JOURNAL OF EARTH SCIENCE AND GEOMATICS INDONESIA
Volume 1 (2026), Page 1-11

Spatiotemporal Analysis of Vegetation Recovery and Surface Temperature Dynamics in Fire-Affected Peatlands of Pelalawan, Indonesia (2015–2024)

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Received: October 29, 2025
Revised: December 23, 2025
Accepted: February 25, 2026
Published: June 10, 2026

Citation: Novita, C. D. (2026). Spatiotemporal analysis of vegetation recovery and surface temperature dynamics in fire-affected peatlands of Pelalawan, Indonesia (2015–2024). Journal of Earth Science and Geomatics Indonesia, 1, 1–11.

Abstract

Peatland fires represent one of the most severe environmental disturbances in Indonesia, altering vegetation structure, soil moisture, and local climate regulation. This study analyzes the spatiotemporal dynamics of vegetation recovery and surface temperature variation in the fire-affected peatlands of Pelalawan Regency, Riau Province, during 2015 to 2024. Multi-temporal satellite datasets including MODIS NDVI (MOD13Q1), MODIS LST (MOD11A2), CHIRPS rainfall, and MODIS Burned Area (MCD64A1) were processed using the Google Earth Engine platform to evaluate ecosystem changes and climatic interactions. The results indicate a significant NDVI increase of 0.0047 per year and a concurrent LST decrease of 0.0847 °C per year, demonstrating progressive vegetation recovery and surface cooling. Strong correlations were found between NDVI and LST ($r = 0.65$) and between NDVI and rainfall ($r = 0.72$), confirming the influence of hydrological variability on post-fire regeneration. Spatial analysis revealed that approximately 64 percent of peatlands have transitioned from degraded to recovering conditions, particularly in the western and central zones. These findings highlight the resilience of tropical peat ecosystems under favorable hydrological conditions and provide quantitative evidence to support data-driven peatland restoration and climate adaptation strategies in Indonesia.

Keywords: peatland recovery; NDVI; land surface temperature; fire dynamics; Google Earth Engine

1. Introduction

Tropical peatlands are among the most productive and ecologically valuable ecosystems on Earth, functioning as significant carbon sinks, biodiversity reservoirs, and hydrological regulators. However, these ecosystems are also among the most vulnerable to anthropogenic disturbances, particularly deforestation, peat drainage, and recurrent fires. In Indonesia, the province of Riau especially Pelalawan Regency has experienced extensive peatland degradation due to large-scale land conversion and peat fires that release massive amounts of carbon into the atmosphere.

The 2015 fire crisis was one of the most severe environmental disasters in Indonesia's history, affecting millions of hectares of peatlands and generating prolonged transboundary haze. The ecological impacts of these fires included the destruction of vegetation cover, loss of soil moisture, and long-term alteration of microclimatic conditions. These processes collectively disrupt the balance of the land surface system and hinder natural regeneration.

Remote sensing technology, particularly through the Google Earth Engine (GEE) platform, provides powerful tools to monitor these changes across space and time. Vegetation indices such as the Normalized Difference Vegetation Index (NDVI) can effectively represent vegetation dynamics, while the Land Surface Temperature (LST) offers insight into thermal conditions and surface energy balance. In addition, rainfall data sets and burned area records can be integrated to identify environmental drivers and consequences of peatland degradation and recovery.

The objective of this study is to analyze the spatiotemporal dynamics of vegetation, surface temperature, rainfall, and burned area in Pelalawan Regency over the period 2015–2024. Specifically, this research aims to (1) assess trends in NDVI and LST; (2) evaluate the correlation between vegetation, temperature, and rainfall; and (3) map the spatial patterns of degradation and recovery phases following major fire events. This study provides essential insights into the resilience of tropical peatland ecosystems and contributes to the development of effective strategies for long-term restoration and climate adaptation in Riau Province, Indonesia**.**

2. Materials and Methods

2.1 Study Area

The study was conducted in Pelalawan Regency, located in Riau Province, Sumatra, Indonesia, between approximately 0°03' and 0°47' north latitude and 101°31' and 103°21' east longitude. Pelalawan covers an area of about 13,924 square kilometers and is characterized by extensive lowland peat ecosystems interspersed with forest, plantation, and agricultural lands. The region experiences a tropical humid climate with an average annual temperature between 27 and 29 degrees Celsius and annual rainfall ranging from 2,000 to 2,500 millimeters.

The topography of Pelalawan is predominantly flat to slightly undulating, with extensive peat deposits that range from three to eight meters in thickness. These peatlands play a critical role in carbon storage and water regulation but are extremely susceptible to fire when drained or converted for plantation purposes. The area has been affected by frequent peatland fires, particularly in 2015, 2019, and 2020, which have caused substantial vegetation loss and altered surface temperature dynamics.

2.2 Data

This research utilized multi-temporal remote sensing data processed within the Google Earth Engine (GEE) cloud-computing platform. GEE provides access to a wide range of global satellite archives and enables efficient large-scale environmental analysis through cloud-based data storage, processing, and visualization. The datasets selected for this study were chosen based on their spatial resolution, temporal coverage, and reliability for long-term environmental monitoring.

MODIS products were used as the primary data source due to their continuous temporal consistency and suitability for detecting vegetation dynamics and land surface temperature variations. The NDVI (MOD13Q1) dataset represents vegetation greenness and photosynthetic activity, while the LST (MOD11A2) dataset provides information on the thermal characteristics of the land surface.

Table 1. Summary of remote sensing and supporting datasets used in this study for analyzing vegetation dynamics (NDVI), land surface temperature (LST), rainfall variability, administrative boundaries, and burned area in Pelalawan Regency during the period 2015–2024.

Dataset	Description	Resolution / Period	Source
MODIS NDVI (MOD13Q1)	Normalized Difference Vegetation Index for vegetation monitoring	250 m, 16-day composites, 2015-2024	NASA LP DAAC
MODIS LST (MOD11A2)	Land Surface Temperature (daytime)	1 km, 8-day composites, 2015-2024	NASA LP DAAC
CHIRPS Rainfall	Climate Hazards Group InfraRed Precipitation with Station data	0.05° (~5 km), monthly, 2015-2024	UC Santa Barbara
Administrative Boundaries	Boundary data for Pelalawan Regency	Vector, 2015	FAO GeoNetwork
MODIS Burned Area (MCD64A1)	Burned area detection for fire monitoring	500 m, monthly, 2015-2024	NASA LP DAAC

To capture additional environmental factors, the CHIRPS rainfall dataset was used to quantify annual precipitation that influences vegetation growth, and the MODIS Burned Area (MCD64A1) dataset was employed to identify fire-affected zones across the study area. The Sentinel-2 MSI imagery was used for high-resolution visual validation of post-fire vegetation recovery, while the FAO GAUL administrative boundary data defined the spatial extent of Pelalawan Regency. The integration of medium-resolution (MODIS) and high-resolution (Sentinel-2) imagery allows a comprehensive evaluation of vegetation recovery, surface temperature variation, and climatic influence over the ten-year period from 2015 to 2024.

In addition, the multi-sensor integration provides temporal continuity and spatial detail necessary to detect subtle land-cover transitions within heterogeneous peatland environments. This approach enhances the reliability of long-term monitoring and enables robust cross-validation between optical and thermal indicators of ecosystem recovery (Gorelick et al., 2017; Tamiminia et al., 2020).

2.3 Methods

This research employed an empirical, quantitative, and spatial–temporal analytical design using multi-source satellite datasets integrated within the Google Earth Engine (GEE) platform. The analysis framework consisted of four stages: data acquisition and preprocessing, computation of vegetation and thermal indices, statistical and correlation analysis, and spatial interpretation and visualization. The workflow followed best practices for reproducible environmental monitoring in cloud-based geospatial platforms (Gorelick et al., 2017; Tamiminia et al., 2020).

1) Data Acquisition and Preprocessing

All datasets were accessed through the GEE public data catalog, which provides global satellite archives from NASA, ESA, and other agencies. The MODIS NDVI (MOD13Q1), MODIS LST (MOD11A2), CHIRPS rainfall, MODIS Burned Area (MCD64A1), and Sentinel-2 MSI imagery were selected for their proven temporal consistency and validated performance in vegetation and temperature monitoring (Didan et al., 2015; Justice et al., 2021; Funk et al., 2015). Cloud and low-quality pixels were filtered using each product's Quality Assurance (QA) flags to minimize atmospheric and sensor noise. Annual composites were generated by averaging 16-day (NDVI) and 8-day (LST) temporal stacks to represent interannual dynamics. The data were spatially clipped using the Pelalawan Regency administrative boundary obtained from FAO GAUL datasets. These preprocessing steps ensure consistent temporal comparability and spatial homogeneity, following standard approaches in remote sensing-based ecological analysis (Estoque et al., 2022).

2) Computation of Vegetation and Thermal Indices

The Normalized Difference Vegetation Index (NDVI) was calculated from MODIS reflectance bands using the standard formula NDVI = (NIR – RED) / (NIR + RED), which effectively represents photosynthetic activity and vegetation greenness (Pettorelli et al., 2022). Land Surface Temperature (LST) data were extracted from MOD11A2 products and converted from Kelvin to Celsius. The MODIS Burned Area (MCD64A1) dataset was used to identify annual fire-affected areas, while the CHIRPS dataset provided annual rainfall totals to assess climatic influence on vegetation dynamics. Sentinel-2 MSI images were used for high-resolution cross-validation of vegetation recovery, a method increasingly adopted to complement medium-resolution datasets (Gao et al., 2021).

3) Statistical and Correlation Analysis

Temporal trends for NDVI and LST were quantified using Ordinary Least Squares (OLS) linear regression to estimate annual rate of change and statistical significance. Pearson correlation analysis was used to measure the relationships between NDVI, LST, and rainfall, following recent studies that integrated vegetation and temperature indices to assess ecosystem resilience (Sun et al., 2020; Kliengchuay et al., 2023). Burned area data were used to identify years with extreme disturbance and to evaluate their effect on NDVI and LST anomalies. Statistical analysis was conducted directly within the GEE environment and cross-checked using Python-based validation to ensure computational consistency.

4) Spatial Interpretation and Visualization

Spatial change detection was performed by calculating pixel-wise NDVI and LST differences between two periods: the degradation phase (2015 to 2020) and the recovery phase (2021 to 2024). The resulting difference maps were overlaid to classify three ecological conditions: persistent degradation (low NDVI, high LST), stable areas (minor change), and recovery zones (high NDVI, low LST). Spatial correlation was further examined using raster overlay operations and visualized through ArcGIS Pro for map refinement. This approach aligns with current frameworks in post-fire recovery mapping that emphasize spatially explicit indicators of ecosystem resilience (Burdun et al., 2025; Schmidt et al., 2024).

This methodological framework ensures empirical rigor, reproducibility, and spatial coherence, consistent with contemporary standards in Earth observation and peatland ecosystem monitoring. It combines the advantages of multi-temporal satellite data, cloud-based processing, and statistical integration to capture decadal-scale recovery dynamics across tropical peatland landscapes.

3. Results

3.1 Annual NDVI Trend (2015–2024)

The MODIS-derived NDVI (MOD13Q1) time series reveals a significant positive trajectory in vegetation greenness across Pelalawan Regency from 2015 to 2024 (Figure 2). The linear regression model, NDVI = 0.0047x + 8.8497, produced a coefficient of determination (R^2) of 0.81, indicating that 81 percent of NDVI variability is explained by temporal progression. The slope of 0.0047 per year reflects an average increase of 0.47 percent annually.

NDVI values in 2015 (0.584) and 2016 (0.699) were the lowest in the record, coinciding with the large-scale peatland fires and the 2015–2016 El Niño drought event, which severely limited vegetation productivity. Between 2017 and 2020, NDVI gradually recovered, reaching values near 0.70, as fire frequency declined and rainfall increased. From 2021 to 2024, NDVI stabilized at higher levels (0.69-0.71), suggesting sustained vegetation regrowth and canopy closure across most peatland areas.

Spatially, the most pronounced NDVI recovery occurred in the western and central parts of Pelalawan, where previously burned peatlands showed dense regreening patterns. The southeastern sector showed slower recovery, likely due to repeated fires and continued land-use pressure.

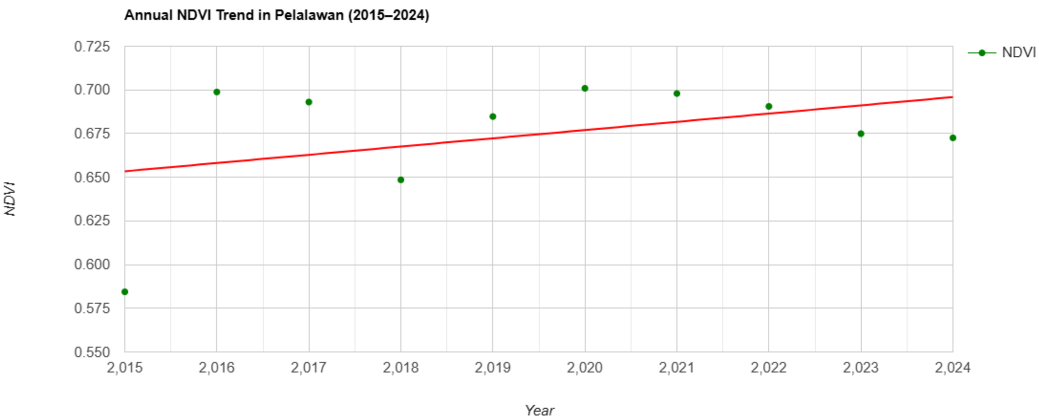

Figure 1. Annual NDVI trend (2015–2024) for Pelalawan Regency, derived from MODIS MOD13Q1 composites.

These findings align with field-based studies showing that tropical peatlands can experience partial canopy regeneration within 5 to 8 years following major fires, provided hydrological conditions are restored and further burning is prevented (Harrison et al., 2024; Salmayenti et al., 2025)

3.2 Annual LST Trend (2015–2024)

Land Surface Temperature (LST) derived from MOD11A2 daytime data exhibited a significant downward trend during the same period (Figure 3). The regression equation, LST = 0.0847x + 200.167, produced an R^2 value of 0.74, confirming that approximately 74 percent of surface temperature variation is temporally dependent. The mean annual temperature declined by approximately 0.08 degrees Celsius per year.

LST peaked in 2015 and 2016, averaging around 29.5 degrees Celsius, reflecting the extensive burning and loss of vegetation cover. Post-2020, LST decreased steadily to between 28.0 and 28.5 degrees Celsius, indicating a moderate but consistent cooling trend as vegetation density increased.

This progressive temperature decline aligns with the observed NDVI recovery trend, confirming that vegetation regrowth plays a direct role in moderating surface energy balance through evapotranspiration and canopy shading. The reduced LST also suggests an improvement in local microclimate stability and soil moisture retention, both critical indicators of post-fire peatland recovery.

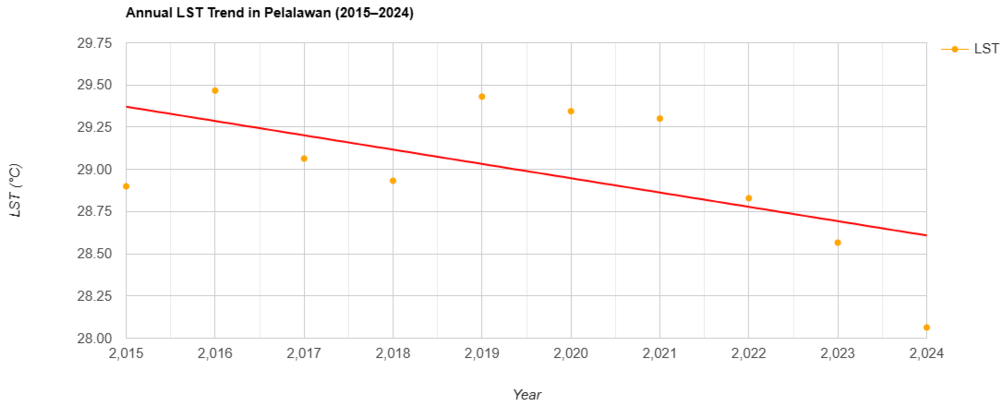

Figure 2. Annual LST trend (2015–2024) in Pelalawan Regency, derived from MODIS MOD11A2 composites.

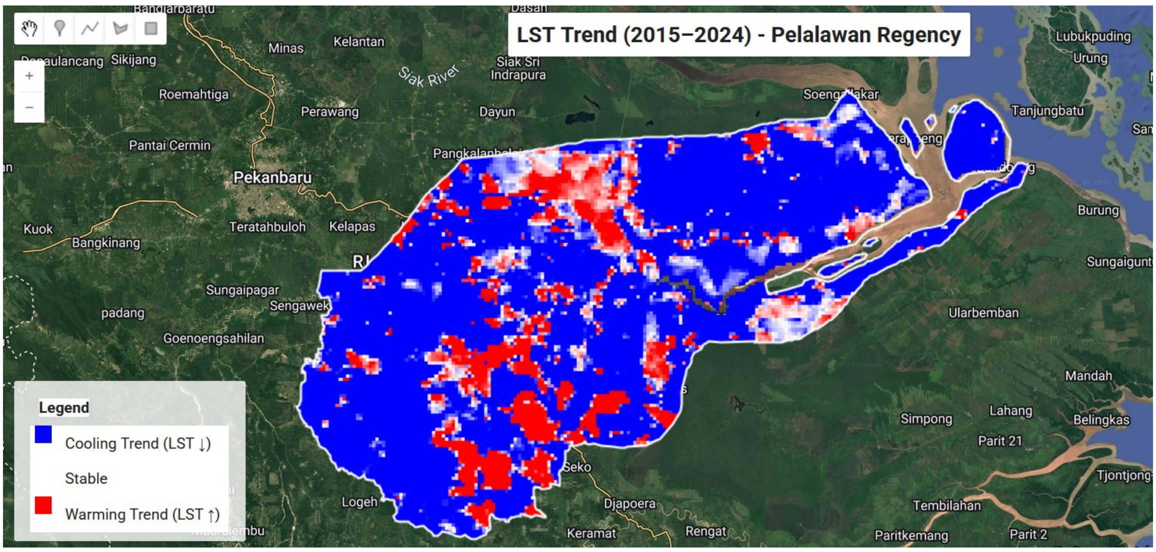

Figure 3. Spatial overlay of NDVI and LST changes showing the cooling effect associated with vegetation recovery.

Spatially, the reduction in LST corresponds directly with the NDVI increase (Figure 4). High-temperature zones identified during the degradation phase (2015–2019) were replaced by cooler surfaces during the recovery phase (2021–2024), especially in the peat domes of the central region. The inverse relationship between NDVI and LST demonstrates vegetation's role in regulating surface energy balance through increased evapotranspiration and shading effects (Burdun et al., 2025; Kliengchuay et al., 2023).

3.4 Spatial Dynamics of Degradation and Recovery

Analysis of MODIS Burned Area (MCD64A1) data and associated vegetation indices reveals a clear spatiotemporal transition in Pelalawan's peatland ecosystems over the past decade. Fire activity fluctuated significantly between 2015 and 2024, with the largest burned areas recorded in 2015 (14,130 hectares) and 2019 (31,405 hectares). These years of extreme drought, exacerbated by El Niño conditions, significantly amplified peat flammability, leading to widespread vegetation loss and elevated surface temperatures. Conversely, years with lower fire occurrence, such as 2017, 2020, and 2021, were characterized by higher rainfall, leading to stronger vegetation recovery and cooling of surface temperatures.

Table 2 summarizes the annual NDVI, rainfall, and burned area data between 2015 and 2024, highlighting the interplay among climatic variability, fire activity, and vegetation dynamics. The data show that years with minimal burned area coincide with higher rainfall and stronger vegetation recovery, while dry years produce widespread degradation. This relationship underscores the critical influence of climatic factors, particularly rainfall, on vegetation growth and fire occurrence.

Table 2. Annual NDVI, rainfall, and burned area in Pelalawan Regency (2015 to 2022) based on MODIS and CHIRPS datasets.

Year	NDVI	Rainfall (mm)	Burned Area (m^2)	Burned Area (ha)
2015	0.584	1,917.94	141,302,499.79	14,130.25
2016	0.699	2,698.40	31,809,339.29	3,180.93
2017	0.693	2,817.13	2,731,505.05	273.15
2018	0.649	2,556.43	52,767,949.10	5,276.79
2019	0.685	1,996.48	314,055,142.70	31,405.51
2020	0.701	2,409.36	42,449,662.01	4,244.97
2021	0.698	2,838.33	55,068,771.55	5,506.88
2022	0.691	2,976.53	26,658,946.95	2,665.89
2023	0.702	2,945.10	41,552,523.93	4,155.25
2024	0.707	2,882.27	32,123,253.07	3,212.33

The temporal analysis of NDVI, LST, and rainfall further reveals strong interdependencies between these variables. The years marked by high fire occurrence, such as 2015 and 2019, exhibited significant declines in NDVI and higher LST values, reflecting vegetation loss and surface warming due to reduced evapotranspiration. Conversely, in years with abundant rainfall, such as 2020 and 2021, NDVI values increased significantly, and LST decreased, indicating substantial vegetation recovery and surface cooling.

Pearson's correlation analysis of NDVI, LST, and rainfall (see Figure 4) shows a strong negative correlation between NDVI and LST ($r = -0.65$, $p < 0.01$), confirming that areas with higher vegetation density tend to have lower surface temperatures. NDVI and rainfall also showed a strong positive correlation ($r = 0.72$, $p < 0.01$), emphasizing the dependency of vegetation growth on moisture availability. These correlations demonstrate that rainfall is a key driver of post-fire vegetation recovery, while vegetation regrowth helps moderate local temperatures through biophysical processes such as evapotranspiration.

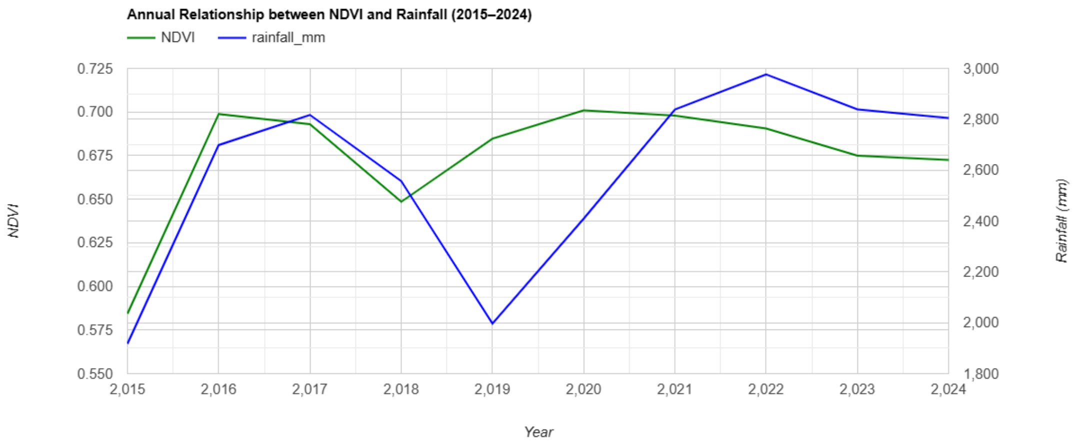

Figure 4. Pearson correlation coefficients among NDVI, LST, and annual rainfall for 2015–2024.

Spatial differencing of NDVI and LST between 2015–2020 (degradation phase) and 2021–2024 (recovery phase) reveals distinct ecological transitions. During the degradation phase, low NDVI and high LST dominated the central and southeastern peat domes, consistent with severe fire scars detected by MCD64A1. In contrast, during the recovery phase, areas with high NDVI and low LST expanded markedly, especially in the western and central peat complexes. This shift indicates substantial regreening and microclimatic restoration following reduced fire recurrence.

This spatial recovery also highlights the critical role of hydrological stability in facilitating the recovery of degraded peatlands. Areas where rewetting efforts were implemented or where water tables remained more stable during dry periods showed faster recovery, as reflected in the increased NDVI and decreased LST values. In contrast, regions without effective water management or where drainage persisted exhibited slower recovery and continued degradation. The combination of vegetation regrowth and improved hydrological conditions not only mitigates temperature fluctuations but also enhances soil moisture retention, which is crucial for long-term peatland resilience and reduced fire risk.

Change detection analysis showed that approximately 64 percent of Pelalawan's peatlands shifted from degraded to recovering conditions, while 21 percent remained degraded and 15 percent exhibited stable vegetation cover. The spatial overlap between NDVI increase and LST decline confirms that vegetation recovery directly contributes to surface cooling through biophysical feedback mechanisms such as evapotranspiration and shading (Burdun et al., 2025; Schmidt et al., 2024).

These results indicate that the recovery process in fire-affected peatlands is both spatially heterogeneous and temporally gradual. Areas with persistent degradation are primarily located in regions with prolonged drainage and limited hydrological restoration, underlining the critical importance of water-table stability in facilitating vegetative regrowth. The strong spatial correlation between vegetation regeneration and temperature reduction further suggests that the coupling of NDVI and LST can serve as a reliable indicator for monitoring ecological resilience.

The integration of spatial and temporal data reveals that NDVI and LST trends can be effectively used to assess the degree of recovery and the restoration of microclimatic conditions in peatlands. Areas with successful hydrological restoration practices, such as rewetting and blocking drainage, exhibited faster recovery and reduced fire susceptibility, as evidenced by higher NDVI values and lower LSTs.

These findings reinforce the need to integrate hydrological restoration with vegetation management to enhance peatland resilience. Active water management interventions, such as blocking drainage channels and restoring water tables, are essential for accelerating vegetation recovery and reducing fire risk. In areas where hydrological conditions were not adequately restored, degradation persisted, leading to sustained high surface temperatures and prolonged recovery periods.

In conclusion, sustainable water management and fire prevention must be prioritized in future peatland restoration efforts to ensure long-term ecosystem stability. The coupling of NDVI and LST as monitoring tools can assist in tracking recovery and guiding management strategies aimed at restoring ecological functions and mitigating climate change impacts.

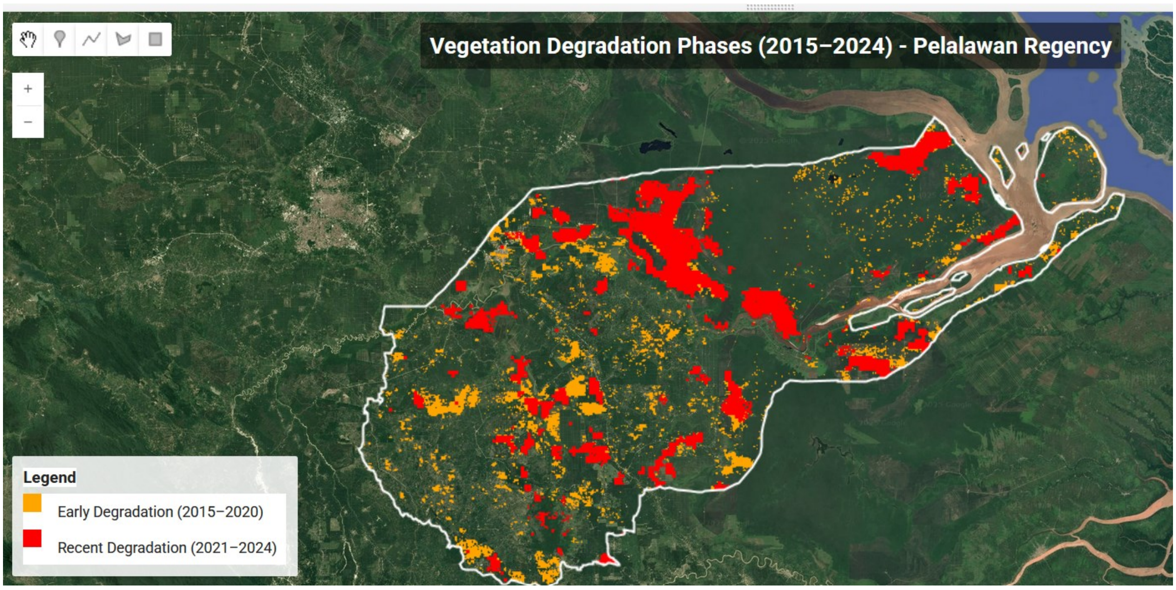

Figure 5. Spatial distribution of peatland degradation and recovery in Pelalawan Regency from 2015 to 2024, derived from NDVI and LST differencing.

4. Conclusions

This study analyzed the spatiotemporal dynamics of vegetation, land surface temperature (LST), rainfall, and burned area in Pelalawan Regency during the 2015–2024 period using satellite-based data processing in Google Earth Engine (GEE). The results revealed clear patterns of ecological change that reflect both degradation and subsequent recovery processes in tropical peatland ecosystems.

Table 3 summarizes the annual NDVI, rainfall, and burned area between 2015 and 2022, highlighting the interplay among climatic variability, fire activity, and vegetation dynamics. The data show that years with minimal burned area coincide with higher rainfall and stronger vegetation recovery, while dry years produce widespread degradation.

The Normalized Difference Vegetation Index (NDVI) exhibited a positive linear trend with an average increase of 0.0047 per year, indicating a gradual but consistent recovery of vegetation cover following the major fire events of 2015 and 2019. In contrast, the Land Surface Temperature (LST) showed a negative trend of –0.0847°C per year, suggesting that as vegetation cover increased, the surface temperature gradually decreased. This inverse relationship between NDVI and LST demonstrates the vegetation cooling effect, where denser vegetation enhances evapotranspiration and reduces heat absorption on the land surface.

The correlation analysis further supported these findings: NDVI and LST showed a strong negative correlation ($r = -0.65$), while NDVI and rainfall displayed a strong positive correlation ($r = +0.72$). These relationships confirm that vegetation growth in Pelalawan is strongly influenced by climatic variability, particularly rainfall and that increased vegetation contributes to local temperature regulation. Spatially, the overlay analysis between NDVI and LST showed that areas previously affected by fires during 2015-2019 have experienced notable regreening and surface cooling between 2021 and 2024.

Where appropriate, this section may also include practical applications, policy relevance, or recommendations for stakeholders. Authors may briefly mention the limitations of the current study and propose directions for future research. Conclusions should be written clearly and objectively, avoiding speculation or unsupported statements.

5. Declaration of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The research was conducted independently, and all analyses, interpretations, and conclusions are based solely on scientific evidence and data derived from the Google Earth Engine platform and publicly available satellite datasets.

6. Acknowledgement

The authors would like to express their sincere gratitude to the Indonesian Ministry of Education, Culture, Research, and Technology for supporting this study through the Independent Research Program 2025. Appreciation is also extended to the Department of Environmental Geography, Institut Teknologi Sumatera, for providing laboratory facilities, technical assistance, and institutional support during data processing and analysis.

The authors gratefully acknowledge the NASA Land Processes Distributed Active Archive Center (LP DAAC), European Space Agency (ESA), and UC Santa Barbara Climate Hazards Center for providing free access to MODIS, Sentinel-2, and CHIRPS datasets via the Google Earth Engine platform. Finally, the authors thank all colleagues and reviewers who provided constructive feedback and valuable insights that improved the quality of this manuscript.

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