JOURNAL OF DEGRADED AND MINING LANDS MANAGEMENT
Volume 13, Number 3 (July 2026):10773-10786, doi:10.15243/jdmlm.2026.133.10773
ISSN: 2339-076X (p); 2502-2458 (e), www.jdmlm.ub.ac.id

Research Article

Spatial and temporal analysis of wild peat fire on island peatlands using remote sensing data

Sigit Sutikno[1,2*], Nur Hidayati[2], Ahmad Muhammad[2,3], Nurul Qomar[2,4], Koichi Yamamoto[5]

[1] Civil Engineering Department, University of Riau, Kampus Bina Widya Km 12.5 Pekanbaru, Indonesia
[2] Center for Peatland and Disaster Studies (CPDS), University of Riau, Kampus Bina Widya Km 12.5 Pekanbaru, Indonesia
[3] Biology Department, University of Riau, Kampus Bina Widya Km 12.5 Pekanbaru, Indonesia
[4] Forestry Department, University of Riau, Kampus Bina Widya Km 12.5 Pekanbaru, Indonesia
[5] Graduate School of Sciences and Technology for Innovation, Yamaguchi University, Ube, Japan

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

Article history:
Received 26 April 2026
Accepted 15 June 2026
Published 20 June 2026

Keywords:
hotspot
island peatland
Landsat
peat fire
remote sensing

Abstract

Indonesia has the largest area of tropical peatland, which is becoming vulnerable to fires. Smoke haze crises due to forest fires that occur annually have plagued many parts of Southeast Asia between 2013 and 2015, with devastating effects on human health and the economy. Fires spread fast on island peatlands in eastern Sumatra because their small catchments drain quickly into the sea. This research dived into the spatial and temporal patterns of peat wildfires in the Peat Hydrological Unit of Bengkalis Island. Drawing on remote sensing sources such as MODIS-C6 Terra/Aqua thermal hotspots from 2001 to 2020 and Landsat images, the findings revealed two clear yearly fire peaks in Bengkalis: Period I (January-March) and Period II (June-August). Hotspot density was concentrated in deep peat areas 57.3% of detections are from the 500-700 cm thickness class, and 93.1% from peat >300 cm. During 20 years, 343 fire-days burned a total of 56,202 ha; the largest single occurrence involved a burnt area of 19,999 ha in 2014. Monthly rainfall is the dominant climatic control, exhibiting a clear inverse relationship with hotspot frequency; rainfall below 100 mm/month defines elevated fire-risk conditions. These findings establish that MODIS hotspot monitoring combined with Landsat burned area mapping provides a robust long-term fire assessment framework, and that rainfall thresholds offer a practical operational basis for fire early warning systems on island peatlands.

To cite this article: Sutikno, S., Hidayati, N., Muhammad, A., Qomar, N. and Yamamoto, K. 2026. Spatial and temporal analysis of wild peat fire on island peatlands using remote sensing data. Journal of Degraded and Mining Lands Management 13(3):10773-10786, doi:10.15243/jdmlm.2026.133.10773.

Introduction

Indonesia holds the greatest area (approximately 21 million ha) of tropical peatlands in the world, representing about half of all globally occurring tropical peat (Koh et al., 2011; Page et al., 2011; Osaki and Tsuji, 2016). These ecosystems are vital carbon sinks, freshwater reserves, and biodiversity hotspots. However, extensive land-use change, the construction of drainage canals, logging, and repeated burning have severely degraded Indonesian peatlands. Fewer than 4% are intact (peat swamp forest) and >20% unmanaged, degraded landscapes (Koh et al., 2011; Miettinen et al., 2016). The destruction of peat swamps leads to a vicious cycle of drying and burning: artificial drainage lowers the water level in the swamps and makes dry peat vulnerable to ignition (Sutikno et al., 2020d; Sutikno et al., 2020e; Sutikno et al., 2023).

Peat fires in Indonesia, which are responsible for releasing toxic gases and air pollutants, strike almost incessantly during drier portions of the year. Unlike ordinary forest fires, peat fires burn both on the surface and below ground (underground peat fire), making them extremely difficult to extinguish; historically, no suppression traces were reported except rainfall being able to stop these flames after ignition (Usup et al., 2004; Sandhyavitri et al., 2018; Sutikno et al., 2020b). Between 2013 and 2015, the worst fires in recent decades took place, resulting in devastating environmental, health, economic, and human costs throughout the region (Marlier et al., 2013; Koplitz et al., 2016). Peat fires were identified as a major and recurrent source of CO_2 emissions to the atmosphere at the global scale (Murdiyarso et al., 2010; Wasis et al., 2019; Yokelson et al., 2022).

Island peatlands are peatlands that develop on small islands where the land area is predominantly composed of peat. Unlike peatlands on the mainland, which form part of extensive lowland peat complexes, island peatlands occupy nearly the entire land surface of their respective islands, making the island itself essentially a peat body surrounded by the sea. These island peatlands are notably susceptible to fire occurrence as they lack large insular catchment areas for groundwater recharge, lateral drainage to the ocean is rapid, and the water table in peats reacts quickly (within weeks) to rainfall deficits (Sutikno et al., 2023). The island peat body has a much smaller capacity to store water than mainland systems, so during dry periods, the limited water storage capacity of the island peat is drained much more quickly; consequently, both island surface peats are particularly prone to desiccation and ignition (Page et al., 2002; Holden et al., 2006; Sutikno et al., 2026). The eastern coast of Sumatra hosts Indonesia's largest peat hydrological area in Riau Province, covering approximately 4.97 million hectares (Illés et al., 2019), equivalent to around 51% of the province's land cover. Peatlands dominate several of its offshore islands: they cover approximately 90%, 95%, 94%, 85%, 94%, and 53% of the land area of Bengkalis, Padang, Tebingtinggi, Rangsang, Mendol, and Rupat islands, respectively (Sutikno et al., 2026).

The government of Indonesia, through the Peatland and Mangrove Restoration Agency (called BRGM), has made considerable efforts towards environmental preservation, particularly for peatlands, designating Bengkalis Island as a national model for restoration. These are part of larger strategies to rehabilitate degraded peatlands and establish effective forest fire prevention programs, which contribute to global peatland carbon conservation and climate regulation. It should, however, be emphasized that, to the best of current knowledge, no comprehensive peer-reviewed assessment focusing on the dynamics of peat fire behaviour on this strategically important island has been made to date. No landscape-scale assessment has been made before, nor has it been done in a detailed spatio-temporal context utilizing remote sensing data.

Remote sensing technologies are essential for monitoring large area peatland fires. Active fires are detected in near-real time with high temporal resolution from MODIS (Moderate Resolution Imaging Spectroradiometer) satellite thermal hotspot data acquired by Terra and Aqua platforms (Harahap, 2018; Putra et al., 2019). Complementarily, Landsat imagery, with its 30-m spatial resolution and decadal archive, facilitates precise mapping of burned area and the temporal progression of burns. Studies utilizing these datasets to monitor tropical peat fires across Indonesia (Siegert and Hoffmann, 2000; Koh et al., 2011; Miettinen et al., 2011; Usman et al., 2015; Putra et al., 2019; Sutikno, et al., 2020a; Sukma and Sutikno, 2025) have also been conducted, but few provide an examination of long-term fire dynamics within island peatland units with a focus on early warning and prevention.

Thus, this study provides a spatial and temporal analysis of wild peat fires that occurred in the PHU Bengkalis Island during 20 years (2001-2020). The explicit objectives were (1) to describe the spatial distribution of fire occurrence with respect to MODIS hotspot density and Landsat burned area mapping, and (2) to quantify the temporal dynamics of fires through recurrent periods, analyze total burned area, fire duration, and fire rate, as well as identify long-term trends during this study.

Materials and Methods

Study area

The research was conducted on the island peatlands of Bengkalis Island, located in East Sumatra at approximately (102°0′-102°30′ E and 1°20′-1°40′ N), Riau Province, Indonesia (Figure 1). The Northern and Western side of the island is bordered by the Malacca Strait, while its Southern edge is bounded by the Strait of Bengkalis, which separates it from the Sumatran mainland. Bengkalis Island itself forms one PHU (Peat hydrological unit) called PHU Bengkalis, where the area of peatland covers approximately 90% of the total land area. The topography creates a unique landscape when compared to the surrounding areas. Being predominantly ombrogenous (rain-fed), peatlands make rainfall the only hydrological input of the system and encourage dome-like accumulations highly responsive to disturbances of water balance. The island's geographic position, bounded on all sides by the Malacca Strait and the Strait of Bengkalis, limits its catchment area and accelerates lateral drainage, making its peatlands more prone to desiccation than mainland peat systems.

PHU Bengkalis covers five Sub-PHUs delineated by the Indonesian government for spatial analysis and peatland management, namely Sub-PHU-1 to -5 (Figure 1). The peat thickness throughout PHU Bengkalis is therefore highly variable (Figure 1). The thickest peat (500-700 cm) is constrained in the dome cores of Sub-PHU-2, Sub-PHU-3, and Sub-PHU-5. In most of the Sub-PHUs, the intermediate thicknesses 300-500 cm dominate the wide transitional area surrounding the dome cores, while 200-300 cm and 100-200 cm peat are typical for crest to fringe transitional zones. The shallowest peat (50-100 cm) indicates the inner mineral-peat transition zone, especially expressed along northern coastal sections of Sub-PHU-2 and Sub-PHU-3 and eastern margins of Sub-PHU-4. The Indonesian government's Peatland and Mangrove Restoration Agency (BRGM) had designated PHU Bengkalis as the national model KHG for peatland restoration and prevention in light of its ecological importance and the scale of fire management challenge.

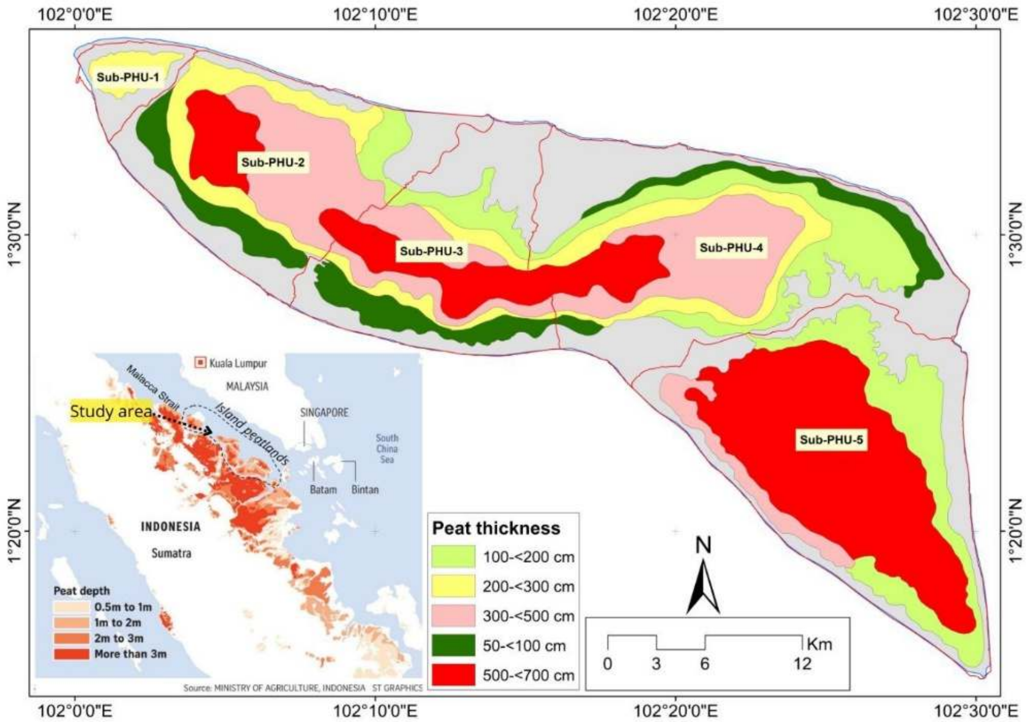


Figure 1. Research site: Bengkalis Island, Riau Province, Indonesia, with peat thickness distribution (by zone colours) and Sub-PHU boundaries (Sub-PHU-1 to Sub-PHU-5). Inset: regional location of Bengkalis Island and surrounding island peatlands in the Malacca Strait relative to Sumatra and Peninsular Malaysia (peat depth data source: Ministry of Agriculture, Indonesia).

MODIS-C6 hotspot and Landsat imagery data

This research used MODIS-C6 hotspot and Landsat imagery data for spatial and temporal analysis of fire events. MODIS Collection 6 (C6) active fire data from both the Terra and Aqua satellites were obtained from NASA Fire Information for Resource Management System (FIRMS), covering January 2001-December 2020. Hotspot detections were filtered based on a confidence threshold (only retaining those with a confidence level>60%), which is generally used to separate real fire events from artifacts of the sensor. MODIS active fire products detect thermal anomalies at a near 1-km^2 pixel resolution.

To assess burned areas corresponding to fire events detected by MODIS hotspot analysis, multi-temporal Landsat imagery was sourced from the USGS Earth Explorer platform. Only cloud-free scenes were selected to ensure the clarity and accuracy of the analysis. This study exploits three types of Landsat sensors, which include Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Landsat 8 Operational Land Imager/Thermal Infrared Sensor (OLI/TIRS). As detailed in Table 1, specific combinations of false-color composite bands were used for each sensor to aid burnt area identification.

Table 1. Landsat band combinations (R/G/B) used for burned area identification.

Landsat Sensor	Band Combination (R/G/B)
Landsat 5 TM	7-4-2
Landsat 7 ETM+	5-4-3
Landsat 8 OLI/TIRS	6-5-3

Hotspot distribution analysis

The MODIS hotspot dataset was then filtered by clipping its extent to the native boundary of PHU Bengkalis Island using GIS software. This ensured that only fire detections relevant to the study area were included in subsequent analyses. A point density analysis was completed to assess the spatial patterning of fire occurrence. This effectively allowed users to visualise areas with significant hotspot detections across the island during the 20-year study period, highlighting regions of higher fire activity. After the point density analysis, overlay operations were carried out to combine the hotspot point data with burned area polygons obtained from Landsat images. This approach involved directly comparing the positions of detected thermal anomalies (hotspots) with mapped extents of actual burned areas through spatial cross-referencing. This methodology provided a complete spatial analysis of both active hot spots and confirmed burnt areas for PHU Bengkalis Island by merging these datasets.

Fire characteristics analysis

Three key fire characteristics were quantified per fire period, per year analyzed in this study. These parameters include:

1. ***Burned area*** (ha): The land where more than 80% of the surface was burned. Landsat false-color composites were used to delineate burned area, and polygons for mapping burned area were digitized.
2. ***Fire duration*** (days): Fire duration was defined as the period of time that elapsed between the first recorded hotspot and the last recorded hotspot within each fire period
3. ***Fire rate*** (ha/day): The fire rate was measured as the ratio between total burned surface and fire duration, assessing how fast the fire burned in each period.

Using the monthly time series of MODIS, annual fire periods were defined: Period I from January to March and Period II from June to August. These periods align with two repeat dry seasons in Riau Province.

Results and Discussion

Spatial characteristics of peat fire

The distribution of MODIS hotspot detections (confidence >60%) for PHU Bengkalis Island from 2001 to 2020 is shown in Figure 2. As evident from the spatial pattern shown in the figure, hotspot occurrences across the island are not uniformly or randomly distributed. The highest hotspot density occurs in areas of thick peat, particularly in central and southeastern zones. Within these regions, Sub-PHU-5, situated in the southeastern area, and Sub-PHU-3, positioned in the central corridor, exhibit the most intense hotspot clustering. This is illustrated by the dense clusters of black dots showing hotspot detections in Figure 2.

A summary of hotspot occurrence relative to peat thickness is presented in Figure 3a, showing the distribution of total hotspot detections across five discrete classes of peat thickness. The results show a tight, positive relationship between peat depth and fire frequency. The class 500-700 cm peat thickness presented the highest number of hotspots, with 1,342 detections (more than half of the total) (Figure 3). The second, a 300-500 cm class, was also well-represented with 838 detections (35.8%). This is in stark contrast to the far fewer hotspots identified in areas of thinner peat, with 68 detections found in the 200-300 cm class, 66 found in the 100-200 cm class, and just 29 hotspots for the shallowest (50-100 cm) locations.

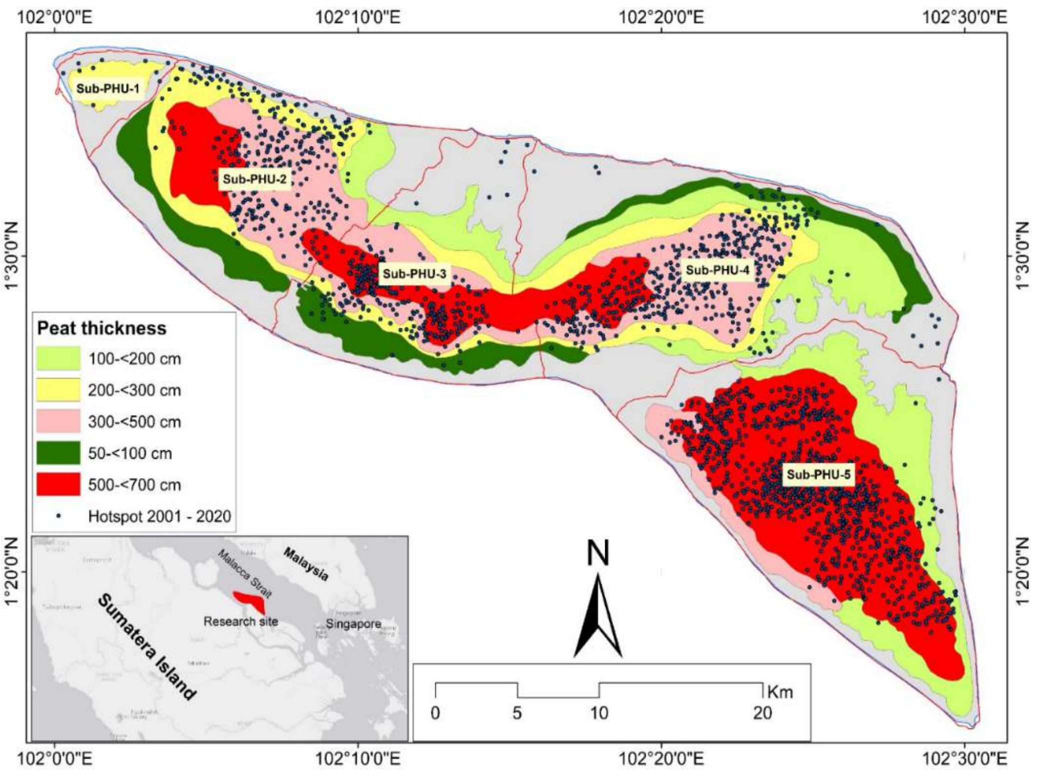
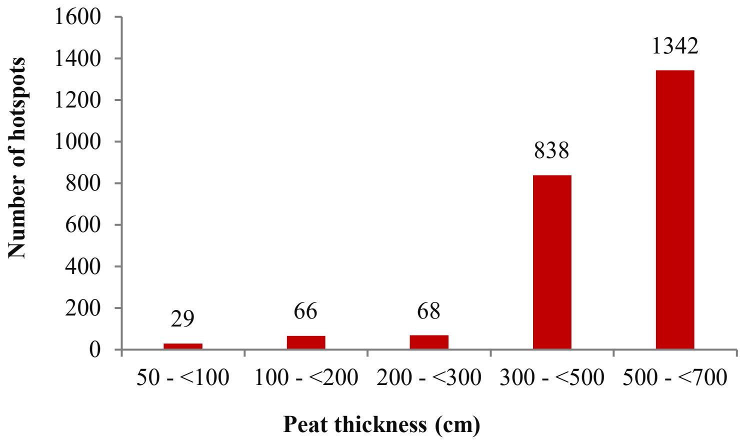


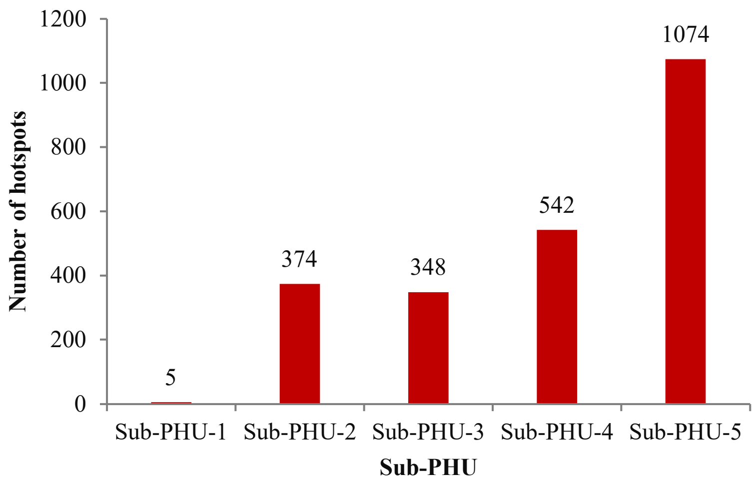
Figure 2. Spatial distribution of cumulative MODIS hotspot detections (confidence >60%) on PHU Bengkalis Island, 2001-2020, overlaid on peat thickness zones and Sub-PHU boundaries.

In summary, these peat depths exceeding 300 cm accounted for 93.1% of the total hotspot detections during the 20-year study period. The distribution confirms that the deepest peat zones represent the main fire-risk areas in PHU Bengkalis.

The hotspot detection by each Sub-PHU (Figure 3b) provides further illustration of the fire activity's spatial distribution within PHU Bengkalis Island. In total, Sub-PHU-5, covering the southeastern part of the island that is characterized by deep (>500 cm to >700 cm) peat deposits, recorded the greatest number of hotspots (1,074 detections). This represents 45.8% of the recorded hotspots across the 20-year study period. The second most frequent hotspot, Sub-PHU-4, only had 542 detections accounting for 23.1% of the total. Sub-PHU-2 and Sub-PHU-3 had 374 and 348 hotspot detections, respectively (16.0% and 14.9% of all records). In contrast, only 5 hotspot detections were recorded at Sub-PHU-1 on the northwestern tip of the island, where peat is thinner and less disturbed. This accounted for under 0.3% of the total number of hotspots seen over the two decades studied. While thinner, undisturbed peat generally does not burn in these events, this distribution illustrates the strong concentration of fire in areas with deeper and more degraded peat.



(a)



(b)

Figure 3 Distribution of cumulative MODIS hotspot detections (2001-2020) by peat thickness class (a) and by Sub-PHU (b), PHU Bengkalis Island.

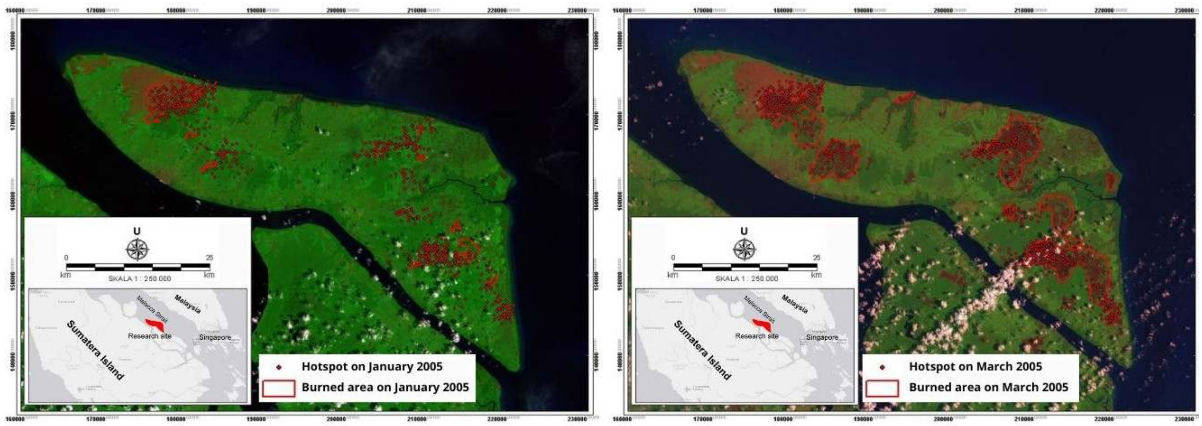
The increase in fire activity concentration within the thickest peat zones can be explained by two compounding factors. First, these deep peat areas coincide with zones of intensive agricultural and plantation development, where extensive drainage canal networks have systematically lowered the water table, exposing thick dry peat profiles to ignition risk (Holden et al., 2006; Jaenicke et al., 2010; Pratama et al., 2020). Second, once initiated, fires in thick deposits of peat smolder longer and deeper as ground fires, producing persistent hot spot detections over a prolonged time period than shallow peat fires (Usup et al., 2004; Turetsky et al., 2015). The repeated clustering of hotspots at the same locations over multiple years, particularly in Sub-PHU-5, shows that chronic burning occurs repeatedly in chronically degraded peat areas, a pattern consistent with findings from other degraded peatland systems across Indonesia (Usman et al., 2015).

Spatial progression of burned area

Figure 4 illustrates the spatial progression of burned area during the most severe fire event recorded in PHU Bengkalis. Taking place during Period I in 2005, the event burned an area totaling 11,165 hectares over a duration of 44 days and is ranked as one of the most catastrophic fires recorded within the 20-year study period. Landsat image composite (Figure 4a), taken on 16 January 2005, Bengkalis at the beginning of Period I, the weather is a dry season, although fire activity is only limited. Some small burn areas (highlighted by the red polygons) are already visible in the northern part of the island, for example, parts of Sub-PHU-1 and Sub-PHU-2, and on the southern edge. These notes suggest ignition had already begun, but the fires did not yet spread across the landscape. Most of the island's surface is still covered in vegetation, indicated by dark green colors in the imagery.

The 23 March 2005 Landsat imagery (Figure 4b), taken at about nine weeks post initiation of fire, shows the landscape at Period I's peak; burned area extent has greatly expanded since 16 January. The March image shows red polygons (along with pink-red) showing that large and contiguous tracts have been impacted from the northwestern sector, central corridor, and especially the southeastern sector of PHU Bengkalis Island. The southeast cluster of burned areas appears particularly extensive, correlating with Sub-PHU-5, which was also consistent with its majority in the 20-year hotspot record—1,074 detections or 45.8% of all hotspots, as discussed regarding Figure 3.

The spatial pattern observed confirms that the fire spread radially outward from the initial ignition points. This expansion was fastest in the degraded peat regions, and especially in thick-peat areas (Sub-PHU-5). In this case, profiles of dry peat continued to exist in the subsurface realm, providing an uninterrupted fuel source that enabled a large spread of fire. The dots, however, are called active hotspot points at the time of image capture, which also explains that fire has been burning in neighbouring or affected areas. In spite of the extensive burning, areas with intact vegetation (shown in dark green) persist, especially in the central peat dome and northeast sector. They include thicker, less-disturbed peat with higher residual moisture content, which could explain their resistance to fire spread and preservation during this catastrophic event (Sutikno et al., 2020c).



a) 16 January 2005 b) 23 March 2005

Figure 4. Landsat imagery showing the spatial extent of peat burning in PHU Bengkalis: (left) pre-fire 16 January 2005; (right) post-fire 23 March 2005.

Temporal characteristics of peat fire

The monthly time series of MODIS-detected hotspots within the PHU Bengkalis region for the study period of 20 years is depicted in Figure 5. Data analysis shows that the annual bimodal structure is stable when hotspots emerge during two periods every year. In particular, periods are denoted by Period I, January-March, and Period II, June–August. These two fire windows correlate with the two dry seasons experienced in Riau Province due to seasonal migration of the Intertropical Convergence Zone (Aldrian and Susanto, 2003). The annual and monthly counts of hotspots across the study area can be found in Table 2.

Analysis of the monthly column totals in Table 2 highlights the clear dominance of Period I in hotspot detections. February was the most noteworthy month with a total of 1,068 hotspots, followed closely by March with 883. Together, these two months comprise 83% of all hotspot occurrences recorded over the 20-year observation period. This finding underscores the critical importance of January to March as the highest-risk window for fires. In stark contrast, Period II is much closer to inactivity; this period is defined by a dramatically reduced level of activity (lower hotspot counts). June recorded 93 hotspots and July 38 hotspots; together, these are the peak months of Period II, though at a substantially lower intensity than

Period I. While much lower than what was seen during the more dynamic Period I, these numbers suggest significant fire activity worthy of attention. This characteristic bimodal pattern is observed in year-on-year counts, with low hotspot counts during wet season months between October and December, when there is very little chance of fire occurrence. There was notable interannual variability of hotspot frequency across the study period spanning 20 years. Fire activity was low between 2001 and 2004. In 2005, a total of 663 hotspots were recorded, with 443 detected in February alone, linked to anomalously low rainfall. After this peak, activity fell between 2006 and 2013. But by 2014, hotspots surged again to 672, with February and March accounting for 359 and 293, respectively, under extremely low rainfall that resulted in damage from large peat fires (Field et al., 2009). Hotspot activity has shown a clear declining trend since 2015, with less activity being detected in 2017 and 2018 under wetter conditions due to government restoration of peatlands (e.g., blocking the canals, rewetting) (Ritzema et al., 2014; Sutikno et al., 2020d; Tan et al., 2022).

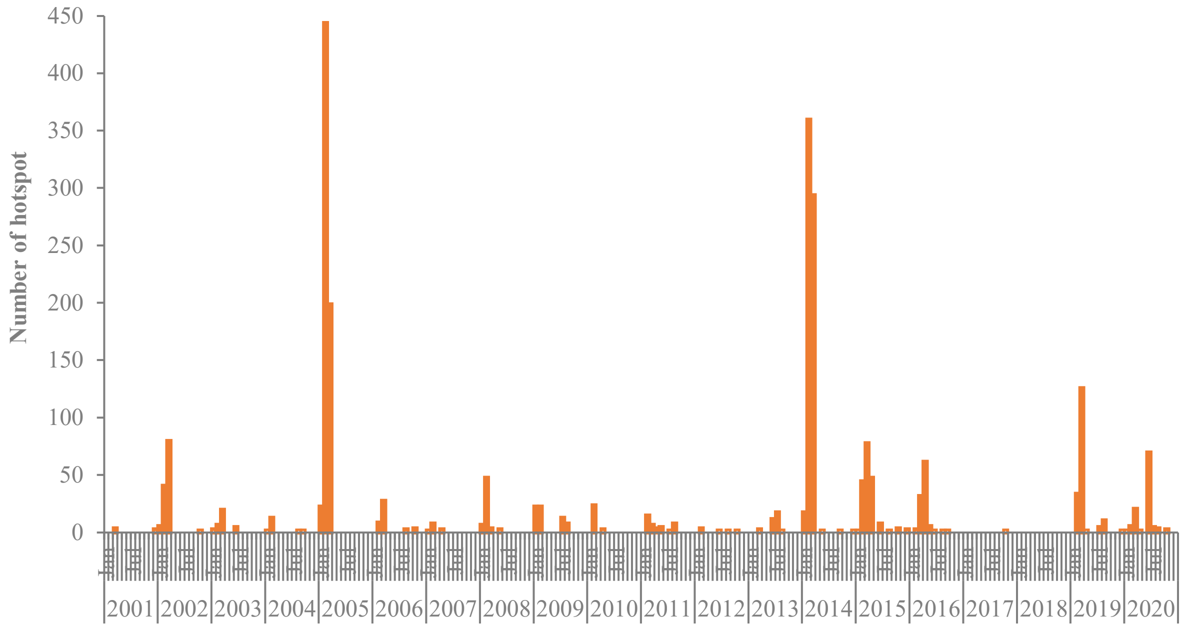


Figure 5. Monthly MODIS hotspot time series for PHU Bengkalis Island (2001-2020).

Table 2. Annual and monthly MODIS hotspot counts (confidence >60%) for PHU Bengkalis Island (2001-2020).

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
2001	0	0	3	0	0	0	0	0	0	0	0	2	5
2002	5	40	79	0	0	0	0	0	0	1	0	0	125
2003	2	6	19	0	0	4	0	0	0	0	0	0	31
2004	1	12	0	0	0	0	0	1	1	0	0	0	15
2005	22	443	198	0	0	0	0	0	0	0	0	0	663
2006	0	8	27	0	0	0	0	2	0	3	0	0	40
2007	1	7	0	2	0	0	0	0	0	0	0	0	10
2008	6	47	3	0	2	0	0	0	0	0	0	0	58
2009	22	22	0	0	0	0	12	7	0	0	0	0	63
2010	0	23	0	2	0	0	0	0	0	0	0	0	25
2011	0	14	6	3	4	0	1	7	0	0	0	0	35
2012	0	3	0	0	0	1	0	1	0	1	0	0	6
2013	0	0	2	0	0	11	17	1	0	0	0	0	31
2014	17	359	293	0	1	0	0	0	1	0	0	1	672
2015	1	44	77	47	0	7	0	1	0	3	0	2	182
2016	0	2	31	61	5	1	0	1	1	0	0	0	102
2017	0	0	0	0	0	0	0	0	0	1	0	0	1
2018	0	0	0	0	0	0	0	0	0	0	0	0	0
2019	0	33	125	1	0	0	4	10	0	0	0	1	174
2020	1	5	20	1	0	69	4	3	0	2	0	0	105
Total	78	1,068	883	117	12	93	38	34	3	11	0	6	2,343

Annual fire trends and severity

Figure 6 shows a dual y-axis chart of the annual burned area with the corresponding data for the hotspot in PHU Bengkalis Island over 20 years. The relationship between these two variables is both clear and consistent: years with a high number of detected hotspots are always associated with large burned areas. 2005 and 2014 were the two most severe fire years on record. There were 663 hotspot detections, with the burned area being 11,165 hectares in 2005. The most severe event occurred in 2014, which had the largest burned area of 19,999 ha and the highest number of hotspots (672). In 2014, the hotspot curve reached its maximum simultaneously with the burned-area bar, confirming that 2014 was the most catastrophic year in the record. A point of interest in Figure 6 is the 2002 event. With a total area burned of 11,985 ha (Period I = 9,080 ha; Period II = 2,905 ha), the number of hotspots detected was only 125. This difference suggests that, once it was ignited, the fire became extensive in 2002, as reflected by a significantly larger area burned per detected hotspot. This pattern may indicate extended dry periods that enabled rapid fire spread in the subsurface before enough hot spots were detected. It highlights the importance of using both burned area and hotspot counts as complementary metrics for evaluating fire severity. Both variables of interest have a downward trend since 2015. The years with near-zero values in 2017 and 2018 were the most fire-free across the entire 20-year record. A partial recovery in fire activity was, however, apparent in 2019 and 2020, visible in both the burned area and hotspot line. This indicates that the underlying fire risk in PHU Bengkalis has not been eliminated.

A further comparison of the number of hotspots during Period I (January-March) and Period II (June-August) for each year in the study period is provided in Figure 7. The data consistently show that Period I is dominant in terms of fire detections, reinforcing the importance of the January-March dry season as the primary window for fire activity in PHU Bengkalis.

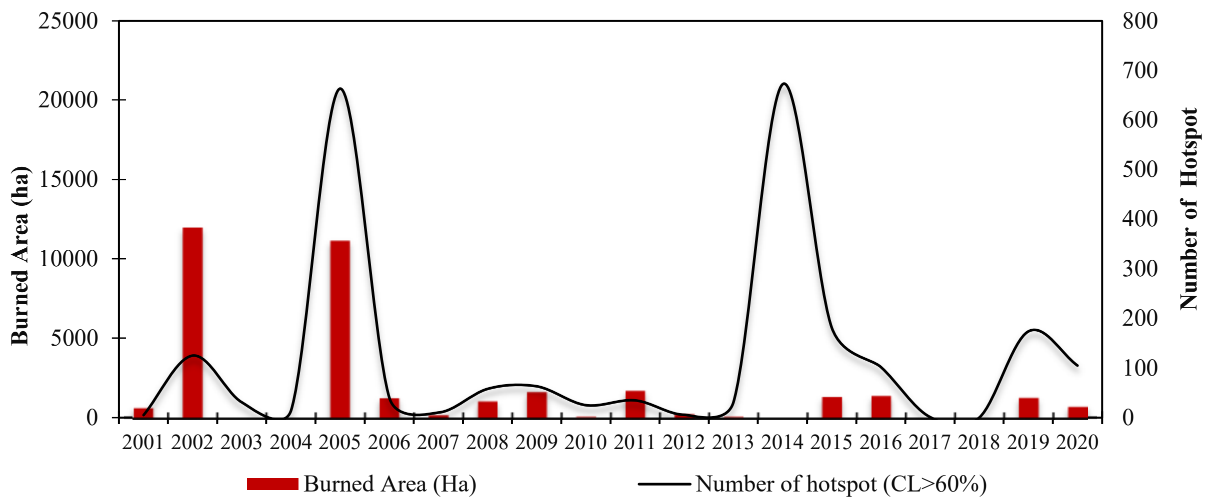


Figure 6. Annual burned area and MODIS hotspot counts for PHU Bengkalis Island, 2001-2020.

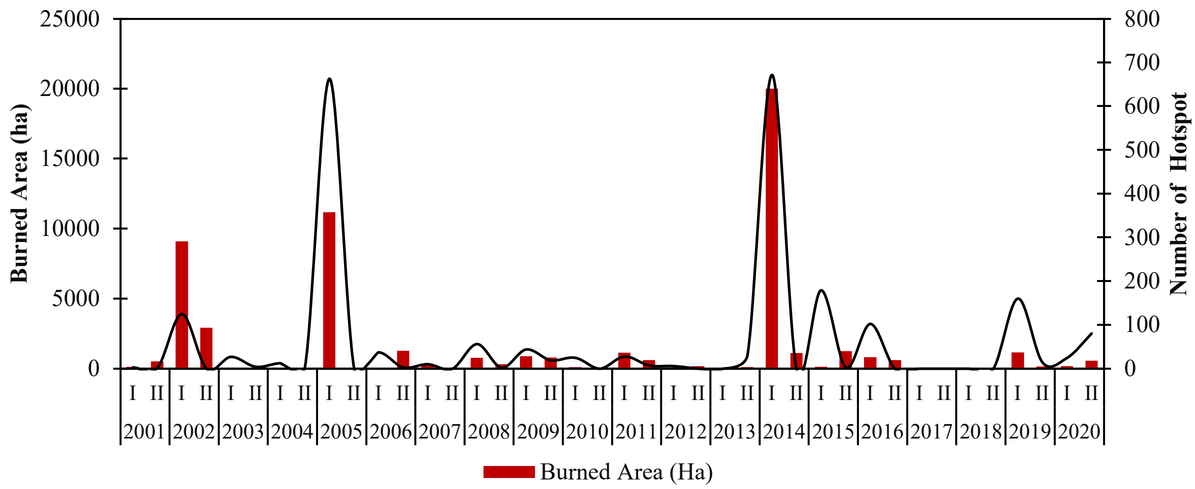


Figure 7 Semi-annual comparison of Period I (Jan-Mar) and Period II (Jun-Aug) hotspot counts, PHU Bengkalis Island, 2001-2020.

This trend is particularly evident in 2005 and 2014, where the number of hotspots identified in Period I was much higher than that of Period II. This difference is clear; however, the contribution of Period II should not be minimized. During some years, specifically those of 2013, 2016, and 2020, for example, Period II represented the majority of the yearly hotspot sum. This shows that June-August is also a high-fire-risk period, and it calls for continuous monitoring and targeted prevention strategies during that timeframe as well.

Fire characteristics

Table 3 presents the three fire characteristic parameters, burned area, fire duration, and fire rate, for each fire period over the 20-year study period. The area burned during a 20-year time series period in PHU Bengkalis was identified as 56,202 ha across 343 fire-days.

The most intense of these events was Period I of 2014, which burned 19,999 hectares in the course of a period spanning 48 days. It is also the highest total burned area in a single period and the longest duration fires recorded in the dataset. The 2005 Period I event, by comparison, lasted 44 days and burned 11,165 ha.Collectively, the fire events of 2014 and 2005 represent a large proportion of total impact: they account for around 55% of the area impacted over the lifetime of these data (20 years). This demonstrates how extreme fire years disproportionately affect the cumulative burned area, influencing the long-term fire history of PHU Bengkalis.

Table 3. Fire characteristics of PHU Bengkalis Island by period (2001-2020).

Year	Period	Burned Area (ha)	Fire Duration (days)	Fire Rate (ha/day)
2001	I	131	1	131
2001	II	517	1	517
2002	I	9,080	25	363
2002	II	2,905	1	2,905
2003	I	—*	13	—
2003	II	—*	3	—
2004	I	0	5	0
2004	II	24	1	24
2005	I	11,165	44	253
2005	II	0	0	0
2006	I	17	14	1
2006	II	1,270	2	635
2007	I	218	6	36
2007	II	0	0	0
2008	I	769	7	109
2008	II	306	2	153
2009	I	876	11	79
2009	II	781	8	97
2010	I	102	10	10
2010	II	0	0	0
2011	I	1,136	13	87
2011	II	597	5	119
2012	I	86	1	86
2012	II	177	3	59
2013	I	0	2	0
2013	II	108	9	12
2014	I	19,999	48	416
2014	II	1,116	3	372
2015	I	118	40	2
2015	II	1,238	3	412
2016	I	816	26	31
2016	II	598	3	199
2017	I	0	0	0
2017	II	0	0	0
2018	I	0	0	0
2018	II	0	0	0
2019	I	1,159	20	57
2019	II	144	7	20
2020	I	178	5	35
2020	II	559	1	559
Total		56,202	343	6,487

* No Landsat imagery available for 2003.

Figure 8 presents the relationship between annual hotspot detection frequency and total area burned across each year (Figure 8a) and within semi-annual periods, Period I and Period II (Figure 8b). Across the 20-year study period, a clearly positive and strong correlation is evident: the years with more hotspot detections burned significantly larger areas. This held true when the data were examined across the two major fire seasons, suggesting that the relationship is solid even at multiple temporal scales. In particular, 2005 and 2014 emerge as the most significant fire years in the historical record. In these years, exceptionally high hotspot counts, 663 in 2005 and 672 in 2014, were directly associated with the largest burned areas, measuring 11,165 ha and 19,999 ha, respectively, during Period I. In contrast, years characterized by low hotspot activity, such as 2001, 2007, 2012, 2017, and 2018, corresponded with either minimal or no recorded burned area. Further analysis of the semi-annual data (Figure 8b) supports the conclusion that this proportional relationship persists within both Period I and Period II individually.

This finding indicates that, at the seasonal level, the number of detected hotspots serves as a reliable indicator of the extent of burned area in PHU Bengkalis.

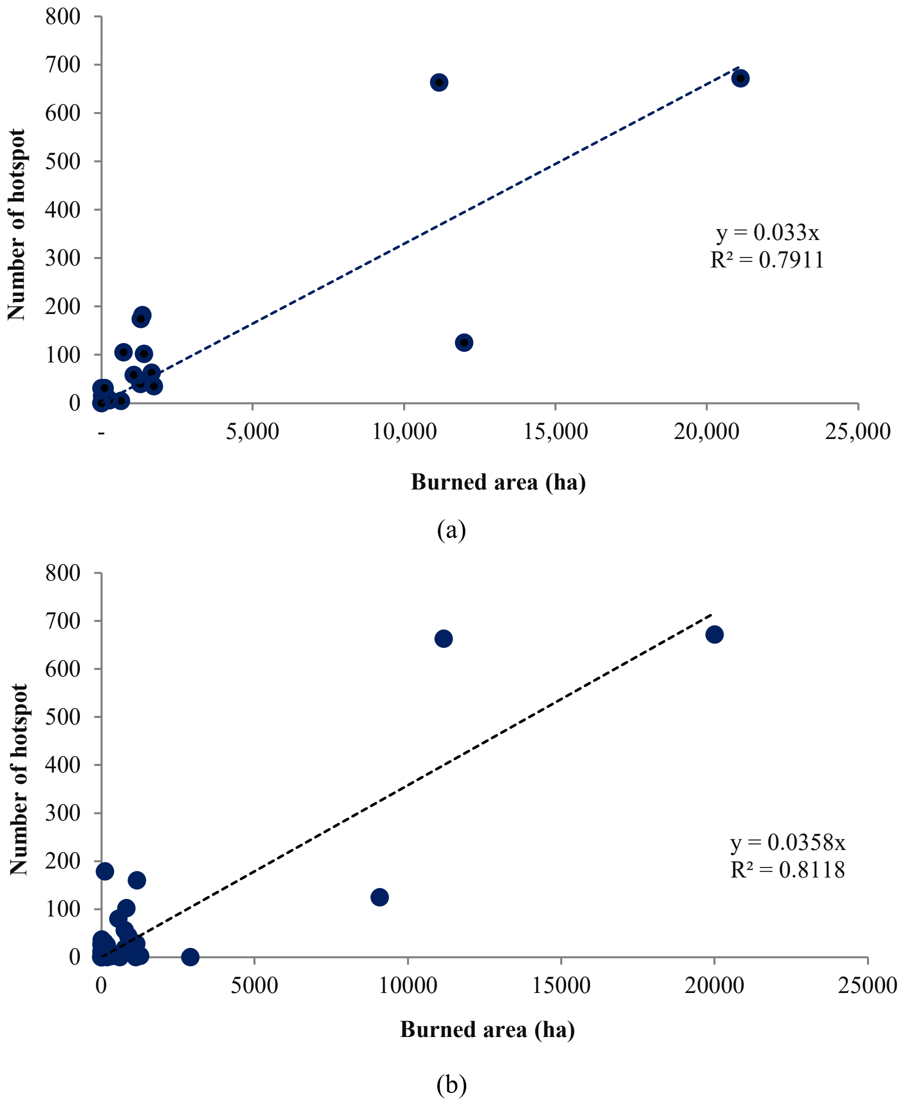


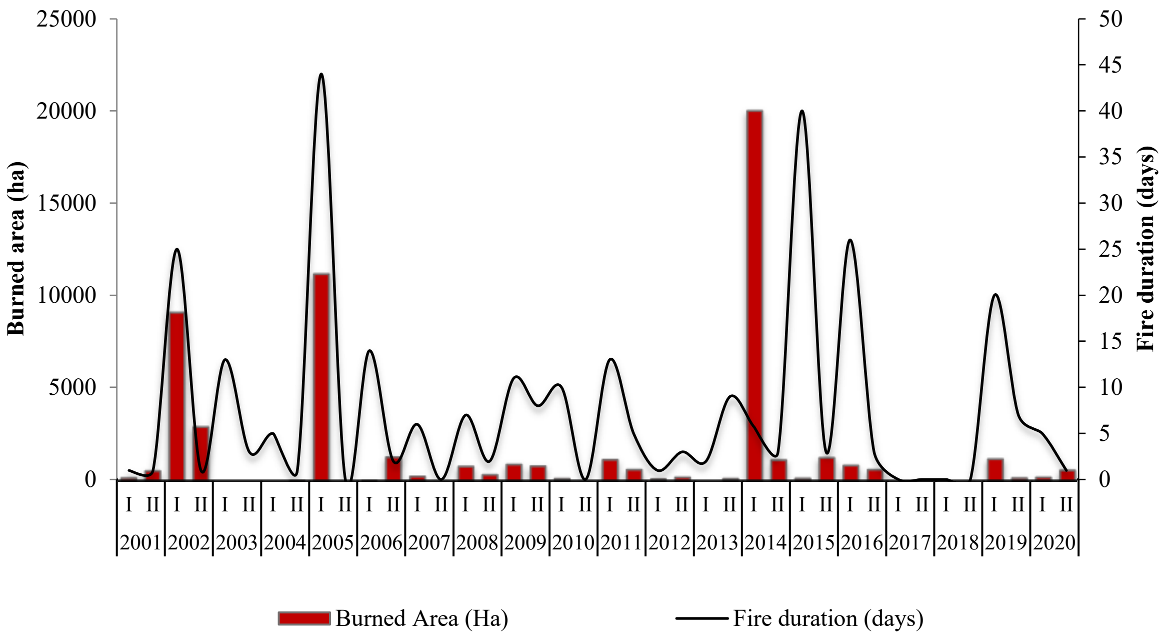
Figure 8. Relationship between annual MODIS hotspot counts and burned area for PHU Bengkalis Island (2001-2020): (a) annual scale; (b) semi-annual scale.

Annual burned area trends

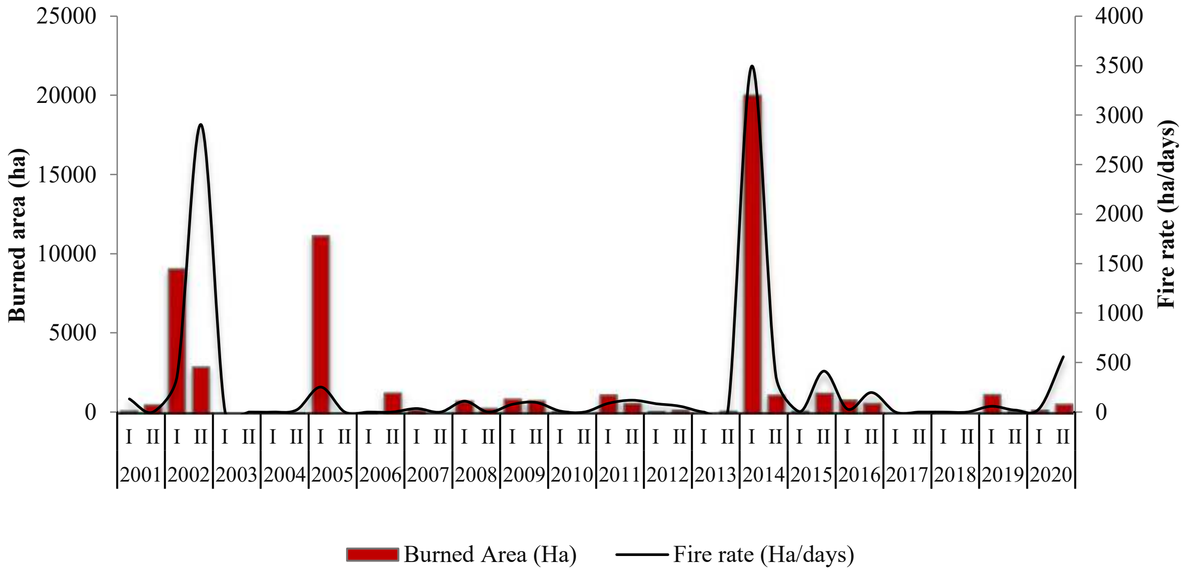
Figure 9 illustrates the changes in three key fire characteristic parameters over the course of the 20-year study period. The annual burned area time series (Figure 9a) highlights the episodic behavior of peat fire dynamics in PHU Bengkalis. Two main peaks occurred in 2005 and 2014, separated by periods of moderate to low fire activity. Particularly from 2016, a substantial drop in burned area can be noted. The distribution of the burned area between Period I (January-March) and Period II (June-August) clearly shows that in most years, the majority occurred during Period I. In some of the other years (such as 2002, 2006, and 2015), there is a significant contribution to annual burned area from Period II.

Fire rate captures the intensity of fire spread, and is highly variable across events (Figure 9b). The maximum fire rates happened in extreme moisture-deficit years: Period II of 2006 (635 ha/day) and Period II of 2014 (372 ha/day). The 2006 Period II fire rate was dominated by a very brief but intense event (1,270 ha burned in only 2 days), while the above-average 2014 Period II rate is indicative of ongoing rapid burning of peat that had been markedly desiccated due to the catastrophic Period I event earlier that year. This trend indicates that Period I fire can burn underground and emerge even more violently in Period II, which has been previously reported for deep peat fires (Usup et al., 2004; Wasis et al., 2019).

Since 2016, fire rates have dropped dramatically, with both 2017 and 2018 showing a burned area of zero. This is due to an increase in annual rainfall and firmer peatland management interventions of the BRGM program, such as by constructing canal blocks to rehydrate degraded peatlands (Jaenicke et al., 2010; Giesen and Sari, 2018). The large-scale increased fire activity in 2019 and 2020 (1,303 ha; 738 ha, respectively) indicated that the fire risk in PHU Bengkalis remains considerable, requiring continuous and long-term hydrological management to prevent its recurrence.



(a)



(b)

Figure 9. Temporal fire characteristics for PHU Bengkalis Island, 2001-2020: (a) burned area; (b) fire rate.

Rainfall-hotspot frequency relationship and practical implications for fire prevention

The relationship between monthly rainfall and hotspot frequency for PHU Bengkalis during 2010-2020 is presented in Figure 10. Data analysis reveals a clear and consistent inverse relationship: months with high hotspot counts invariably correspond to periods of low rainfall. In contrast, wet months (rainfall exceeding 200 mm/month) consistently record negligible hotspot activity. Dry months, defined as months with rainfall below 100 mm, consistently coincide with elevated fire danger. Most notably, February 2014 recorded only 1.83 mm of rainfall, the lowest monthly total in the study period, which coincided with the most catastrophic fire event in the 20-year record. This pattern is consistent with the trend observed in other tropical peatlands elsewhere in Indonesia, reinforcing previous conclusions that precipitation is the main climatic driver of fire activity on peat in archipelagic regions (Susilo et al., 2013; Marlier et al., 2015).

This inverse relationship between rainfall and fire risk is of considerable practical significance for fire prevention strategies. Near-real-time monthly rainfall data from the TRMM satellite can be used as a very valuable operational trigger for early warning alerts. If observed or predicted monthly precipitation reaches the lower threshold of 100 mm/month during Period I (January-March) and Period II (June-August), it is advised for fire prevention entities to take action that ensures increased monitoring and early water management measures. Such actions may include the closure of canal dams and an increase in rewetting efforts on vulnerable coastal peat, thus minimizing the occurrence and impact of fire during pivotal periods.

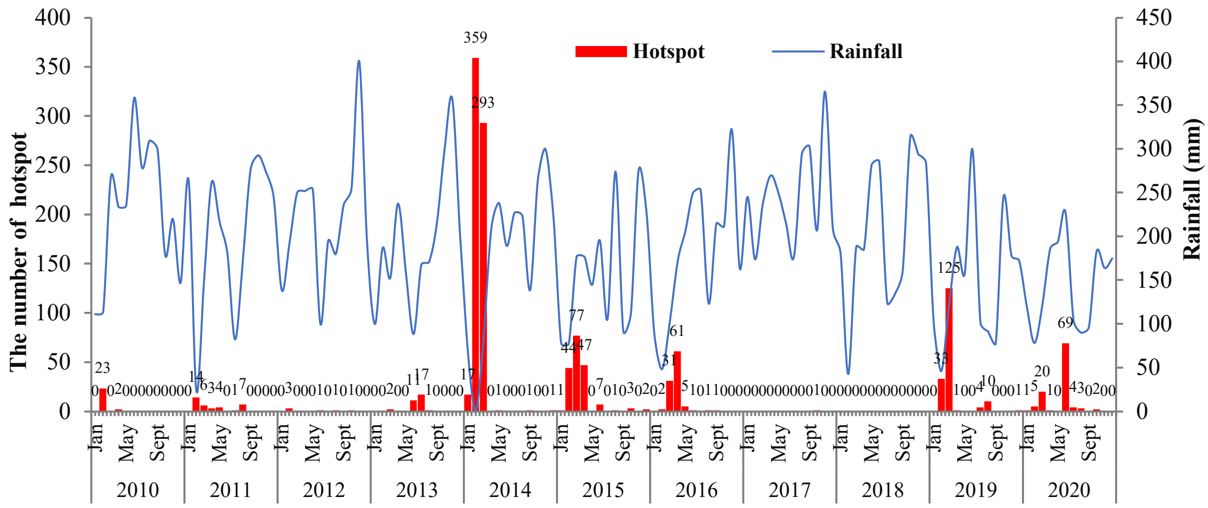


Figure 10. Monthly rainfall vs. MODIS hotspot frequency for PHU Bengkalis Island (2010-2020).

Conclusion

This study presents a comprehensive spatial and temporal analysis of wild peat fires on PHU Bengkalis Island, located in Riau Province, Indonesia, from 2001 to 2020, utilizing MODIS-C6 hotspot data and Landsat imagery. The principal findings are as follows:

1. Based on its seasonality, PHU Bengkalis Island consists of two main fire seasons annually, Period I (January-March) and Period II (June-August). The most severe fire years were 2005 and 2014. Fire activity showed a general declining trend from 2015 onward, reaching zero detections in 2018, though a partial resurgence was observed in 2019 and 2020.
2. The hotspot occurrences are spatially concentrated in zones of the deepest peat: 93.1% of detections were peat deeper than 300 cm. At the Sub-PHU level, a total of 45.8% were reported from Sub-PHU-5, followed by Sub-PHU-4 (23.1%), Sub-PHU-2 (16.0%), and Sub-PHU-3 (14.9%) detections. These zones correspond to regions of intense agricultural drainage, which lowers the water table and leaves dry peat exposed to ignition.
3. The cumulative burned area was 56,202 ha over the 20-year period. The largest individual fire event was Period I of 2014, with a duration of 48 days during which 19,999 ha were burned. Fire duration, burned area, and fire rate are positively and significantly correlated. Very high fire rates in Period II of selected years (e.g., 2006 and 2014) are explained by the persistence of underlying peat fires from extreme events caused by conditioning during Period I.
4. The main climatic variable controlling peat fire occurrence in PHU Bengkalis is monthly rainfall. The hotspot frequency exhibits a strong inverse relationship with respect to monthly precipitation. Dry-month fire risk conditions are defined by monthly rainfall less than 100 mm/month. Near-real-time TRMM satellite rainfall monitoring

provides a practical and cost-effective operational foundation for a fire early warning system in this remote island peatland setting.

Acknowledgements

This work was supported by the Ministry of Higher Education, Science, and Technology, Republic of Indonesia, under Grant No. 19593/UN19.4.1.3/AL.04/2025.

References

Aldrian, E. and Susanto, R.D. 2003. Identification of three dominant rainfall regions within Indonesia and their relationship to sea surface temperature. *International Journal of Climatology* 23(12):1435-1452, doi:10.1002/joc.950.

Field, R.D., van der Werf, G.R. and Shen, S.S.P. 2009. Human amplification of drought-induced biomass burning in Indonesia since 1960. *Nature Geoscience* 2(3):185-188, doi:10.1038/ngeo443.

Giesen, W. and Sari, E.N.N. 2018. Tropical peatland restoration report: the Indonesian case. Berbak Green Prosperity Partnership, MCA-Indonesia, Jakarta.

Harahap, R.M. 2018. High intensity hotspot distribution areas in Riau Province 2005-2014. *Jurnal Geografi Lingkungan Tropik* 2(1):11-25, doi:10.7454/jglitrop. v2i1.30 (*in Indonesian*).

Holden, J., Evans, M.G., Burt, T.P. and Horton, M. 2006. Impact of land drainage on peatland hydrology. *Journal of Environmental Quality* 35(5):1764-1778, doi:10.2134/jeq2005.0489.

Illés, G., Sutikno, S., Szatmári, G., Sandhyavitri, A., Pásztor, L., Kristijono, A., Molnár, G., Yusa, M. and Székely, B. 2019. Facing the peat CO_2 threat: digital mapping of Indonesian peatlands—a proposed methodology and its application. *Journal of Soils and Sediments* 19(11):3663-3678, doi:10.1007/s11368-019-02328-0.

Jaenicke, J., Wösten, H., Budiman, A. and Siegert, F. 2010. Planning hydrological restoration of peatlands in Indonesia to mitigate carbon dioxide emissions. *Mitigation and Adaptation Strategies for Global Change* 15(3):223-239, doi:10.1007/s11027-010-9214-5.

Koh, L.P., Miettinen, J., Liew, S.C. and Ghazoul, J. 2011. Remotely sensed evidence of tropical peatland conversion to oil palm. *Proceedings of the National Academy of Sciences* 108(12):5127-5132, doi:10.1073/ pnas.1018776108.

Koplitz, S.N., Mickley, L.J., Marlier, M.E., Buonocore, J.J., Kim, P.S., Liu, T., Sulprizio, M.P., DeFries, R.S., Jacob, D.J., Schwartz, J., Pongsiri, M. and Myers, S.S. 2016. Public health impacts of the severe haze in Equatorial Asia in September-October 2015: demonstration of a new framework for informing fire management strategies to reduce downwind smoke exposure. *Environmental Research Letters* 11(9):94023, doi:10.1088/1748-9326/11/9/094023.

Marlier, M.E., DeFries, R.S., Kim, P.S., Koplitz, S.N., Jacob, D.J., Mickley, L.J. and Myers, S.S. 2015. Fire emissions and regional air quality impacts from fires in oil palm, timber, and logging concessions in Indonesia. *Environmental Research Letters* 10(8):85005, doi:10.1088/1748-9326/10/8/085005.

Marlier, M.E., DeFries, R.S., Voulgarakis, A., Kinney, P.L., Randerson, J.T., Shindell, D.T., Chen, Y. and Faluvegi, G. 2013. El Niño and health risks from landscape fire emissions in Southeast Asia. *Nature Climate Change* 3(2):131-136, doi:10.1038/nclimate1658.

Miettinen, J., Shi, C. and Liew, S.C. 2011. Deforestation rates in insular Southeast Asia between 2000 and 2010. *Global Change Biology* 17(7):2261-2270, doi:10.1111/j.1365-2486.2011.02398.x.

Miettinen, J., Shi, C. and Liew, S.C. 2016. Land cover distribution in the peatlands of Peninsular Malaysia, Sumatra and Borneo in 2015 with changes since 1990. *Global Ecology and Conservation* 6:67-78, doi:10.1016/ j.gecco.2016.02.004.

Murdiyarso, D., Hergoualc'h, K. and Verchot, L.V. 2010. Climate mitigation and food production in tropical landscapes special feature: Opportunities for reducing greenhouse gas emissions in tropical peatlands. *Proceedings of the National Academy of Science* 107(46):19655-19660, doi:10.1073/pnas.0911966107.

Osaki, M. and Tsuji, N. 2016. *Tropical Peatland Ecosystems*. Springer, doi:10.1007/978-4-431-55681-7.

Page, S.E., Rieley, J.O. and Banks, C.J. 2011. Global and regional importance of the tropical peatland carbon pool. *Global Change Biology* 17(2):798-818, doi:10.1111/ j.1365-2486.2010.02279.x.

Page, S.E., Siegert, F., Rieley, J.O., Boehm, H.D.V., Jaya, A. and Limin, S. 2002. The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature* 420(6911):61-65, doi:10.1038/nature01131.

Pratama, H., Sutikno, S. and Yusa, M. 2020. Modeling of groundwater level fluctuation in the tropical peatland area of Riau, Indonesia. *IOP Conference Series: Materials Science and Engineering* 796(1):12037, doi:10.1088/1757-899X/796/1/012037.

Putra, E.I., Cochrane, M.A., Saharjo, B.H., Graham, L., Thomas, A., Applegate, G., Saad, A., Setianto, E., Sutikno, S. and Prayitno, A. 2019. Developing a better understanding of tropical peat fire occurrences and dynamics. *IOP Conference Series: Earth and Environmental Science* 394(1):12044, doi:10.1088/ 1755-1315/394/1/012044.

Ritzema, H., Limin, S., Kusin, K., Jauhiainen, J. and Wösten, H. 2014. Canal blocking strategies for hydrological restoration of degraded tropical peatlands in Central Kalimantan, Indonesia. *Catena* 114:11-20, doi:10.1016/ j.catena.2013.10.009.

Sandhyavitri, A., Perdana, M.A., Sutikno, S. and Widodo, F.H. 2018. The roles of weather modification technology in mitigation of the peat fires during a period of dry season in Bengkalis, Indonesia. *IOP Conference Series: Materials Science and Engineering* 309(1):12016, doi:10.1088/1757-899X/309/1/012016.

Siegert, F. and Hoffmann, A.A. 2000. The 1998 forest fires in East Kalimantan (Indonesia): A quantitative evaluation using high resolution, multitemporal ERS-2 SAR images and NOAA-AVHRR hotspot data. *Remote Sensing of Environment* 72(1):64-77, doi:10.1016/S0034 -4257(99)00092-9.

Sukma, E.W. and Sutikno, S. 2025. Spatio-temporal analysis of meteorological drought index and peat fires using Google Earth Engine (GEE) in Pelalawan Regency, Riau. *International Journal of Peatland Research and Innovation* 1(1):44-55.

Susilo, G.E., Yamamoto, K. and Imai, T. 2013. Modeling groundwater level fluctuation in the tropical peatland areas under the effect of El Nino. *Procedia Environmental Sciences* 17:119-128, doi:10.1016/ j.proenv.2013.02.019.

Sutikno, S., Afdeni, S., Rinaldi, and Handayani, Y.L. 2020a. Analysis of tropical peatland fire risk using drought standardized precipitation index method and TRMM rainfall data. *AIP Conference Proceedings* 2255(1):70018, doi:10.1063/5.0013880.

Sutikno, S., Amalia, I.R., Sandhyavitri, A., Syahza, A., Widodo, H. and Seto, T.H. 2020b. Application of weather modification technology for peatlands fires mitigation in Riau, Indonesia. *AIP Conference Proceedings* 2227(1):30007, doi:10.1063/5.0002137.

Sutikno, S., Hidayati, N., Rinaldi, Nasrul, B., Putra, A. and Qomar, N. 2020c) Classification of tropical peatland degradation using remote sensing and GIS technique. *AIP Conference Proceedings* 2255(1):70022, doi:10.1063/5.0013881.

Sutikno, S., Rinaldi, M.Y., Nasrul, B., Yesi, C., Prayitno, A., Putra, A. and Ardi, M.G. 2023. Water management for integrated peatland restoration in Pulau Tebing Tinggi PHU, Riau. In: *Vulnerability and Transformation of Indonesian Peatlands* (pp 161-168), doi:10.1007/978-981-99-0906-3_9.

Sutikno, S., Rinaldi, R., Putri, R.A. and Khotimah, G.K. 2020d. Study on the impact of canal blocking on groundwater fluctuation for tropical peatland restoration. *IOP Conference Series: Materials Science and Engineering* 933(1):12052, doi:10.1088/1757-899X/933/1/012052.

Sutikno, S., Rinaldi, R., Saputra, E., Kusairi, M., Saharjo, B.H. and Putra, E.I. 2020e. Water management for hydrological restoration and fire prevention in tropical peatland. *IOP Conference Series: Materials Science and Engineering* 933(1):12053, doi:10.1088/1757-899X/933/1/012053.

Sutikno, S., Yusa, M., Rinaldi, R., Muhammad, A., Saputra, H., Wardani, K.S. and Yamamoto, K. 2026. Hydrological modeling of small coastal peat island in degraded peatlands of Bengkalis Island, Riau Province. *Journal of Degraded and Mining Lands Management* 13(1):9163-9175, doi:10.15243/jdmlm.2026.131.9163.

Tan, Z.D., Carrasco, L.R., Sutikno, S. and Taylor, D. 2022. Peatland restoration as an affordable nature-based climate solution with fire reduction and conservation co-benefits in Indonesia. *Environmental Research Letters* 17(6):64028, doi:10.1088/1748-9326/ac6f6e.

Turetsky, M.R., Benscoter, B., Page, S., Rein, G., Van Der Werf, G.R. and Watts, A. 2015. Global vulnerability of peatlands to fire and carbon loss. *Nature Geoscience* 8(1):11-14, doi:10.1038/ngeo2325.

Usman, M., Sitanggang, I.S. and Syaufina, L. 2015. Hotspot distribution analyses based on peat characteristics using density-based spatial clustering. *Procedia Environmental Sciences* 24:132-140, doi:10.1016/j.proenv.2015.03.018.

Usup, A., Hashimoto, Y., Takahashi, H. and Hayasaka, H. 2004. Combustion and thermal characteristics of peat fire in tropical peatland in Central Kalimantan, Indonesia. *Tropics* 14(1):1-19, doi:10.3759/tropics.14.1.

Wasis, B., Saharjo, B.H. and Putra, E.I. 2019. Impacts of peat fire on soil flora and fauna, soil properties and environmental damage in Riau Province, Indonesia. *Biodiversitas* 20(6):1770-1775, doi:10.13057/biodiv/d200632.

Yokelson, R.J., Saharjo, B.H., Stockwell, C.E., Putra, E.I., Jayarathne, T., Akbar, A., Albar, I., Blake, D.R., Graham, L.L.B., Kurniawan, A., Meinardi, S., Ningrum, D., Nurhayati, A.D., Saad, A., Sakuntaladewi, N., Setianto, E., Simpson, I.J., Stone, E.A., Sutikno, S., Thomas, A., Ryan, K.C. and Cochrane, M.A. 2022. Tropical peat fire emissions: 2019 field measurements in Sumatra and Borneo and synthesis with previous studies. *Atmospheric Chemistry and Physics* 22(15):10173-10194, doi:10.5194/acp-22-10173-2022.