast, years with milder drought influence show weaker correlations. Notably, 2016, 2018, and 2020 have correlation magnitudes around 0.34–0.46 (weak-to-moderate), suggesting that in those years other factors (e.g. human ignition activities or peatland management) may have played a relatively larger role in fire occurrences, or that drought was less uniformly severe across all months. Year 2021 is an outlier where the correlation is essentially zero (r ≈ –0.06), meaning no apparent linear relationship between SPI and fires – consistent with the observation that 2021 had very few hotspots regardless of SPI, likely due to predominantly wet conditions or successful fire suppression in that year. Overall, however, the statistical analysis confirms a strong negative correlation between the meteorological drought index and peat fire events in Pelalawan (pooled over the full 2012–2023 record, the correlation is approximately $r = –0.75$, significant at $p < 0.01$). This quantitatively reinforces the earlier qualitative observations: as SPI drops (indicating worsening drought), the number of fires rises. Such correlation analysis, performed both via manual calculation and using the Google Earth Engine platform, highlights that drought severity is a reliable indicator of fire risk in peatland ecosystems.

Table 1. Pearson correlation between monthly SPI and hotspot counts by year (2012–2023). Negative values indicate an inverse relationship (drier conditions associated with more fires). The strength of correlation is categorized qualitatively in parentheses.

Year	Correlation, r (SPI vs Hotspots)	Relationship Strength
2012	–0.77	Strong Negative
2013	–0.72	Strong Negative
2014	–0.74	Strong Negative
2015	–0.61	Strong Negative
2016	–0.34	Weak Negative
2017	–0.76	Strong Negative
2018	–0.34	Weak Negative
2019	–0.77	Strong Negative
2020	–0.35	Weak Negative
2021	+0.08	(Negligible)
2022	–0.60	Strong Negative
2023	–0.75	Strong Negative

These results underscore that meteorological drought (as measured by SPI) is a dominant environmental factor influencing peat fire occurrence in Pelalawan Regency. Practically, this means SPI can be used as an early warning indicator for peat fire risk. When SPI forecasts or real-time data show a drop below -1.5 (severe drought), authorities should anticipate a surge in fire activity. The few exceptions (e.g., 2021) remind us that anthropogenic factors (like land-use change, canal drainage, or fire bans) and other climate influences can modulate the drought-fire relationship in certain years. Nonetheless, the overall consistent correlation over 12 years provides confidence in integrating SPI-based drought monitoring into fire management strategies. By leveraging GEE's ability to compute SPI and correlate it with hotspot data rapidly, local agencies can monitor drought conditions across the peatland landscape in near real-time and identify emerging high-risk zones for fires. This study's spatio-temporal analysis thereby contributes to developing a proactive fire prevention system: one that couples meteorological drought indices with on-the-ground fire surveillance. In sum, maintaining peatland wetness is critical – when meteorological droughts are detected, peatland water tables should be raised (through canal blocking or water supplementation) in the most drought-prone areas to reduce the likelihood of ignition. The strong drought-fire linkage evidenced here highlights the importance of early drought detection and swift mitigation efforts to protect these sensitive peat ecosystems from fire damage.

5. Conclusions

This study highlights the critical relationship between meteorological drought and peatland fire occurrences in Pelalawan Regency, Riau. The Standardized Precipitation Index (SPI), computed at multiple timescales using TRMM satellite-gauge blended precipitation data, effectively captured drought patterns and their impact on fire activity. Severe drought conditions (SPI < –1.5) were found to be strongly associated with increased peat fire incidents, particularly during prolonged dry seasons and El Niño years when regional rainfall deficits are pronounced. Spatial and temporal analysis demonstrated that drought-stricken peatlands, especially in degraded or drained areas, experienced the most frequent and intense fires. By leveraging Google Earth Engine for data processing, we successfully integrated climate indices with fire observations to provide a comprehensive spatio-temporal assessment of drought-fire dynamics. The negative correlation between SPI and fire occurrences, along with the identified 1–2 month lag, suggests that monitoring meteorological drought can facilitate early warnings for peat fire risk.

In practical terms, these findings advocate for the inclusion of drought indices in fire management and disaster preparedness plans for peatland regions. Agencies could use real-time SPI monitoring to anticipate periods of elevated fire danger and allocate firefighting resources accordingly. Additionally, the clear linkage between land-use-related peatland degradation and fire vulnerability reinforces the need for peatland restoration and sustainable management as long-term solutions to recurring fires.

In conclusion, this study confirms that the Standard Precipitation Index (SPI) is a reliable indicator of meteorological drought closely linked to peat fire risk in Pelalawan Regency. Severe drought conditions (SPI < -1.5) correspond to significantly higher fire occurrences, and fire hotspots cluster in specific peatland zones — especially degraded peat and plantation areas — that experience frequent moisture deficits. Notably, major fire events typically occur about 1–2 months after the onset of severe drought, providing a critical window for early warning. These findings highlight the importance of SPI-based drought monitoring in identifying vulnerable peat zones and emphasize its potential as an early warning tool to support proactive peat fire mitigation strategies.

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