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RESEARCH ARTICLE

Spatiotemporal Dynamics of Mangrove Cover in Aceh Tamiang Regency, Indonesia (2020–2024): An NDVI-Based Remote Sensing Assessment

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Abstract

This study examines spatiotemporal changes in mangrove cover and canopy density in Aceh Tamiang Regency, Indonesia, between 2020 and 2024, using an integrated remote sensing and field-based approach. High-resolution PlanetScope imagery (3 m) and Sentinel-2A data (10 m) were analyzed within a GIS framework, with the Normalized Difference Vegetation Index (NDVI) employed to classify mangrove density into three categories: dense (NDVI ≥ 0.43), moderate (0.33 ≤ NDVI < 0.43), and sparse (NDVI < 0.33). Results reveal a net loss of 379.65 hectares of mangrove cover—declining from 10,796.76 ha in 2020 to 10,417.11 ha in 2024—with over 99% of deforestation occurring in production forest zones, primarily due to conversion for aquaculture and oil palm plantations. Concurrently, dense mangrove areas decreased by 2,226 hectares (–18.9%), while sparse mangrove coverage expanded by 1,542 hectares (+28.1%), signaling ecosystem degradation despite localized natural regeneration. These structural changes undermine critical ecological functions, including coastal protection, blue carbon storage, and habitat provision for species such as Batagur borneoensis. The findings underscore the urgent need to integrate satellite-derived monitoring into district-level spatial planning, prioritize community-based rehabilitation in transitional zones, and strengthen enforcement of mangrove protection under Indonesia's Government Regulation No. 27 of 2025 to ensure long-term coastal resilience.

Keywords: mangrove, NDVI, land cover change, remote sensing, Aceh Tamiang, coastal management

1. Introduction

Mangrove ecosystems represent some of the most biologically rich and productive habitats in tropical coastal regions. They contribute significantly to ecological stability, climate change mitigation through blue carbon storage, and the socio-economic resilience of coastal populations (Alongi, 2012 ; Donato et al., 2011; Murdiyarso et al., 2010). Acting as natural coastal defenses, mangroves reduce the impacts of erosion, storm surges, and saltwater intrusion, while also providing critical habitat for diverse flora and fauna including threatened species such as the painted terrapin (*Batagur borneoensis*)(Giri et al., 2011; Saputra et al., 2021).

In addition to their ecological roles, mangroves support vital economic activities. They function as essential nursery grounds for commercially valuable fisheries, including fish, shrimp, and crabs, which underpin the livelihoods of millions of coastal residents (Barbier et al., 2011). Furthermore, mangrove-based ecotourism is emerging as a promising avenue for sustainable development, linking conservation with community-based income generation (Hussain et Badola, 2010).

At the national scale, Indonesia harbors one of the world's largest mangrove extents. The 2021 National Mangrove Map indicates that the country currently maintains approximately 3.4 million hectares of mangrove cover, with an additional 756,000 hectares identified as potential restoration sites . However, historical data reveal that Indonesia lost about 1.3 million hectares (31%) of its original 4.2 million hectares of mangrove between 1980 and 2005, primarily due to human-induced pressures. Aquaculture expasion has been the leading cause of mangrove conversion, followed by oil palm plantations, resulting in the degradation of nearly 800,000 hectares over three decades much of which now consists of unproductive or abandoned ponds (Ilman et al., 2016)

Despite these values, mangrove ecosystems in Aceh Tamiang Regency one of the areas with the most extensive mangrove cover in Aceh Province have faced increasing pressure from anthropogenic activities in recent years. Land conversion for aquaculture ponds, expansion of oil palm plantations, residential development, and unsustainable logging for charcoal and firewood have led to significant mangrove degradation (Alongi, 2012 ; Richards et Friess, 2016). This loss not only diminishes mangrove extent but also disrupts critical ecological functions, threatening biodiversity and the survival of species dependent on mangrove habitats.

To objectively assess these changes, spatially explicit approaches have become a global standard in coastal ecosystem monitoring. The Normalized Difference Vegetation Index (NDVI), derived from multispectral satellite imagery, is a reliable method for evaluating vegetation density and distinguishing between healthy, degraded, and deforested mangrove areas (Giri et al., 2011; Kuenzer et al., 2011). Theoretically, NDVI values range from -1 to +1 but the mangrove vegetation index values are generally in the range between +0,1 to +0,7. (Rizki et al., 2017) . While several studies have examined mangrove conditions across Aceh, a focused spatiotemporal analysis of Aceh Tamiang during the 2020–2024 period remains limited despite this interval encompassing accelerated coastal development and the implementation of Indonesia's strengthened legal framework for mangrove conservation under Government Regulation of the Republic of Indonesia No. 27 of 2025 on the Protection and Management of Mangrove Ecosystem. This study employed a comparative longitudinal remote sensing approach to assess spatio temporal changes in mangrove cover and canopy density in Aceh Tamiang Regency between 2020 and 2024.

Mangrove mapping using remote sensing technology is developing rapidly. Remote sensing technology in the marine sector, especially the classification and distribution of mangroves ((Maulana et al., 2026)). This methodology integrates multi-source satellite imagery, geospatial analysis, and standard vegetation indexing to ensure reproducibility and scientific accuracy.

Therefore, this study addresses the following research questions: (1) How has the spatial extent and canopy density of mangrove cover in Aceh Tamiang Regency changed between 2020 and 2024? and (2) what are the primary anthropogenic and ecological drivers underlying these changes? To answer these questions, the study (1) analyzes spatiotemporal dynamics of mangrove cover using NDVI derived from Sentinel-2 imagery, and (2) identifies dominant drivers through integrated spatial analysis and field-based interviews.

Fig 1. Geographic location of Aceh Tamiang Regency, Aceh Province, Indonesia, showing administrative boundaries and major coastal features, including the Tamiang River estuary and coastline along the Malacca Strait. The study area encompasses all mangrove zones within the regency's 65-km coastal stretch

2. Methodology

2.1 Study Area

The research was conducted in Aceh Tamiang Regency, Aceh Province, Indonesia (3°53′18.81″–4°32′56.76″ N, 97°43′41.51″–98°14′45.41″ E), at elevations of 20–700 m above sea level (Figure 1). The regency shares borders with East Aceh Regency and Langsa City (north), North Sumatra Province (east), Gayo Lues Regency (south), and East and Southeast Aceh Regencies (west). Its 65-km coastline along the Malacca Strait includes extensive mangrove forests, particularly in the Tamiang River estuary.

2.2 Data Sources

Two satellite datasets were used: PlanetScope imagery (3 m resolution; orthorectified Surface Reflectance product) acquired on June 30, 2020, and August 22, 2024, sourced via an academic license from Planet Labs through the NICFI Satellite Data Program. These images served as reference layers for manual digitization and validation.

Sentinel-2A Level 2A imagery (10 m resolution) from the Copernicus Open Access Hub, processed to bottom-of-atmosphere reflectance. Sentinel-2A imagery used in this study is relatively new to remote sensing. Sentinel-2A imagery is a satellite image that can be accessed for free and has a high spatial resolution of 10x10 m2 /pixel compared to other free satellite images that are often used, such as Landsat imagery which has a spatial resolution of 30x30 m2/pixel (Mastu et al., 2018) Sentinel is capable of observing the Earth's surface both during the day and at night, and its radar signals can penetrate cloud cover, making it unaffected by weather conditions (Chandra et al., 2025) . All images from 2020 and 2024 with cloud coverage <10% were selected using the cloudy pixel percentage metadata filter in Google Earth Engine (GEE).

2.3 Data Preprocessing

Sentinel 2A images underwent no additional atmospheric correction as Level 2A data are pre-processed with the Sen2Cor algorithm (v2.9). PlanetScope images were geometrically and radiometrically calibrated using standard orthorectification and reflectance scaling procedures in ArcGIS Pro 3.1. A median composite was generated in GEE for each year to minimize residual cloud and noise effects.

2.4 NDVI Calculation and Mangrove Density Classification

The Normalized Difference Vegetation Index (NDVI) was computed in GEE using the formula:

$$NDVI = \frac{(NIR+Red)}{(NIR-Red)}$$

The NDVI values derived from this formula were subsequently used as the basis for classifying mangrove canopy density. Higher NDVI values indicate denser and healthier vegetation conditions. In this study, NDVI was calculated using Sentinel-2A satellite imagery by utilizing the Near Infrared (NIR) band and the Red band, which are particularly effective for distinguishing vegetation vigor and canopy density in mangrove ecosystems. Referring to the Guidelines for Mangrove Inventory and Identification published by the Ministry of Forestry (2006), the classification of mangrove canopy density using the NDVI method is as follows:

a) Dense canopy cover ($0.43 \leq NDVI \leq 1.00$)
b) Moderate canopy cover ($0.33 \leq NDVI \leq 0.42$)
c) canopy cover ($-1.00 \leq NDVI \leq 0.32$)

2.5 Mangrove Extent Delineation

Mangrove boundaries for 2020 and 2024 were manually digitized by visual interpretation of PlanetScope imagery in ArcGIS Pro 3.1, using spectral pattern, texture, and spatial context as interpretive keys. Only areas dominated by mangrove species (e.g., *Rhizophora, Avicennia*, *Sonneratia*) were included. The resulting vector layers served as baseline and validation datasets.

2.6 Change Detection and Spatial Analysis

Temporal change in mangrove extent was quantified by overlaying the 2020 and 2024 digitized layers. Area computations (in hectares) and percentage change were derived using the "Tabulate Intersection" tool in ArcGIS Pro. Spatial hotspots of loss and gain were mapped to identify priority zones for conservation or restoration.

2.7 Accuracy Assessment

The land cover interpretation analysis was conducted using PlanetScope satellite imagery with a spatial resolution of 3 meters. The interpretation results were subsequently validated using high-resolution satellite imagery from Google Earth. This approach was adopted due to the author's limitations in conducting field surveys, particularly under post-disaster conditions in Aceh Tamiang Regency, which restricted mobility and access to the study area.

Examples of the validation process are presented in the accompanying figure 2, which illustrates the visual comparison between PlanetScope imagery and Google Earth data for selected locations. This comparison demonstrates a strong spatial correspondence between the interpreted mangrove classes and the reference imagery. Based on this validation approach, the author is confident that the interpretation results achieve a high level of accuracy. However, it should be noted that the NDVI analysis was conducted exclusively using ArcGIS Pro software based on satellite data, without direct field verification

Fig 2. Accuracy assessment map of the study area based on a visual comparison between PlanetScope satellite imagery and Google Earth high-resolution imagery. The figure illustrates the spatial correspondence between interpreted mangrove classes and reference data, serving as validation of mangrove cover classification results within Aceh Tamiang Regency.

3. Results And Discussion

3.1 Results

The mangrove ecosystem in Aceh Tamiang Regency is distributed across various forest areas with distinct functional classifications. In 2020, the total mangrove forest cover in the region was recorded at 10,796.76 hectares, comprising 4,465.64 hectares within protected forest areas and 6,331.12 hectares within production forest areas.

Between 2020 and 2024, Aceh Tamiang Regency experienced a significant loss of mangrove cover. Based on the author's interpretation of satellite imagery, approximately 67 hectares of mangroves were lost within protected forest areas and about 435 hectares within production forest areas. In total, this represents an estimated loss of nearly 512 hectares of mangrove ecosystems over the study period, indicating substantial pressure on both conservation and production forest zones.

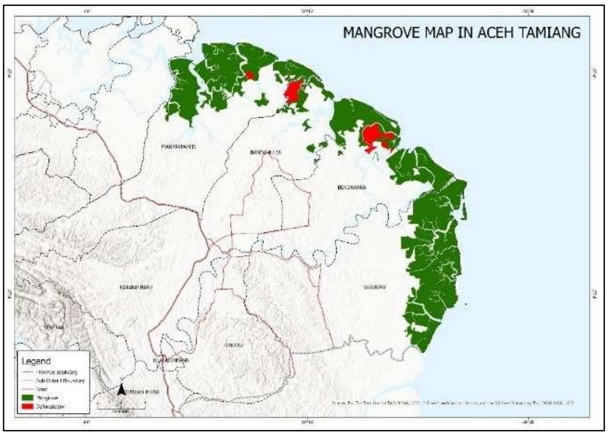

Fig 3. The mangrove map shows that mangrove cover in Aceh Tamiang is mainly concentrated along the eastern coastline and estuarine areas. Deforestation appears in scattered patches within and around mangrove stands, indicating localized land cover conversion. This pattern suggests that while mangroves remain relatively extensive, certain coastal zones are experiencing ongoing degradation.

In 2020, the total mangrove cover in Aceh Tamiang Regency was 10,796.76 hectares. Of this, 4,465.64 hectares were located within protected forest (HL) zones, and 6,331.12 hectares within production forest (HP) zones (Table 1). Non-mangrove land cover in the same areas totaled 7,790.61 hectares, with 229.36 hectares in HL and 7,561.25 hectares in HP. Consequently, mangroves occupied 95.1% of the protected forest area but only 45.6% of the production forest area. Mangrove Distribution in 2020 by Forest Function Zone.

Table 1. Land cover distribution in Aceh Tamiang by forest function in 2020 (hectares)

Land Cover Type	Protected Forest (HL)	Production Forest (HP)	Total
Mangrove	4,465.64	6,331.12	10,796.76
Non-mangrove	229.36	7,561.25	7,790.61
Total	4,695.00	13,892.38	18,587.38

By 2024, the total mangrove area had decreased to 10,417.11 hectares, representing a net loss of 379.65 hectares over the four-year period (Table 2). The reduction was almost entirely concentrated in production forest zones, which lost 376.20 hectares (from 6,331.12 ha to 5,954.92 ha). Protected forest zones showed a minimal decline of 3.45 hectares (from 4,465.64 ha to 4,462.19 ha). Spatial analysis identified 503.43 hectares of mangrove area converted to non-mangrove land uses, while 122.77 hectares of new mangrove cover emerged, primarily in estuarine and intertidal zones with low human activity.

Table 2. Land cover distribution in Aceh Tamiang by forest function in 2024 (hectares)

Land Cover Type	Protected Forest (HL)	Production Forest (HP)	Total
Mangrove	4,462.19	5,954.92	10,417.11
Non-mangrove	232.81	7,937.46	8,170.27
Total	4,695.00	13,892.38	18,587.38

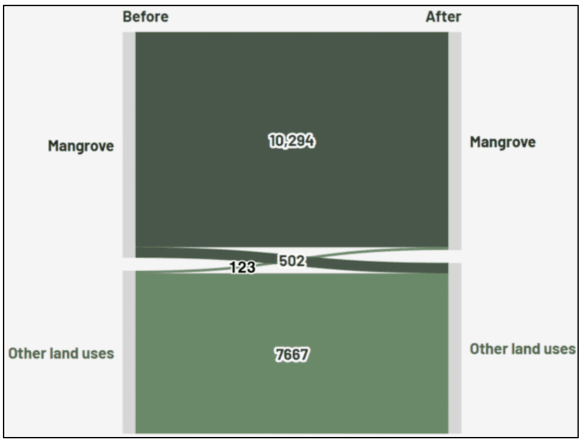

Fig 4. Sankey diagram illustrating land cover transitions in mangrove ecosystems of Aceh Tamiang between 2020 and 2024. Flow width represents area (in hectares) converted from mangrove to non-mangrove (e.g., aquaculture, plantation) and vice versa. Arrows indicate direction of change based on manual digitization of PlanetScope imagery.

Based on the spatial analysis, the results indicate that land cover dynamics in Aceh Tamiang are not limited to mangrove deforestation alone. In addition to the loss of mangrove areas, there is also a positive transition where mangrove cover expanded into areas that were classified as non-mangrove in 2020. By 2024, these areas had developed mangrove cover, with a total estimated extent of approximately 123 hectares. This finding suggests the occurrence of natural regeneration or rehabilitation processes in certain locations.

One of the potential regeneration factors of plants is internal biological factors (reproduction) and external (habitat). (Wairara et Sianturi, 2019). Natural regeneration of mangrove species is influenced by several biological and physical factors, namely soil stability and inundation, elevation of the growing area, salinity, and availability of propagules. The trend of changes in mangrove vegetation can also be caused by rapid growth due to its ability to adapt to low to moderate salinity levels and rapid development through water-borne seeds (Usman Zakaria et al., 2025).

The Sankey diagram illustrates these two-way land cover transitions between mangrove and other land uses over the study period. The dominant flow represents the conversion of mangrove areas to other land uses (502 ha), indicating deforestation as the primary trend. Conversely, a smaller but notable flow from other land uses to mangrove (123 ha) highlights localized mangrove gains, providing a more nuanced understanding of mangrove dynamics beyond net loss figures.

3.2 Changes in Mangrove Canopy Density (2020–2024)

NDVI-based classification revealed notable shifts in mangrove canopy structure between 2020 and 2024

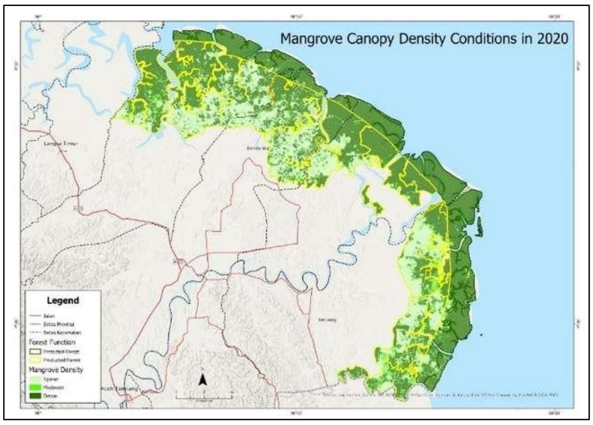

Fig 5. Spatial distribution of mangrove canopy density in Aceh Tamiang in 2020 classified using Normalized Difference Vegetation Index (NDVI) derived from Sentinel-2A imagery

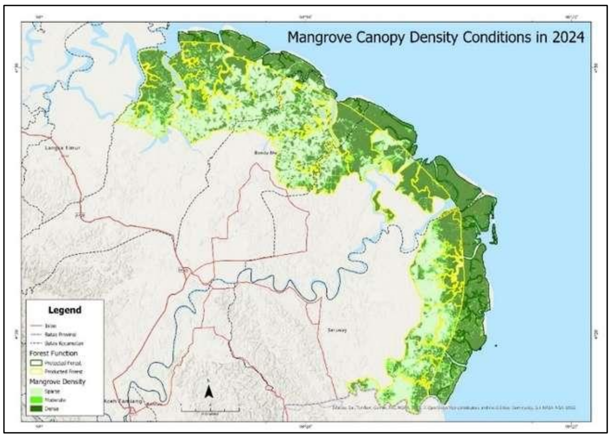

Fig 6. Spatial distribution of mangrove canopy density in Aceh Tamiang in 2024 classified using Normalized Difference Vegetation Index (NDVI) derived from Sentinel-2A imagery.

3.3 Changes in Mangrove Canopy Density (2020–2024)

NDVI-based classification indicates substantial changes in mangrove canopy structure in Aceh Tamiang between 2020 and 2024 (Table 3; Figures 4 and 5). The most pronounced trend is the significant decline in dense mangrove cover (NDVI ≥ 0.43), which decreased by 2,226 hectares, from 11,749 hectares in 2020 to 9,523 hectares in 2024. This reduction suggests increasing degradation of previously healthy mangrove stands, likely associated with land conversion, logging, or other anthropogenic pressures.

Conversely, mangrove areas classified as sparse (NDVI < 0.33) expanded considerably, increasing by 1,542 hectares over the same period. This expansion reflects a growing extent of degraded or young mangrove vegetation with lower canopy closure. In parallel, moderate-density mangroves (0.33 ≤ NDVI < 0.43) also showed an increase of 678 hectares, which may indicate transitional stages of mangrove regeneration or partial recovery in certain areas. Overall, these shifts highlight a structural transformation of mangrove ecosystems, characterized by a decline in dense, mature mangroves and a concurrent rise in sparse and moderately dense stands, underscoring the need for strengthened conservation and restoration efforts.(Alongi, 2012 b)

Table 3. Mangrove canopy density classification based on NDVI (2020–2024)

Density Class	2020 (Ha)	2024 (Ha)	Absolute Change
Sparse	5,485	7,027	+1,542
Moderate	1,689	2,367	+678
Dense	11,749	9,523	–2,226

4. Discussion

The observed reduction in canopy cover and tree density may not always signify total deforestation; however, it often reflects underlying ecosystem stress or degradation driven by both natural and anthropogenic factors. As noted in a recent assessment of mangrove rehabilitation in Indonesia’s outer islands, “open land comprises areas devoid of vegetative cover, whether of natural origin or due to human activities. Such areas are typically located along coastlines or estuarine zones and often arise from land conversion for infrastructure development, aquaculture, or are the product of natural erosion processes (Metananda et al., 2025).

The net loss of mangrove covers in Aceh Tamiang between 2020 and 2024 concentrated almost entirely in production forest zones reflects a persistent pattern of land-use prioritization favoring short-term economic gain over long-term ecological security. This spatial disparity between protected and production forests aligns with national-scale observations in Indonesia, where formal conservation status significantly reduces deforestation risk((Ilman et al., 2016 b; Richards et Friess, 2016)). The relative stability of mangroves within protected areas thus validates the role of legal designation as a critical first line of defense against large-scale clearance.

The concurrent decline in dense mangrove and expansion of sparse/moderate classes suggests a complex transition: while some areas show signs of natural regeneration (e.g., in sheltered intertidal zones), the overall trajectory points toward ecosystem degradation. This pattern mirrors findings in other degraded mangrove landscapes across Sumatra, where increased “greenness” from pioneer species masks underlying losses in structural complexity, biodiversity, and carbon storage capacity (Murdiyarso et al., 2015; Saputra et al., 2021). The loss of high-canopy mangrove habitats essential for species like Batagur borneoensis is particularly concerning, as it erodes the very foundation of ecological functionality.

Notably, these changes persist despite the introduction of strengthened national mangrove governance under Government Regulation No. 27 of 2025. This indicates a significant gap between policy intent and on-the-ground implementation, particularly in production forests where regulatory oversight is often weaker and economic incentives for conversion remain strong. While our field interviews (not shown in detail here due to scope) suggest that livelihood pressures and unclear land tenure contribute to smallholder-driven conversion, the dominant drivers appear linked to larger-scale aquaculture and plantation investments.

We acknowledge that without extensive ground-truthing, specific land-use transitions (e.g., shrimp pond vs. oil palm) remain inferred from spatial context. Future studies should integrate high-resolution remote sensing with household surveys and land-use policy analysis to unpack the socio-ecological drivers of change more precisely.

5. Conclusion

The findings of this study carry significant implications for coastal governance and ecosystem based policy design in Aceh Tamiang and similar mangrove-rich regions. Rather than merely documenting loss, this research underscores the urgent need to translate spatial evidence into actionable management strategies. First, NDVI-derived change maps should be formally integrated into district-level spatial planning (Rencana Tata Ruang Wilayah) to strengthen monitoring of illegal land conversion in production forests. Second, national mangrove rehabilitation programs particularly under Government Regulation No. 27 of 2025 must prioritize areas showing early signs of natural regeneration (e.g., sparse-to-moderate density transitions) through community-assisted enrichment planting, rather than focusing solely on large-scale monoculture restoration. Third, local conservation strategies should empower coastal communities as co-managers by linking mangrove stewardship to livelihood alternatives such as blue carbon incentives or ecotourism cooperatives. Ultimately, the long-term resilience of Aceh Tamiang's mangroves depends not on data alone, but on institutional mechanisms that embed scientific insight into adaptive, participatory, and legally enforceable governance frameworks**.**

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