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Monitoring of Post-fire Vegetation Succession on Peatland in Bengkalis Island, Riau Province

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Abstract

Peatlands are characterized by the accumulation of decomposed plant remains, which result in an organic carbon content of approximately 16 percent and form a layer at least 40 cm thick. Peat ecosystems play a crucial role in supporting biodiversity conservation, maintaining water availability, and regulating the climate. However, human activities threaten these functions, especially during the dry season, which often leads to extensive fires. Post-fire succession is a natural process through which the land attempts to restore its original state. Monitoring succession after peatland fires can be conducted using satellite-based remote sensing technology, which provides spatiotemporal information. This study utilized a time series of three Landsat satellites, namely Landsat 5 (TM), Landsat 8 (OLI), and Landsat 9 (OLI2), to monitor succession in burnt peat areas on Bengkalis Island from 2000 onward. Additionally, hotspot data from FIRMS NASA and MODIS were incorporated. The results showed a total of 3,689 hotspots recorded between 2005 and 2023. The confirmed land cover types in the succession area include swamps, water bodies, and oil palm plantations. The information from this research is expected to inform policymaking by the government or peatland area managers, and serve as a reference for further studies.

Keywords: fire activity, peatland, succession

1. Introduction

A peatland is a wetland ecosystem that functions as a global carbon store and is highly sensitive to climate change. Indonesia has 13.3 million hectares of tropical peatlands [1], which are mostly formed from the remains of dead plants that accumulate on wet or flooded land over long periods, eventually reaching a thickness of at least 40 cm and containing approximately 16 percent organic carbon. Peat ecosystems hold great potential for food crop agriculture because their hydrological systems can support water availability. However, the stability of the water supply depends on the condition of the land cover. Unsustainable land use, such as extensive plantation development, can alter peat thickness, lower the water table, and increase the risk of land fires during the dry season [2].

Land monitoring can be conducted using satellite-based remote sensing technology, which efficiently provides information on the dynamics of surface changes on Earth [3]. Additionally, unmanned aerial vehicle (UAV)-based technologies provide small-scale, high-resolution coverage [4]. The development of Earth observation satellite technology has produced various platforms suitable for surface monitoring. For instance, the Landsat satellite program has been operational for more than 30 years, culminating in the launch of the ninth-generation Landsat-9 satellite in September 2021 [5,6]. These satellites have provided vital information on Earth's surface dynamics, facilitating remote research. The

Landsat-9 series (L9), along with its predecessor (L8), offers reliable specifications with a spatial resolution of up to 30 meters and a temporal resolution of 16 days [7,8]. Landsat time-series imagery has been widely used in studies of vegetation cover dynamics. For example, Hu et al. [9] utilized Landsat 4/5 TM and Landsat 8 OLI imagery to monitor post-mining land reclamation in Antaibao, Shanxi Province. Similarly, Sirin and Medvedeva [10] reported evidence of peatland fires in Moscow, Russia.

The recurring threat of fires has jeopardized peatland ecosystems and may reduce the ecosystem services they provide. The social, economic, and health impacts of forest and peatland fires in Indonesia require active involvement from multiple stakeholders. Further research on post-fire recovery is needed to ensure that peatland ecosystems can resume their ecological functions effectively. Studying post-fire vegetation succession is essential to understanding how ecosystem services can be restored. Shepherd et al. [11] emphasized that recovery efforts on post-fire peatlands are crucial for conserving biodiversity and maintaining carbon storage. Peatland areas on Bengkalis Island are also vulnerable to fire events due to their extensive coverage and frequent occurrence of hotspots. Nevertheless, peatland vegetation can undergo natural succession following fire disturbances [12–14]. To explore the dynamics of this process, this study aims to monitor the occurrence of hotspots and post-fire vegetation development in the island's peatlands, located in Riau Province. The results are expected to provide insights into the number and spatial distribution of hotspots, as well as vegetation succession patterns derived from remote sensing data.

2. Materials and Methods

2.1. Study area

This research was conducted on Bengkalis Island, Bengkalis Regency, Riau Province (**Figure 1**). Bengkalis Regency is an area that covers the eastern part of the island of Sumatra. Bengkalis Regency has a lowland area with an average height between 2 and 6.1 meters above sea level (MSL). Other tropical climates are strongly influenced by the marine climate, with temperatures of 26°C to 32°C.

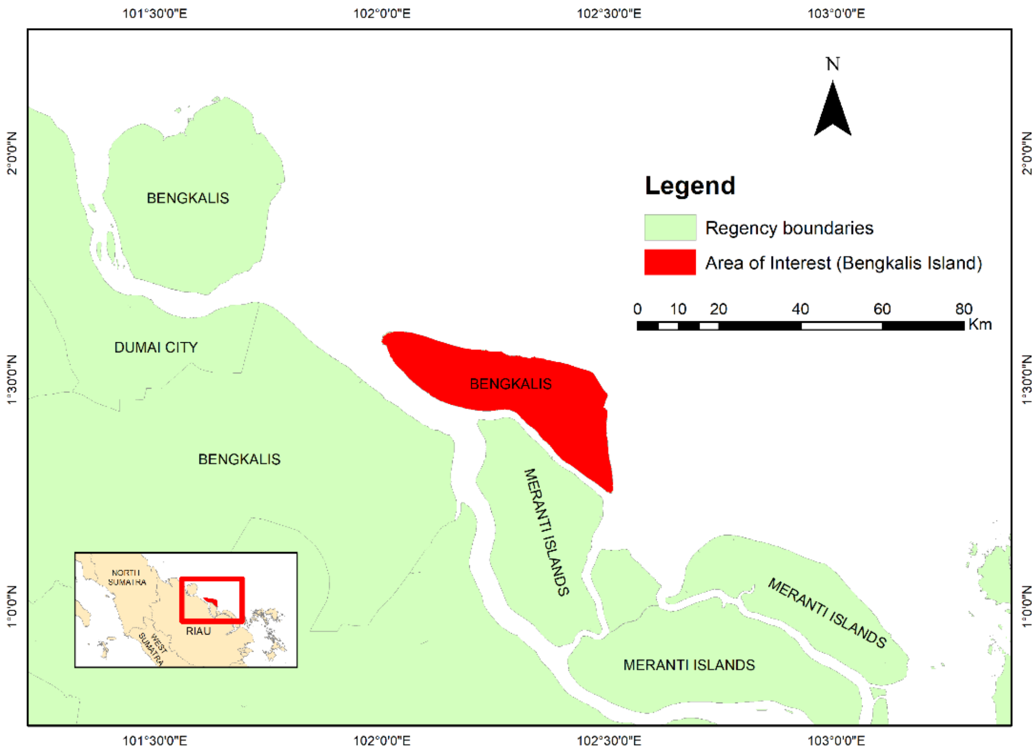

Figure 1. Research location in Bengkalis Island.

2.2. Data and data sources

This study utilizes two types of data, categorized by their functions: vegetation and fire monitoring data. Fire monitoring data utilized hotspot data from the Fire Information for Resource Management System (FIRMS) (https://firms.modaps.eosdis.nasa.gov/), which is owned by the National Aeronautics and Space Administration (NASA). This FIRMS data is a derivative product of data captured by the MODIS and VIIRS instruments. To monitor vegetation damaged by fire and succession, Landsat-5 Thematic Mapper (TM) and Multispectral Scanner (MSS), Landsat-8 Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS), and Landsat-9 Operational Land Imager 2 (OLI2) and Thermal Infrared Sensor 2 (TIRS2) satellite imagery were used. The Landsat time-series data were downloaded from the Earth Explorer platform (https://earthexplorer.usgs.gov/) of the United States Geological Survey (USGS). In addition, other image data used are MODIS (Moderate Resolution Imaging Spectroradiometer) images (https://modis.gsfc.nasa.gov/data/).

2.3. Fire identification

Fire identification was done using hotspot data derived from the FIRMS data. Hotspot data were collected from 2000 to 2023, resulting in information on fire trends for each year. These data were used as an indication of fire occurrences. The verification was conducted by comparing hotspot points and changes in vegetation cover, which demonstrated the impact of the fire. The Landsat data used covers the entire monitoring year, including both pre-fire and post-fire periods. This fire impact data will become the basis for succession monitoring.

2.4. Succession analysis

Succession analysis was conducted by monitoring time-series image data. Utilized time-series image data from the Landsat satellite with image acquisition from 2000 to 2023 (Landsat 5, Landsat 8, and Landsat 9). Additionally, this analysis utilized MODIS time-series imagery, producing output in the form of NDVI (Normalized Difference Vegetation Index) and EVI (Enhanced Vegetation Index) bands. The MODIS image (MODIS/006/MOD13A1) was acquired through a cloud computing process on the Google Earth Engine platform.

3. Results and Discussions

3.1. Result

3.1.1. Spatiotemporal monitoring of vegetation succession

Hotspots in the study area had been successfully detected using NASA FIRMS Hotspot data from 2000 to 2023, with a total of 3,689 hotspots. The highest number of hotspots, 998, was recorded in 2005, while the lowest number, one hotspot, was observed in 2018. **Figure 2** illustrates the spatiotemporal distribution of hotspots in the study area. Based on **Figure 2**, two years had a very high number of hotspots, 2005 (998 hotspots) and 2014 (986 hotspots), exceeding the average number of hotspots per year (160 hotspots).

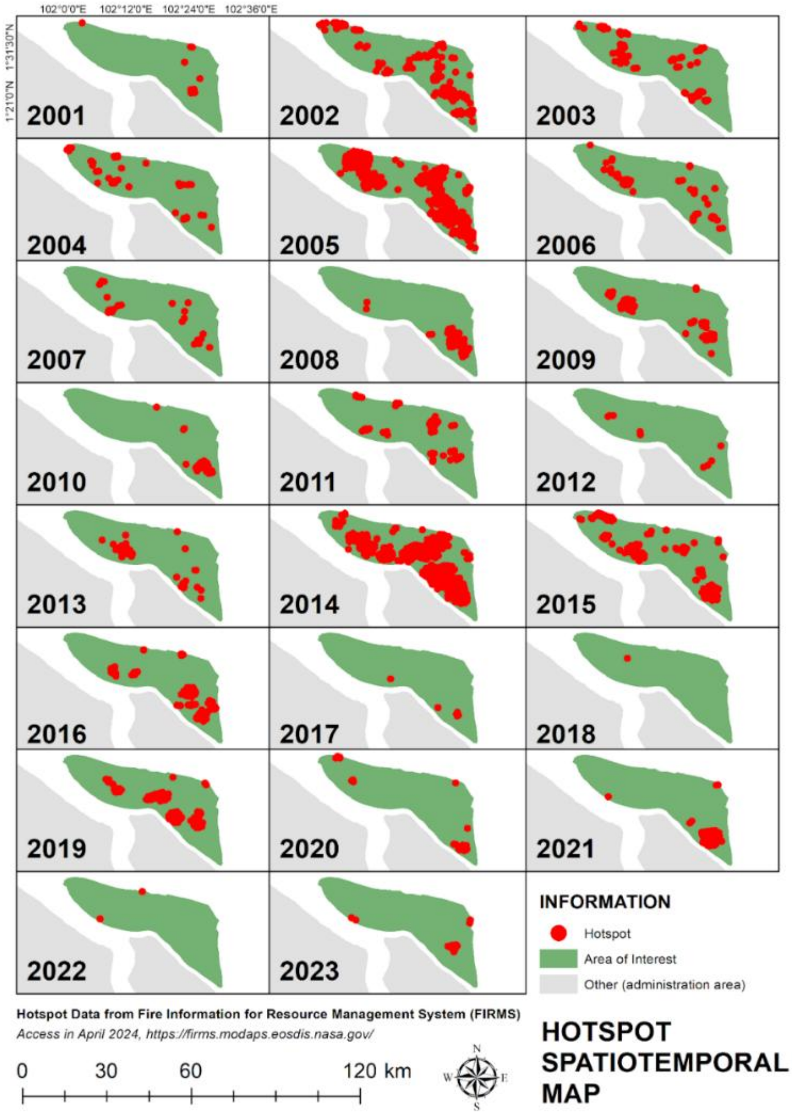

Figure 2. The spatiotemporal hotspot distribution map for 2001 – 2023 was used to see the hotspot distribution pattern based on 22 years on Bengkalis Island.

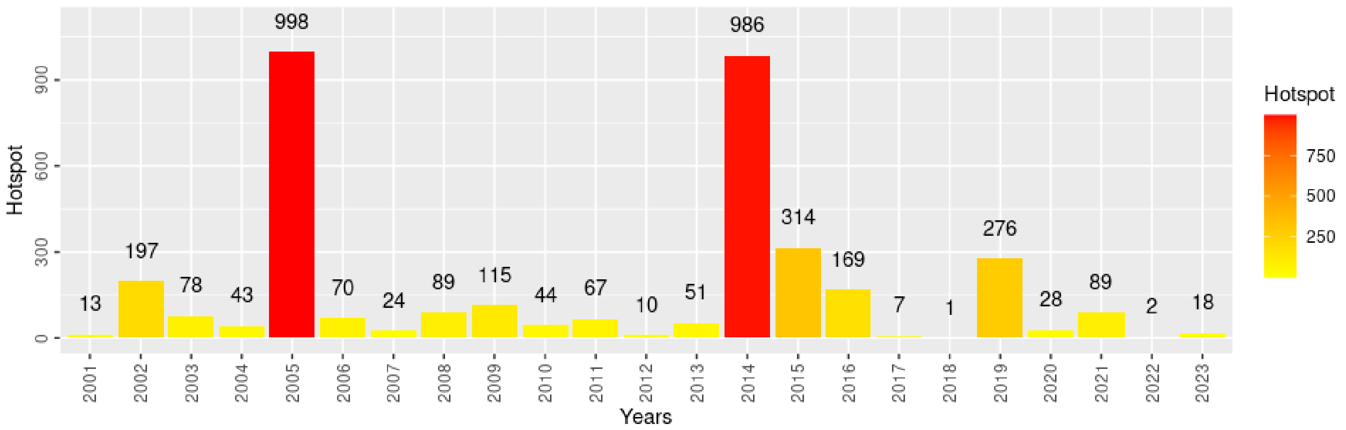

Figure 3. The hotspot detection from 2001 to 2023 decreased significantly and was represented by color from light (low) to dark (high) in 22 22-year period on Bengkalis Island based on FIRMS hotspot data. The highest number of hotspots was seen in 2005, reaching 998, while in 2014, the number reached 986.

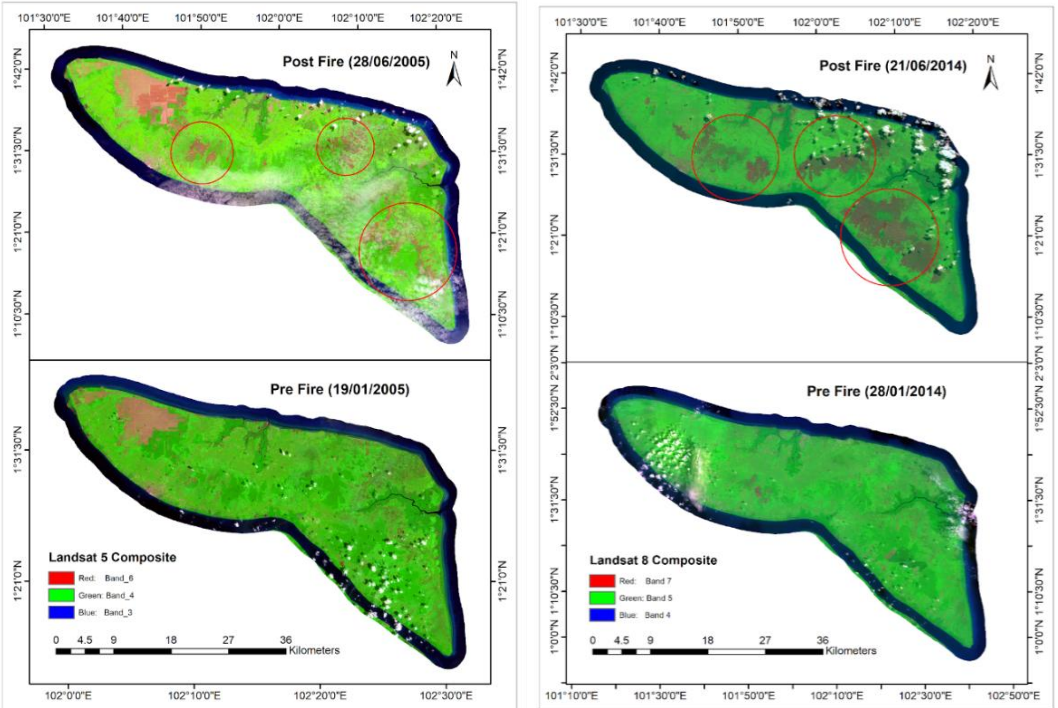

Figure 4. Vegetation damage due to fire activity in 2005 and 2014 was identified based on conditions before and after the fires. The pre-fire conditions in 2005 and 2014 are described. Post-fire conditions in 2005 and 2014 described the area's condition after the fire.

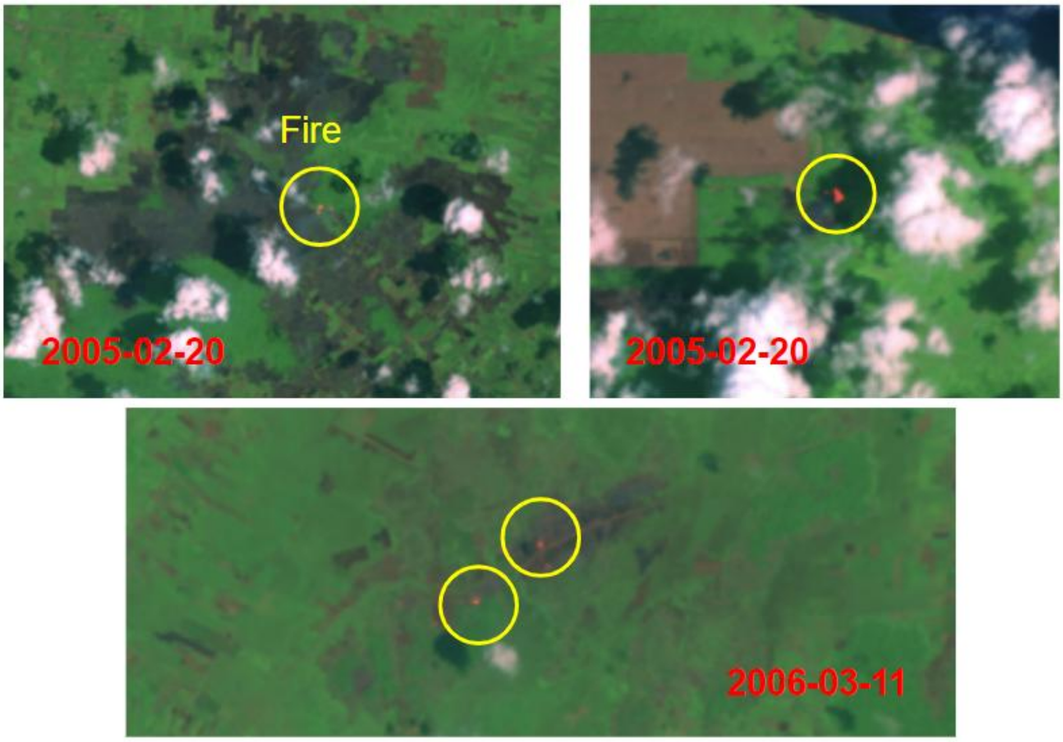

Figure 5. The fires that occurred can be detected spatially (red color in yellow circle) in Landsat images using the RGB composite (SWIR-NIR-Red).

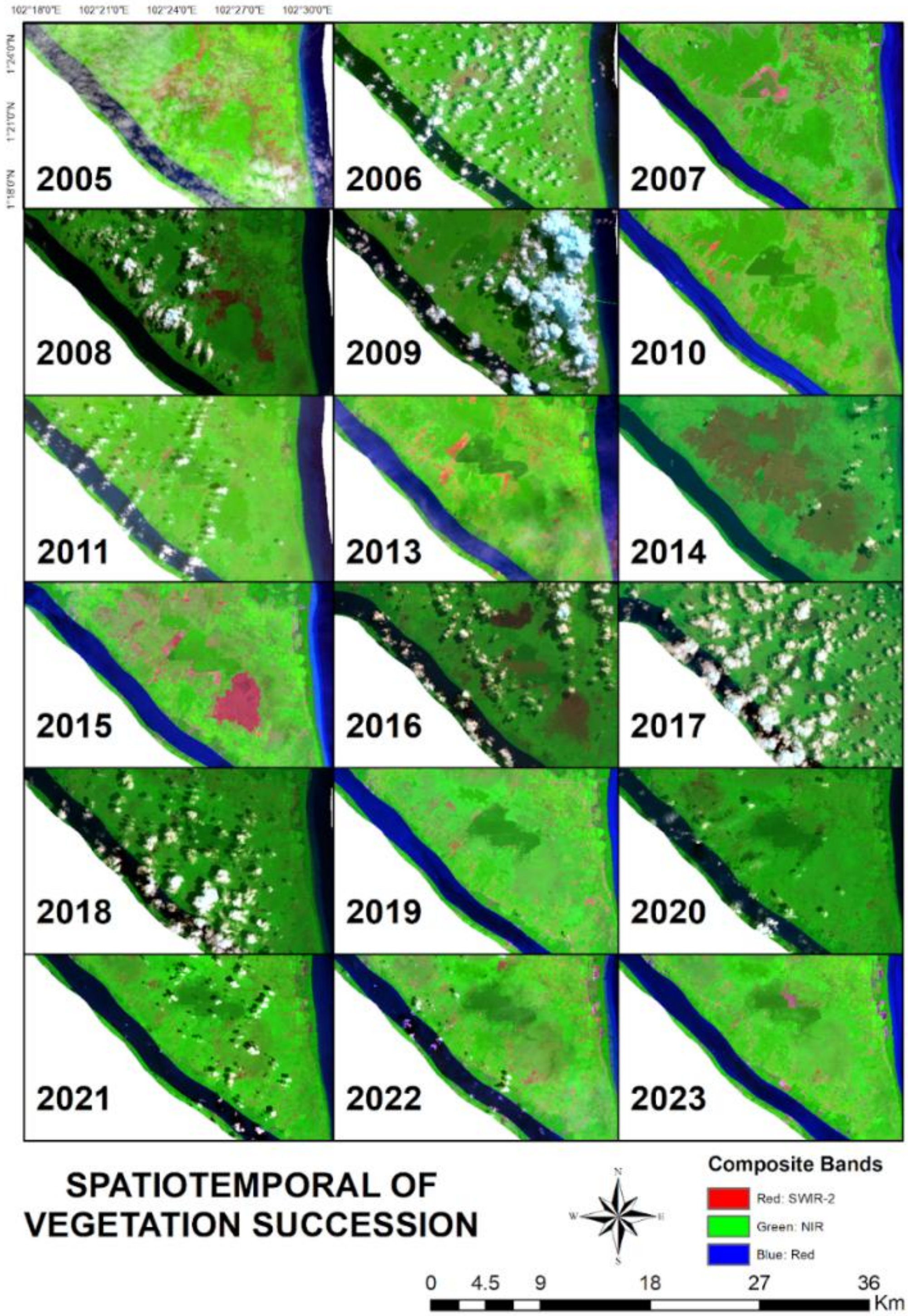

Figure 6. Spatiotemporal data on vegetation succession from 2005 to 2023 are used to examine the condition of vegetation succession over 18 years.

3.1.2. The trend of NDVI and EVI values

The evaluation of peatland succession after burning can be seen in **Figure 7**. This figure illustrates the trend of NDVI and EVI values from 2004 to 2020. The figure has two colors: the pink box indicates a change in the trend of NDVI and EVI values. The pink box indicates the presence of land fires, which can reduce NDVI and EVI values. This is due to the loss of vegetation after the fire.

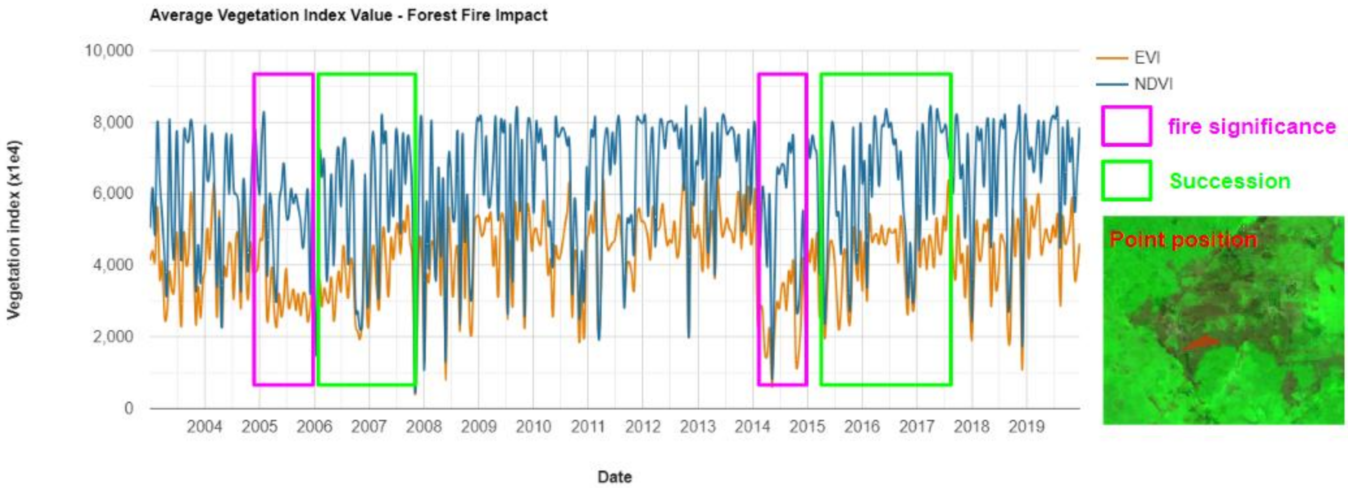

Figure 7. The trend of NDVI and EVI values from 2004 to 2019 visualizes the impact of fire and vegetation succession.

Forest fires and ecological succession processes were monitored using NDVI and EVI indices. Both indices exhibited significant declines during the 2005 – 2006 post-fire succession period, with NDVI reaching its nadir at approximately 0.3 while EVI remained marginally above 0.2. The most acute deterioration occurred in early 2006 when both indices fell below 0.2, signalling extensive vegetation loss. As a general pattern, NDVI values consistently exceed EVI values, reflecting their differential sensitivity to vegetation characteristics. The recovery phase persisted from 2015 through early 2018, during which EVI rebounded beyond 0.6 and NDVI recovered to 0.8. Trend analysis demonstrated that throughout the 2006–2008 succession interval, NDVI increased from approximately 0.3 to above 0.8, whereas EVI rose from around 0.2 to approximately 0.6. The comparatively faster recovery rate of EVI underscores its enhanced sensitivity in detecting early-stage vegetation regeneration.

3.2. Discussions

Bengkalis Island experiences an increase in the number of hotspots every five years. The global climate influences this, specifically the El Niño climate anomaly caused by the flow of water vapor mass from Indonesia to the Indian Ocean, which brings dry air [15]. The El Niño effect causes a delay in the onset of the rainy season, resulting in a longer dry season. Bengkalis Island is dominated by peatlands, an area prone to fires due to the fragile nature of peat. The presence of drainage, land clearing by burning, and the support of El Niño make peatlands highly susceptible to fire. These hotspots covered the study area indicated as peat (based on data from the Ministry of Agriculture, Indonesia) and the surrounding areas on Bengkalis Island [16]. Other regions with peatland conditions also face a high risk of fires every year. Another example is Riau Province, specifically in Meranti Islands Regency on Rangsang Island. The peat type on this island forms its own archipelago located along the coastline. Based on research conducted by [17], the distribution of hotspots in the Rangsang Island KHG tends to be in coastal areas. Coastal peat areas are highly vulnerable to fires due to the dominance of low-growing shrubs and the presence of shallow peat. These conditions cause island-type peat to have a high number of hotspots.

Bengkalis Island was chosen as the research location over other peatland areas in Riau because it has a significantly larger proportion of peatland than its total area, even larger than that of other areas in Riau. Approximately 65–74% of Bengkalis is covered by peatland. Additionally, the peat depth in Bengkalis tends to be deeper, meaning that if it catches fire, the flames are difficult to extinguish and can smoulder underground for extended periods, producing thick, prolonged smoke. Furthermore, according to [18], Bengkalis District has the second-highest number of hotspots from 2005 to 2023, following Rokan Hilir District. Therefore, these conditions necessitate special attention to the peatlands on this island in efforts to monitor forest and land fires. Bengkalis' geographical location, as an island close to the Malacca Strait, also has a high potential for causing transboundary smoke pollution that can affect neighboring countries, such as Malaysia and Singapore. This is not just a local issue but also a regional and international concern, so fire mitigation efforts in Bengkalis are crucial to prevent such impacts.

Burning peat will result in a decrease in function and existing biodiversity, disrupting ecological interaction processes. Monitoring the level of pre-fire and post-fire changes is necessary to observe the extent of environmental changes caused by fires. Based on **Figure 4**, the difference can be visually seen: 2014 had the worst fire intensity compared to 2005. Red circles indicate the burned areas (**Figure 4**). Post-fire vegetation damage does not correlate with the obtained hotspots (**Figure 3**). Although the number of hotspots in 2014 was less than in 2005, visually, the burned area was wider than in 2005. Hotspots do not always indicate forest fires, but many clustered hotspots (**Figure 2**) can indicate forest fires [19]. Hotspots can be used as indicators of potential forest fires [20]. The level of environmental change caused by fires can be seen through the succession process. Succession is an ecological process that shows changes in the structure of plant communities over time until a climax community is reached in a disturbed ecosystem [21]. Forest disturbances such as fires have created barren land in the area. This barren land becomes a site for secondary succession, a crucial part of the ecological restoration process.

Research on succession began in 2005, following fires on Bengkalis Island. Based on **Figure 6**, after the 2005 fires, the land recovered from 2006 to 2011. However, more severe fires occurred in 2014, and recovery occurred again in 2015 – 2023. The composite selection in **Figure 6** for 2005 – 2011 was obtained from Landsat-5, while 2013 – 2020 was obtained from Landsat-8 and 2021 – 2023 from Landsat-9. This composite selection was carried out to highlight both vegetated and non-vegetated areas. Composites involving infrared band combinations are one solution because they can display vegetation and non-vegetation land cover. The following research by Yuan et al. [22] Shows that the ability of infrared bands in NIR and SWIR bands can detect vegetation. In **Figure 5**, for example, on February 20, 2005, hotspots were in the burned area. This indicates that the burned land still has the potential to ignite. This information is essential for effective fire management in peatlands. Therefore, periodic land inspections and thorough fire suppression can be used in peatland fire management procedures. Another image in **Figure 5**, February 20, 2005, shows fires near oil palm plantations (east). In February, the fires were still outside the plantation area. Compared to the June 2005 image, the fires had spread to the oil palm plantation area. Vegetated areas have a green reflection, while burned areas (open land) are displayed in reddish-brown van Gerrevink [23].

Land fires affect ecological functions because they can eliminate some or all vegetation layers, thereby altering the composition and structure of forest types [24]. Changes in the composition and structure of forest types can potentially increase land degradation processes, such as soil erosion. Soil will be easily eroded because there is no ground cover vegetation. Vegetation functions as a soil binder. Additionally, there is a decrease in the availability of soil nutrients, which disrupts the life of microorganisms that play a crucial role in the decomposition process. The process of secondary succession can generally be categorised into two types: natural succession, which occurs without human involvement, and artificial succession, which involves human intervention. Natural succession can occur due to the ability of seed banks to germinate and the natural assistance of wild animals, which spread seeds by carrying them in their feces [25]. Naturally, secondary succession will occur after forest fires, a condition marked by the growth of pioneer vegetation until it reaches climax. According to Saharjo and Gago [26], succession typically begins with ground cover vegetation, such as grasses and shrubs, when a forest is damaged by natural or human causes. The forest will recover into a young secondary forest in 15 to 20 years if the soil is not severely damaged by erosion. Then it will become an old secondary forest in 50 years. Natural post-fire succession in secondary forests will approach the dominance of species in the natural succession community of unburned secondary forests. The natural post-fire succession community of secondary forests will gradually develop and form a community similar to that of an unburned secondary forest. Land recovery in 2006 – 2011 and 2013 –

2023 looks the exact (**Figure 6**). The forest can reach a climax state again if both forest communities are not disturbed [26].

According to Pérez-Cabello et al. [27] , land fires provide the potential for vegetation loss, affecting the value of vegetation indices in multispectral imagery. Conversely, 2-3 years after the fire, there is an increase in EVI and NDVI values (**Figure 7**). This increase in vegetation index values (EVI and NDVI) is influenced by post-fire vegetation succession. This increase in index values is consistent with spatial data in 2015 and 2016 in **Figure 6**, which shows vegetation cover in burned areas. This is consistent with research by Wang et al. [28], which explains that the increase in EVI values is influenced by vegetation growth and climate conditions. In addition, vegetation land cover correlates with NDVI values from MODIS imagery, so it can be used to predict the presence of vegetation [29]. Therefore, vegetation data (including above-ground biomass) obtained from field calculations can be used as parameters for assessing the impact of fires and correlated with fire index values (NBR, normalized burn ratio) [30].

Forest and land fires on Bengkalis Island occur frequently and form a five-year trend due to the influence of climate change, including El Niño, land clearing by burning, and ecosystem destruction through canal construction, which results in peat easily drying and being prone to fire. Peat fires will affect the succession process. Monitoring the succession process is necessary for ecosystem management. Succession monitoring is conducted using suitable satellite imagery. In addition, effective peat management and community efforts are necessary from both the government and the community. The recovery of burnt peat ecosystems depends on the landscape, the extent of damage, and the species present in it. Human intervention is necessary in sustainable peat management to facilitate a rapid recovery process. Therefore, coordinating various parties is essential in preventing more severe peat fires.

4. Conclusions

The vegetation recovery process following fires is reflected in the increase of both vegetation indices, with 3689 hotspots detected on Bengkalis Island from 2000 to 2023. Using satellite imagery provided information on the large fires in 2005 (998 hotspots) and 2014 (986 hotspots), NDVI showed a 0.5 increase while EVI demonstrated a 0.4 increase. This information is crucial for mitigating periodically recurring peatland fires (approximately every 10 years). Furthermore, these findings can serve as a valuable reference for post-fire recovery management and future research on post-fire ecological succession.

Author Contributions

NHP: Conceptualization, Methodology, Software, Investigation, Writing; **HBP**: Review, Editing, Supervision; **RA**: Conceptualization, Methodology, Software, Investigation, Writing; **MZ**: Review, Editing, Supervision; **LLN**: Review, Editing, Supervision; **HRS**: Conceptualization, Methodology, Software, Investigation, Writing; **FAR**: Investigation, Writing; **YS**: Review & Editing, Supervision

Conflict of Interest

We declare no conflict of interest with any financial, personal, or other relationships with other people or organizations related to the material discussed in the manuscript.

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