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Evaluation of mangrove area and density changes in the North Rupat Regional Marine Reserve Conservation Area, Riau, Indonesia

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Abstract. Mangrove ecosystems in coastal regions provide vital ecological, protective, and socio-economic benefits. This study analyzes mangroves' spatial distribution and density changes in the North Rupat Regional Marine Reserve Conservation Area (KKPD), Riau, Indonesia, over 34 years (1989-2023). The research utilized Landsat satellite imagery with Random Forest classification methods and applied Normalized Difference Vegetation Index (NDVI) calculations to categorize mangrove canopy density. An innovative mathematical approach assessed changes in mangrove distribution and density. Results show a decrease in mangrove area from 10,822.84 hectares in 1989 to 10,613.38 hectares in 2023. Canopy density analysis reveals dominance of stable low-density areas (4,311.27 hectares) and significant degradation (3,651.57 hectares). NDVI analysis demonstrates a drastic degradation in mangrove quality, with mean NDVI values dropping from 0.309873 in 1989 to -0.03113 in 2023, indicating severe vegetation stress. Complex change patterns and succession followed by degradation indicate mangrove ecosystem dynamics influenced by natural and anthropogenic factors. This research highlights the importance of targeted conservation strategies and long-term monitoring for sustainable mangrove management in the North Rupat KKPD.

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1 Introduction

Mangrove ecosystems are vital in coastal regions, offering numerous ecological, protective, and socio-economic benefits [1]. These unique ecosystems primarily produce coastal food webs, providing critical habitats, feeding grounds, and nursery areas for marine and terrestrial fauna [2]. Local communities depend on mangroves for food sources, income, and well-being [3]. Mangroves safeguard coastal areas against climatic and geological disasters such as solid waves, storms, and tsunamis. Mangroves prevent saltwater intrusion on small islands, ensuring freshwater supplies for local populations [4].

In climate change, mangroves are essential to the blue carbon ecosystem [5]. This term refers to coastal and marine ecosystems that can absorb and store large amounts of carbon, mitigating global warming. Mangroves are highly effective, as they can absorb greenhouse gases and store carbon in their biomass and sediments [6]. However, the degradation of mangrove quantity and quality has reduced these essential ecological services, affecting environmental and socio-economic dynamics. Healthy mangroves are pivotal in mitigating coastal disasters and maintaining ecosystem balance [7].

Understanding and addressing mangrove degradation is a complex task that requires a thorough evaluation of mangrove health [8]. Fortunately, researchers have developed various methodologies for mangrove health assessments, including stand structure analysis, biodiversity assessments, soil studies, socio-economic analyses, and remote sensing techniques such as the Normalized Difference Vegetation Index (NDVI) [9]. The potential of remote sensing to monitor mangrove density and health over large areas, providing critical biophysical information without direct contact with the ecosystem, is a reason for optimism in mangrove conservation [10, 11]. This technology offers hope for the future of mangrove ecosystems.

Indonesia's commitment to expanding marine conservation areas aligns with the Ministry of Marine Affairs and Fisheries' ambitious goal to develop 20 million hectares of marine conservation by 2020. This initiative, part of a more considerable global effort to protect marine ecosystems, targeted Riau Province to contribute 110,000 hectares. By 2017, Riau had established 269,818.76 hectares of conservation areas, with the North Rupat region designated for further expansion [12]. However, coastal development activities, including land conversion, aquaculture, and other anthropogenic disturbances, pose significant threats to mangroves in this region [13].

Given the critical role of mangroves in coastal protection, habitat provision, and carbon sequestration, the results are imperative. The study aims to analyze the spatial distribution and density of mangroves in the North Rupat regional marine conservation area, which is a scientific endeavor and a crucial step towards effective and sustainable mangrove management practices. These results will help to support the conservation efforts planned by the government. The data generated from this study will prove essential for policymakers and stakeholders, making their involvement necessary in preserving the mangrove ecosystems in North Rupat, Riau.

2 Materials and methods

2.1 Study area

The North Rupat KKPD in Riau, Indonesia, serves as the site for this research (Figure 1). The Riau Governor established this KKPD through Decree Number: Kpts.565/II/2019, designating the KKPD in Bengkalis Regency [12]. The North Rupat KKPD falls under Bengkalis Regency and North Rupat District, encompassing eight villages: Hutan Ayu, Kadur, Putri Sembilan, Suka Damai, Tanjungmedang, Tanjungpunak, Telukrhu, and Titi Akar. This area boasts two crucial coastal ecosystems: mangroves and seagrasses. The area harbors 12 true mangrove species, including *Avicennia alba, A. lanata, Bruguiera gymnorrhiza, B. sexangula, Ceriop tagal, Lumitzera littorea, Rhizophora apiculata, R. mucronata, Sciphipora hydrophillacea, Sonneratia caseolaris, S. alba,* and *Xilocarpus granatum* [14]. However, human activities threaten these mangroves. Local communities and developers have constructed fishing ports, passenger terminals, settlements, and oil palm plantations, increasing pressure on this delicate ecosystem. The seagrass meadows, though less diverse, play an equally important role. Two species comprise these meadows, *Enhalus acoroides,* and *Thalassia hemprichii* dominate the area. When healthy, these seagrasses help combat sedimentation and prevent coastal erosion, safeguarding the shoreline for wildlife and people. Marine life thrives in these waters. Locals and researchers frequently observe cetaceans swimming offshore, including finless porpoises and playful dolphins. The area likely serves as a habitat for the elusive dugong (*Dugong dugon*). Reports indicate occasional strandings of these gentle creatures on beaches and accidental capture in fishermen's nets [12].

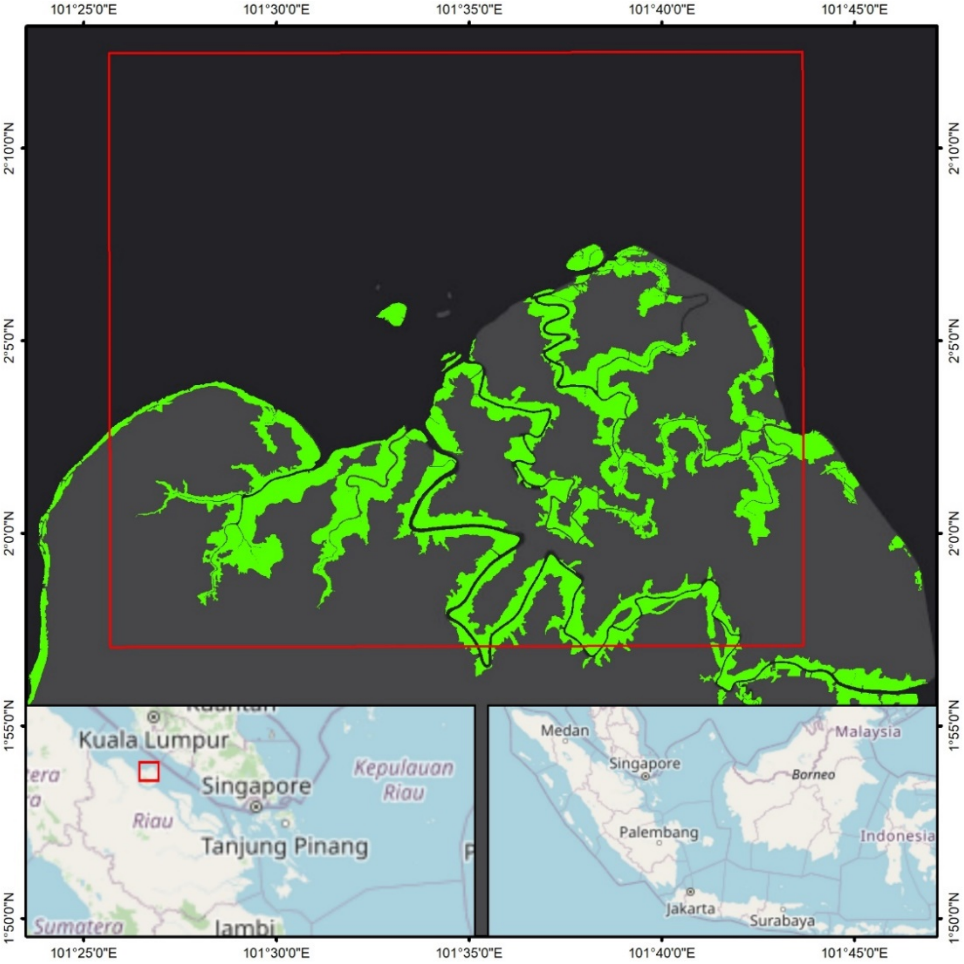

Fig 1. Map of the study area in the North Rupat KKPD, Riau, Indonesia. The map illustrates mangrove distribution based on the 2021 National Mangrove Map [15]. Green areas indicate the distribution of mangrove ecosystems within the study region.

2.2 Data

This study examined changes in mangrove density and area in the KKPD area using satellite imagery from three periods. The analysis incorporated Landsat 5 Thematic Mapper (TM) images from December 16, 1989, and August 9, 2006, along with Landsat 9 Operational Land Imager 2 (OLI2) imagery from March 9, 2023. All images underwent processing to Level 2A, which includes surface reflectance correction. This processing step minimizes atmospheric distortions and ensures accurate land surface measurements. Using multi-temporal Landsat data allowed a comprehensive assessment of mangrove changes over 34 years. The selection of images from different seasons (December, August, and March) also accounted for potential seasonal variations in mangrove characteristics.

This robust dataset formed the foundation for subsequent mangrove distribution and density dynamics analyses in the study area.

2.3 Mangrove classification

The image classification played a critical role in distinguishing mangrove from non-mangrove areas. The study employed a supervised classification method using the Random Forest algorithm [16], known for its exceptional efficiency [17, 18]. This algorithm's efficiency and accuracy in handling complex datasets make it suitable for environmental studies involving extensive spatial data. The Random Forest classifier configuration included 500 decision trees to maximize classification accuracy. A bag fraction 0.632 introduced variability into the model by randomly sampling the input data. The classification process did not impose predefined limits on the number of variables per split or the maximum number of nodes. This approach allowed the algorithm to determine these parameters adaptively based on the input data. The Random Forest method demonstrated exceptional suitability for this mangrove classification task due to its ability to handle high-dimensional data and its resistance to overfitting. This robust classification technique provided a solid foundation for subsequent analyses of mangrove distribution and density changes in the study area [19].

2.4 Mangrove Density

After the initial classification, the process applied a majority filter to refine the results. This filter smoothed the classified map by reducing noise and eliminating isolated misclassified pixels, thus enhancing the clarity and accuracy of the final map [20]. The majority filter employed a circular kernel with a 3-pixel diameter, effectively addressing small-scale noise while preserving the integrity of larger mangrove patches. The study assessed mangrove canopy density by calculating each period's Normalized Difference Vegetation Index (NDVI) [21]. NDVI, a well-established index, compares the difference between near-infrared and red-light reflectance, offering a reliable measure of vegetation health and density. The analysis categorized NDVI values into three classes representing different levels of canopy density: dense canopy ($NDVI \geq 0.43$), moderate canopy ($0.33 \leq NDVI < 0.43$), and sparse canopy ($-1.0 \leq NDVI < 0.33$) [22]. This categorization enabled a nuanced analysis of changes in mangrove canopy density.

Google Earth Engine (GEE) facilitated all data processing, including image classification, filtering, and NDVI calculation. GEE, a cloud-based platform, provides powerful tools for efficiently processing large-scale geospatial data. Its extensive library of datasets and algorithms allowed for seamless integration and analysis of the Landsat imagery used in this study. Using GEE enhanced data processing efficiency and ensured consistency in the analysis across the multi-temporal dataset. This approach enabled a comprehensive assessment of mangrove changes over the 34-year study period, providing robust results for further interpretation and analysis.

2.5 Mangrove distribution and density changes

Detecting and quantifying changes in mangrove ecosystems over time provides crucial insights for understanding their dynamics and implementing effective conservation strategies. This study employs a novel mathematical approach, underpinned by a conceptual framework of mangrove and canopy density changes, to quantify mangrove distribution and density changes. The equation $S = 100P_1 + 10P_2 + P_3$ quantifies distribution changes, where S represents the distribution change score, and P_1, P_2, P_3 are binary values (0 or 1) indicating the presence or absence of mangroves in each respective year. This method allows quick identification of patterns such as consistent presence (111), complete loss (100), or reappearance (101) of mangroves, corresponding to Unchanged, Gain, and Loss categories.

Concurrently, the equation $T = 100D_1 + 10D_2 + D_3$ assesses changes in mangrove density, where T represents the total density value, and D_1, D_2, D_3 represent the density levels (1 for Sparse, 2 for Moderate, 3 for Dense) in each year. This equation enables the detection of various density change scenarios outlined in the conceptual model, from stable conditions (e.g., 111 for Stable Low or consistently sparse) to degradation (e.g., 321 for Gradual Degradation) or improvement (e.g., 123 for whole succession or increasing density).

The combination of these two analytical methods, referenced to the conceptual framework, allows for a comprehensive assessment of spatio-temporal changes in mangrove ecosystems. This integrated approach provides valuable insights into mangrove resilience, vulnerability, and overall health trends over the 34-year study period, aligning with the complex dynamics represented in the conceptual model. For instance, a combination of S = 111 (consistent presence) and T = 231 indicates a Succession followed by degradation.

3 Result and Discussion

The mangrove ecosystem on Rupat Island has undergone significant dynamic changes over 34 years, from 1989 to 2023. Satellite image analysis reveals fluctuations in mangrove areas, reflecting complex interactions between natural and anthropogenic factors. The 1989 image classification results indicate a mangrove area of 10,822.84 hectares. This satellite imagery shows that the mangrove ecosystem had experienced prior pressure, evidenced by numerous ginger pink spots in the RGB SWIR2, NIR, and Red image combination. These spots indicate human intervention, primarily in mangrove logging for charcoal production and building materials [23]. Nevertheless, infrastructure development remained minimal, and Rupat Island had yet to become a primary development focus. Massive peat swamp forests surrounded the mangrove areas, alongside rubber plantations and other community plantations.

By 2006, the mangrove area had decreased to 10,719.09 hectares, a reduction of 103.75 hectares from 1989. This year's satellite imagery demonstrates increasing pressure on the Rupat Island ecosystem. Large corporations began converting peat swamp forests into oil palm plantations, reaching as far as one of the upstream tributaries of the Nyiur River. Infrastructure development, including the trans-Rupat Island road, started to divide several mangrove areas, causing fragmentation and potentially triggering ecosystem degradation.

In 2023, the mangrove area continued to decline to 10,613.38 hectares, a further reduction of 105.71 hectares from 2006. Satellite imagery reveals dramatic changes in the landscape surrounding the mangroves. The peat swamp forests that once protected the mangroves from the landward side have now transformed into oil palm plantations owned by corporations and local communities. Mangroves in the Nyiur and Lemas Rivers appear surrounded by oil palm plantations, with most areas integrated into the plantations, marked by clear plot patterns and roads. Additional pressure emerges from infrastructure development by industrial plantation forest companies extending to the Morong Strait, utilizing water facilities for transporting production outputs.

The analysis of mangrove area changes from the 1989-2023 period reveals complex dynamics. An increase (gain) of 227.63 hectares occurred, alongside a more significant decrease (loss) of 429.44 hectares, with 10,385.75 hectares of mangrove area remaining unchanged. Referring to Table 1, which details mangrove changes, these observations can be made:

- 127.02 hectares of new mangroves emerged in 2023.
- 240.38 hectares of mangrove present in 1989 had disappeared by 2006 and did not reappear by 2023.
- 151.77 hectares of mangrove observed in 2006 no longer existed in 2023.
- A recovery phenomenon occurred in some areas, where 37.30 hectares of mangrove lost in 2006 reappeared in 2023, and 44.94 hectares of new mangrove area grew in 2023 after being observed in 2006.
- Most significantly, 10,385.75 hectares of mangrove persisted from 1989 to 2023.

Table 1. Details of mangrove area change in Rupat Island based on temporal dynamics (1989-2023)

No	Detailed changes	Hectares
1	A new mangrove emerged in 2023	127,02
2	Mangrove decreased in 2023 after being present in 1989 and 2006	240,38
3	Mangrove only existed in 1989, but not in 2006 and 2023	151,77
4	Mangrove only existed in 2006, but not in 2023	37,30
5	Mangrove reappeared or increased in 2023 after existing in 1989	44,94
6	Mangrove reappeared or increased in 2023 after existing in 2006	55,66
7	Mangrove consistently present from 1989, 2006, to 2023	10.385,75

Mangrove area additions generally occurred in coastal sections [24], primarily due to accretion found in the western part of the Nyiur River estuary and Tanjungpunak beach. Growing small islands also became locations for mangrove expansion, where mangroves act as pioneer plants. Conversely, mangrove area reductions resulted from abrasion, especially in the eastern part of the Nyiur River, and the conversion of mangrove land into roads, settlements, and shrimp ponds. Despite facing various threats and pressures, the mangrove ecosystem on Rupat Island demonstrates impressive resilience. Although the total area decreased, the persistence of specific areas and the emergence of new mangroves indicate the potential for natural regeneration and the possible success of conservation efforts. However, drastic changes in the surrounding landscape, particularly the conversion of peat swamp forests into oil palm plantations, pose new challenges for the future sustainability of the mangrove ecosystem (Figure 2).

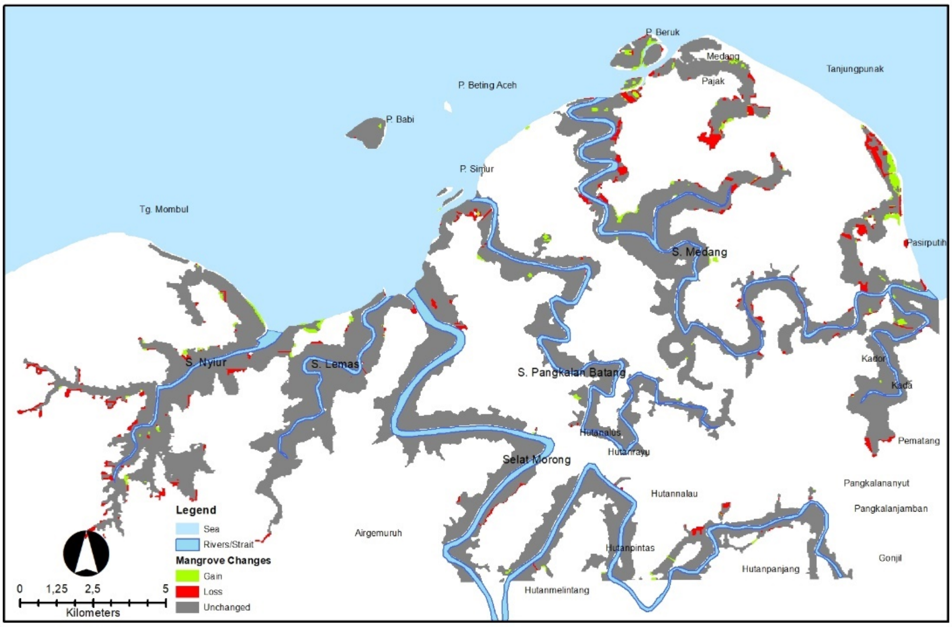

Fig 2. Dynamics of mangrove changes from 1989 to 2023. Quantitatively, no substantial changes in the area occurred, either in addition or reduction of the region. This stability is a vital aspect of the study's findings.

Considering the importance of mangrove ecosystems in ecological and socio-economic contexts, more intensive conservation efforts and sustainable management are necessary. Management strategies must consider the complex dynamics of change, including natural factors such as accretion and abrasion, as well as anthropogenic pressures like land conversion and infrastructure development. With proper management and support from various stakeholders, the mangrove ecosystem on KKPD can continue to survive and even thrive, ensuring the preservation and sustainability of its benefits for future generations.

The descriptive statistics of NDVI (Table 2) demonstrate significant changes over the period. In 1989, NDVI values ranged from 0 to 0.436298, with an average of 0.309873, indicating relatively good mangrove vegetation conditions. 2006 showed a slight increase with an average NDVI of 0.321451 despite a negative minimum value (-0.030064). However, the most striking observation is the drastic decrease in 2023, with an average NDVI of -0.03113 and a maximum value of only 0.045311, indicating a significant degradation. The z-score, a measure of how many standard deviations a data point is from the mean, was calculated to be -7.6845, further confirming the severe degradation in mangrove vegetation quality.

Table 2. Descriptive statistics of mangrove NDVI values in the study area (1989-2023)

Year	Minimum	Maximum	Range	Mean	Std
1989	0	0,436298	0,436298	0,309873	0,04406
2006	-0,03006	0,430077	0,460141	0,321451	0,043732
2023	-0,05663	0,045311	0,101936	-0,03113	0,008432

The analysis of mangrove canopy density changes from 1989 to 2023 reveals significant dynamics in the mangrove ecosystem. The heatmap visualization (Figure 3) summarizes these changes, highlighting the most prominent trends. Stable low-density mangroves dominate the landscape, covering 4,311.27 hectares. This category primarily consists of areas that remained sparse throughout the study period (4,124.61 ha), with smaller contributions from areas sparse in different combinations of years. The prevalence of stable low-density areas suggests that a significant part of the mangrove ecosystem has maintained a consistent, albeit low, canopy density. This stability could indicate resilience in these areas but also points to the persistent challenge of achieving higher-density growth. Degradation emerges as a significant concern, affecting 3,651.57 hectares of mangroves. Most of this degradation (2,577.42 ha) occurred in areas moderate in 1989 and 2006 but became sparse by 2023.

Additionally, 1,021.86 hectares experienced a decline from moderate in 1989 to sparse in 2006 and 2023. This trend highlights the ongoing threats to mangrove ecosystems, potentially stemming from natural and anthropogenic factors. The extent of degradation underscores the urgent need for targeted conservation efforts and management strategies to mitigate further loss.

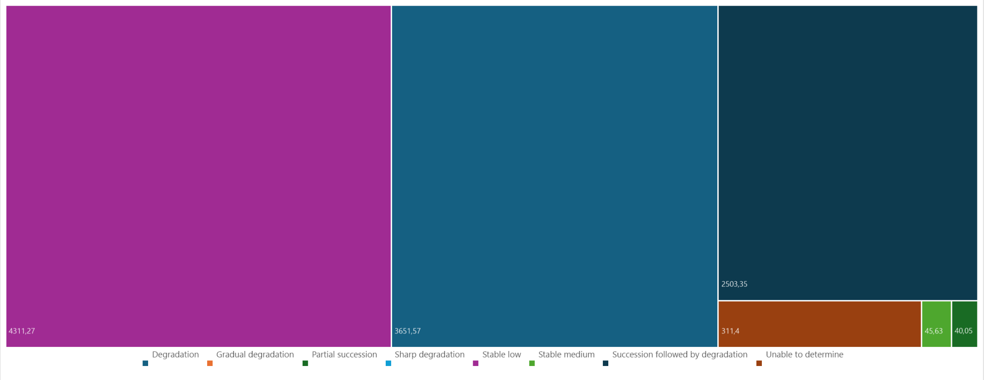

Fig 3. Heatmap visualization of mangrove canopy density change patterns and their corresponding areas.

An intriguing pattern emerges in the succession followed by degradation category, covering 2,503.35 hectares. Most of this area (2,503.26 ha) showed an initial improvement from sparse in 1989 to moderate in 2006 but then regressed to sparse by 2023. This pattern suggests that while natural regeneration or restoration efforts may succeed, maintaining these gains proves challenging. Understanding the factors that led to the initial improvement and subsequent decline could provide valuable insights for long-term mangrove management strategies. The study also reveals areas of uncertainty, with 311.4 hectares falling under the unable to determine category. This uncertainty affects various temporal combinations, with the most significant area (125.37 ha) indeterminate for 2023. These uncertain areas emphasize the challenges in the long-term monitoring of mangrove ecosystems and highlight the need for improved monitoring techniques and data collection strategies.

Positive changes, though limited, appear as partial succession over 40.05 hectares, which transitioned from sparse in 1989 to moderate in 2006. While this improvement is encouraging, its limited scale compared to areas of degradation underscores the difficulties in achieving substantial enhancements in mangrove canopy density. Stable medium-density areas cover 45.63 hectares, representing regions that maintained moderate density from 1989 to 2006. Although smaller than other categories, these areas represent pockets of relatively healthy mangrove ecosystems that have resisted degradation. Understanding the factors contributing to the stability of these medium-density areas could provide valuable insights for conservation and restoration efforts. Extreme changes, such as sharp and gradual degradation, affected only 0.09 hectares. While rare, these cases signal the potential for rapid or gradual loss of mangrove canopy under certain conditions. Investigating the specific circumstances leading to these extreme changes could help develop early warning systems for mangrove conservation.

The map of mangrove canopy change distribution (Figure 4) reveals spatial patterns across the landscape that inform targeted management approaches. Stability, degradation, and improvement areas cluster in ways that suggest underlying environmental factors or localized human influences shape these changes. Stable, low-density, and degraded areas dominate the landscape, necessitating a dual management strategy. Conservation efforts must prioritize preventing further degradation in stable, low-density areas, while restoration initiatives should focus on reversing negative trends in degraded zones. The observed pattern of succession followed by degradation highlights the need for sustained, long-term restoration efforts to ensure lasting improvements in canopy density.

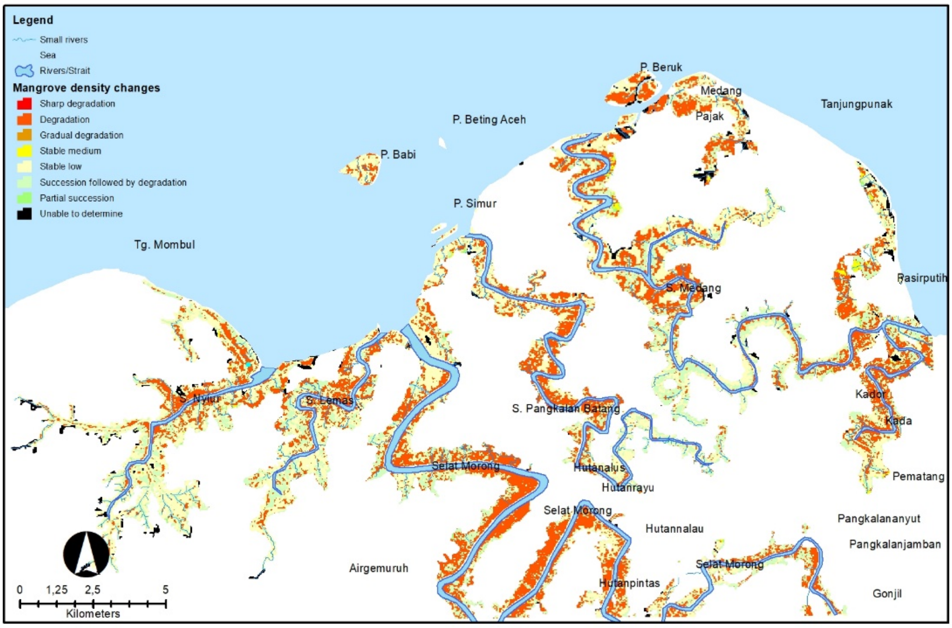

Fig 4. Spatial distribution of mangrove canopy cover changes in the KKPD (1989-2023)

The research reveals quantitative and qualitative changes in mangrove areas, highlighting their dynamic nature. Changes in mangrove canopy density serve as an early warning signal, prompting further investigation. Comprehensive field measurements of mangrove community structure, including canopy cover, tree density, stem diameter, and tree height, provide essential and enlightening data. Adopting hemispherical photography methods for determining canopy cover percentage marks a significant advancement in the field [11]. These detailed studies hold paramount importance due to the diverse characteristics of mangroves across locations, offering a wealth of information for future research and conservation efforts. Spectral calibration of mangrove data across different time series implemented through pseudo-invariant object techniques, is crucial in standardizing spectral recording conditions between images. This calibration ensures comparability across time points, enhancing the accuracy of temporal analyses.

Kuenzer et al, [25] identified soil, water, and mangrove vegetation as three key factors influencing mangrove spectral conditions. Understanding these factors and atmospheric conditions during image acquisition significantly affects the interpretation of mangrove spectral signatures. Integrating specialized mangrove indices significantly enhances the robustness of the study, moving beyond commonly used indices like the Soil-Adjusted Vegetation Index (SAVI) [26] and Enhanced Vegetation Index (EVI) [27]. These specialized indices, including the Mangrove Vegetation Index (MVI) [28], Mangrove Index (MI) [29], Automatic Mangrove Map and Index (AMMI) [30], and Combined Mangrove Recognition Index (CMRI) [31], capture the unique spectral characteristics of mangrove ecosystems. Their application yields more accurate assessments of mangrove health and distribution, providing a more comprehensive view of ecosystem dynamics. The research achieves a more comprehensive and nuanced understanding of mangrove ecosystem dynamics by combining specialized mangrove indices with traditional vegetation indices. With its potential to capture subtle mangrove health and distribution changes that single indices might overlook, this multi-index approach offers robust and detailed insights, inspiring us about its transformative potential in conservation and management strategies in the KKPD and similar coastal ecosystems.

4 Conclusion

This study reveals the complex dynamics of the mangrove ecosystem in the North Rupat KKPD over 34 years. Despite an overall area decrease, most mangrove areas (10,385.75 hectares) remained unchanged, indicating resilience to environmental pressures. However, significant degradation occurred in many areas, particularly from moderate to sparse density. The pattern of succession followed by degradation underscores the challenges in maintaining long-term improvements. Factors such as land conversion, infrastructure development, and changes in surrounding landscapes contribute to these dynamics. The findings emphasize the need for a dual management strategy: conserving stable low-density areas and restoring degraded zones. Using mangrove-specific vegetation indices and a multi-index approach provides deeper insights into ecosystem conditions. To ensure the sustainability of mangroves in the North Rupat KKPD, intensive conservation efforts, continuous monitoring, and stakeholder engagement are necessary. This research provides a robust scientific basis for developing effective and sustainable mangrove management strategies in the future.

Acknowledgments

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