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SPATIOTEMPORAL ANALYSIS AND PREDICTION OF MANGROVE DYNAMICS FOR NATURE-BASED SOLUTIONS IN TANJUNG CARAT, SOUTH SUMATRA

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ABSTRACT: Mangrove ecosystems play a crucial role in coastal resilience, yet their long-term spatial and ecological dynamics remain insufficiently quantified in tropical delta environments. This study examines multi-class land-cover changes and mangrove canopy dynamics in Tanjung Carat, South Sumatra, Indonesia, from 2016 to 2024, using Landsat 8/9 imagery and NDVI-based classification. The results show that mangrove area declined from 96,630.95 ± 120 ha to 91,184.88 ± 140 ha, representing a 5.6 % (≈ 5,446 ha) net loss, primarily in Muara Sungsang and Sungsang I–III, where conversion to aquaculture, settlements, and agricultural fields was most intense. In contrast, Sungsang IV remained relatively resilient, with only a 1.4 % (≈ 1,171 ha) decline due to stable hydrology and limited accessibility. NDVI values (0.12–0.59) indicated canopy degradation in fragmented zones and dense cover in the core areas. The Artificial Neural Network (ANN) model achieved 98 % overall accuracy and a Kappa coefficient of 0.98049, validating the robustness of the predictive framework. The 2032 projection suggests an additional 4.6 % decline (≈ 4,195 ha; ≈ 0.58 % yr^{-1}) under a business-as-usual scenario. These findings underscore the urgent need for Nature-based Solutions (NbS) integrating hydrological restoration, adaptive zoning, and community stewardship to balance coastal development and mangrove conservation in South Sumatra's deltaic landscape.

Keywords: Mangrove Dynamics, NDVI, Nature-based Solutions (NbS), Coastal Resilience, Spatiotemporal Analysis

1. INTRODUCTION

Mangrove forests are among the most productive coastal ecosystems, providing critical services such as carbon sequestration, biodiversity support, nutrient cycling, and shoreline protection [1]. Globally, they cover about 14.7 million ha across more than 120 tropical and subtropical countries [2], yet have declined sharply since the 1980s, with continuing losses in both extent and carbon stocks [3]. Indonesia hosts the world's largest mangrove area, about 3.36 million ha (≈20% of global total), but much of it remains degraded and requires improved management [4]. As mangrove soils store substantial blue-carbon stocks, their protection and restoration are vital for climate mitigation and adaptation [5].

The Tanjung Carat coast in South Sumatra illustrates Indonesia's challenge of reconciling conservation with rapid development. Situated on low-lying alluvial plains prone to tidal flooding and erosion, it has been targeted for port and industrial expansion, intensifying ecological pressure [6]. Similar conflicts across Southeast and East Asia show that aquaculture and urbanization continue to reshape coastal landscapes [7].

Recent studies highlight Nature-based Solutions (NbS) as a strategy to balance development and ecosystem protection, positioning mangroves as green infrastructure that mitigates coastal hazards while supporting carbon storage and local livelihoods [8,9]. However, recent reviews highlight that implementing NbS in tropical regions frequently suffers from a lack of consistent spatiotemporal data needed to assess ecosystem changes and restoration results [10]. Although remote sensing has become the main approach for mangrove monitoring, many studies remain descriptive, focusing on change detection rather than future projections, and seldom integrate vegetation indices such as NDVI with predictive models [11,12].

This study advances mangrove monitoring by combining multi-temporal Landsat analysis (2016–2024) with Artificial Neural Network (ANN) modeling to forecast future mangrove change under ongoing land-use pressures. It further links NDVI-based canopy assessment with NbS-oriented spatial planning, delineating resilient core zones, restoration priorities, and adaptive-use areas in the Tanjung Carat delta. The research demonstrates how predictive spatial modeling can inform sustainable coastal development. Specifically, this study aims to: (1) map multi-class land cover and quantify changes in mangrove extent, (2) assess canopy condition using NDVI as an indicator of vegetation vigor, and (3) interpret these findings into actionable guidance for NbS planning in a rapidly developing delta landscape.

The remainder of this paper is structured as follows: Section 2 presents the research significance;

Section 3 outlines the methodology; Section 4 presents and discusses the results; and Section 5 concludes with management recommendations and directions for future research.

2. RESEARCH SIGNIFICANCE

This research contributes to advancing spatially explicit approaches for sustainable coastal management in tropical delta systems. By integrating multi-temporal Landsat imagery, NDVI-based canopy assessment, and Artificial Neural Network (ANN) modeling, the study provides a robust framework for quantifying and predicting mangrove landscape dynamics. The results deliver actionable insights to support Nature-based Solutions (NbS), particularly for reconciling economic development and ecosystem conservation in South Sumatra. Beyond its local relevance, the methodological framework offers broader applicability for policy design, restoration prioritization, and adaptive coastal planning in other mangrove-rich regions.

3. METHODOLOGY

3.1 Study Area Overview

This study was conducted in the Tanjung Carat coastal region, Banyuasin Regency, South Sumatra Province, Indonesia. The area encompasses six estuarine villages—Marga Sungsang, Muara Sungsang, Sungsang I, II, III, and IV—within the Sungsang estuary (Fig. 1). The landscape consists of a low-lying deltaic plain (0–5 m a.s.l.) formed by alluvial deposits and highly susceptible to abrasion and seawater intrusion [6].

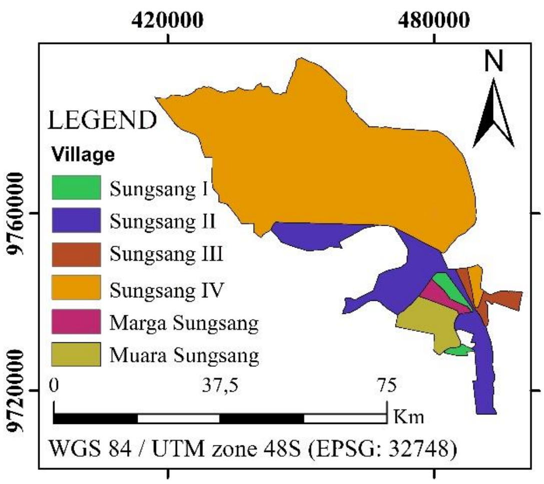

Fig. 1 Study Area

Tanjung Carat is a strategic development zone designated for an international port, generating economic opportunities but intensifying ecological pressure on mangrove ecosystems. Mangroves serve as natural buffers that reduce tidal flooding, regulate sedimentation, and support local fisheries and livelihoods [13]. Yet extensive conversion to aquaculture, settlements, and infrastructure has accelerated habitat loss [14]. As a result, the area represents a critical interface between ecological value and anthropogenic stress, making it suitable for assessing mangrove dynamics within a Nature-based Solutions (NbS) framework. The distribution of land area across villages is shown in Table 1, highlighting the dominance of Sungsang IV and the comparatively smaller extents of Marga Sungsang, Sungsang I, and Sungsang III.

Table 1 Land Area Distribution by Village in Tanjung Carat

Village	Total (ha)
Marga Sungsang	3,107.24
Muara Sungsang	10,406.73
Sungsang I	3,529.72
Sungsang II	37,704.68
Sungsang III	4,977.70
Sungsang IV	173,536.68
Total	**233,262.75**

3.2 Data and Information Sources

All satellite images were derived from Landsat 8 and Landsat 9 datasets with a 30 m spatial resolution, obtained from the United States Geological Survey (USGS) for the years 2016, 2017, 2019, 2021, 2023, and 2024. These periods were selected for their cloud-free conditions and suitability to represent medium-term coastal vegetation dynamics. All images were projected to the UTM Zone 48S (WGS 84) coordinate system to ensure spatial consistency before generating natural color composites and NDVI layers.

Ground validation involved GPS-based ground control points (GCPs), drone observations, and cross-verification with local spatial data. Community interviews were conducted to contextualize land-cover changes and identify human activities contributing to mangrove degradation and restoration in Tanjung Carat.

3.3 Land Cover Classification (2016–2024)

NDVI values were used to distinguish mangrove vegetation and assess canopy condition [15]. Classification employed the Maximum Likelihood algorithm, with NDVI-based training samples and reference polygons collected during the 2024 field survey. Six land-cover classes were analyzed i.e. mangrove, field, plantation, shrub, settlement, and river, identified from spectral reflectance and verified with high-resolution imagery.

A hybrid classification combining visual interpretation, NDVI composites, and on-screen digitizing in QGIS 3.34 improved accuracy in spectrally complex zones. After automated classification, manual edits refined class boundaries and corrected confusions between mangrove and field areas.

3.4 Predictive Land Cover Modeling Using Artificial Neural Networks (ANN)

The Artificial Neural Network (ANN) model was developed in QGIS MOLUSCE using multi-temporal land-cover maps from 2016 and 2024 to estimate transition probabilities and spatial change potential among six land-cover classes: mangrove, field, shrub, plantation, settlement, and river. The trained model was applied to project future land-cover scenarios, with predictive reliability assessed through overall accuracy and Kappa statistics.

A feed-forward multilayer perceptron (MLP) with one hidden layer was implemented using backpropagation and Levenberg–Marquardt optimization to minimize RMSE. Data were split into training (70%), validation (15%), and testing (15%) sets. After testing several configurations, the final model achieved 98% overall accuracy and a Kappa coefficient of 0.98049, indicating excellent predictive performance validated against 2024 observations.

The trained network projected 2032 land cover under a business-as-usual scenario, mapping areas of potential mangrove loss, agricultural expansion, and stable ecosystems to support targeted management and restoration planning.

3.5 Vegetation Density Analysis

Canopy vigor was assessed using the Normalized Difference Vegetation Index (NDVI) derived from near-infrared (NIR, Band 5) and red (RED, Band 4) reflectance of Landsat 8/9 sensors. NDVI was calculated using the standard equation [16] as shown in Eq. (1):

$$NDVI=\frac{(NIR-RED)}{(NIR+RED)} \tag{1}$$

NDVI values range from −1.0 to +1.0, with negative values indicating water, near-zero values representing bare surfaces, and higher values reflecting denser vegetation. Thresholds were defined through literature review, 2023 field calibration, and histogram analysis, and validated against regional mangrove studies using similar Landsat thresholds. The final classes include:

- Dense mangrove canopy: NDVI > 0.55
- Moderate mangrove canopy: 0.30 ≤ NDVI ≤ 0.55
- Sparse or degraded vegetation: 0.12 ≤ NDVI < 0.30
- Non-vegetated or water areas: NDVI < 0.12

These ranges were verified using Sentinel-2 and Google Earth imagery, ensuring consistency across years. NDVI results supported mapping vegetation condition and identifying degradation hotspots for NbS planning.

3.6 Integration with the Nature-based Solutions (NbS) Framework

The final step integrated spatial and NDVI analyses within the NbS framework to delineate management zones. Areas with stable extent and high NDVI were classified as conservation cores, while those showing significant decline were marked as restoration priorities. Moderate-density areas functioned as adaptive buffer zones supporting assisted natural regeneration. This integration enables the translation of remote-sensing results into actionable strategies for coastal resilience and sustainable mangrove management in Tanjung Carat.

4. RESULTS AND DISCUSSION

4.1 Land Cover Classification and Spatiotemporal Dynamics (2016–2024)

Between 2016 and 2024, the Tanjung Carat coast underwent substantial land-cover shifts across six classes (Table 2; Fig. 2). Mangroves declined from 96,630.95 ha to 91,184.88 ha (−5.6%, ≈5,446 ha), mirroring regional losses linked to land conversion and aquaculture intensification [7, 17]. Fields and plantations expanded by ≈5,822 ha and ≈4,360 ha, consistent with agricultural trends reported in Vietnam and coastal China [7, 18]. Shrub cover decreased, settlements grew slightly around the planned port, and the total mapped area remained constant (≈233,263 ha), supporting classification reliability.

Most mangrove loss occurred along estuarine and tidal margins in Muara Sungsang and Sungsang I–II, largely converting to ponds (46.8%), settlements (32.4%), and agriculture or bare land (20.6%). Sungsang IV showed only a 1.4% decline (≈1,171 ha) due to favorable hydrology and strong community management, while Marga Sungsang experienced near-total loss. Conversion patterns strongly align with new access roads and port development, indicating anthropogenic dominance, whereas natural processes contributed <5% of change.

Despite minor decline, Sungsang IV remains comparatively resilient owing to geomorphic stability, sediment input from the Musi River, and initiatives such as the Mangrove Arboretum and the CIFOR–ICRAF SMART program, which help maintain canopy density (NDVI > 0.55). The contrast between resilient Sungsang IV and degraded Muara Sungsang and Sungsang I–II underscores the importance of geomorphology, hydrological connectivity, and governance. To assess future risks, an ANN model was applied to project land-cover change to 2032, identifying restoration priorities.

Table 2 Land-Cover Area Changes in Tanjung Carat (2016–2024)

Land Cover	2016	2017	2019	2021	2023	2024
Field	16,735.42	17,994.76	20,516.34	21,542.53	21,971.68	22,557.42
Mangrove	96,630.95	96,356.29	93,855.26	92,739.37	92,219.84	91,184.88
Plantation	34,254.34	34,519.75	34,794.76	36,525.50	36,945.62	38,617.07
River	23,356.09	23,356.09	23,356.09	23,356.09	23,356.09	23,356.09
Settlement	104.60	119.75	120.15	137.12	147.02	171.76
Shrub	62,181.35	60,916.10	60,620.14	58,962.14	58,622.50	57,375.52
Total	**233,262.75**	**233,262.75**	**233,262.75**	**233,262.75**	**233,262.75**	**233,262.75**

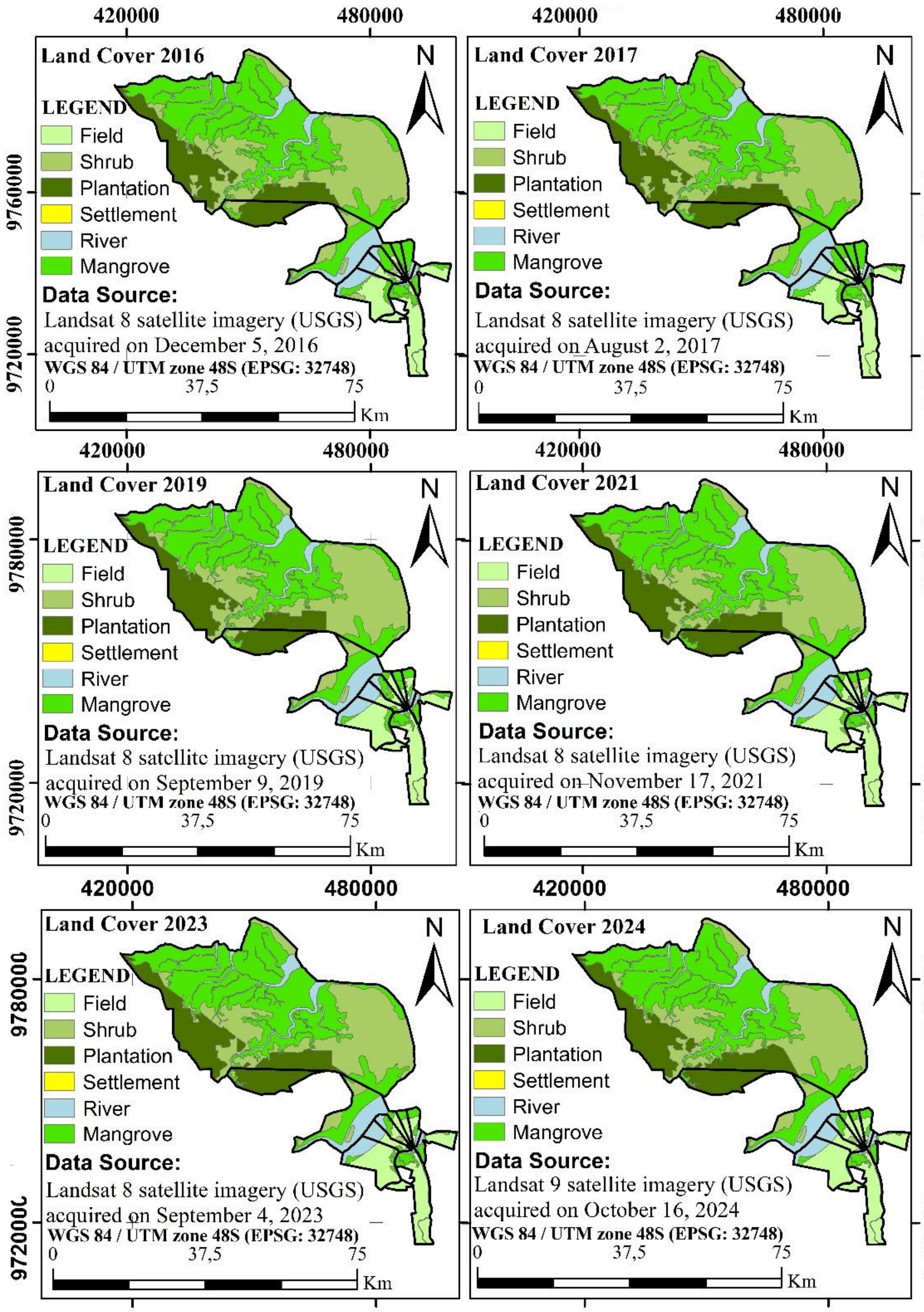

Fig. 2 Spatial Patterns of Land-Cover Change in Tanjung Carat, South Sumatra (2016–2024)

4.2 Predictive Land Cover Projection (2032)

The Artificial Neural Network (ANN) model projected ongoing land-cover change in the Tanjung Carat coastal zone through 2032 (Table 3; Fig. 3). Trained on 2016–2024 multi-temporal data, the model simulated transition probabilities among major land-cover classes, achieving 98% overall accuracy and a Kappa coefficient of 0.98049. The projection indicates a further 4.6% decline in mangrove area, from 91,184.88 ha in 2024 to approximately 86,990.38 ha by 2032. Similar ANN-based applications in China and Indonesia have likewise demonstrated high predictive reliability for coastal vegetation mapping [19].

Table 3 Observed (2016–2024) and Predicted (2032) Land-Cover Area in Tanjung Carat

Land Cover	2016	2024	2032
Field	16,735.42	22,557.42	23,748.70
Mangrove	96,630.95	91,184.88	86,990.38
Plantation	34,254.34	38,617.07	41,989.13
River	23,356.09	23,356.09	23,349.70
Settlement	104.60	171.76	172.39
Shrub	62,181.35	57,375.52	60,895.29
Total	233,262.75	233,262.75	233,262.75

The ANN projection indicates continued expansion of field and plantation areas, increasing by over 8,500 ha due to reclamation and intensified land use near tidal channels and port-access corridors. Settlements are expected to grow modestly around Muara Sungsang and Sungsang I–II, reflecting infrastructure and population pressures. Meanwhile, shrub and degraded vegetation classes are projected to shrink, as disturbed areas convert into managed land uses, patterns consistent with land-use transitions reported in other Indonesian coastal zones [20].

Spatially, the model highlights high-risk zones for mangrove loss along the southeastern delta and estuarine margins near the planned port site, while Sungsang IV remains relatively stable due to sustained sediment input and limited accessibility. Without targeted interventions such as hydrological rehabilitation, assisted natural regeneration (ANR), and strict conservation zoning, mangrove area could decline by over 9,600 ha between 2016 and 2032.

The spatially explicit ANN outputs provide a practical foundation for Nature-based Solutions (NbS) design. Moderately degraded zones in Marga Sungsang and Sungsang II should be prioritized for community-based restoration under the CIFOR–ICRAF SMART framework, integrating predictive modeling with participatory monitoring to strengthen coastal resilience [21].

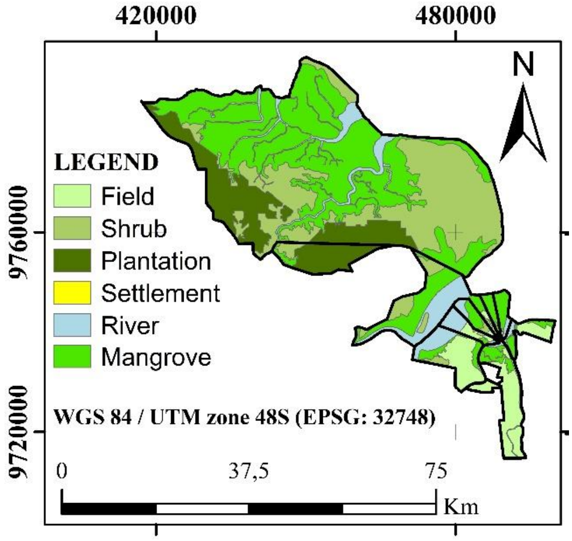

Fig. 3 Predicted Land-Cover Map of Tanjung Carat in 2032 (ANN Model Output)

4.3 Vegetation Density and NDVI Dynamics (2016–2024)

NDVI analysis reveals marked spatial and temporal variability in vegetation vigor (see Table 4 and Figure 4). Values ranged from 0.12–0.59, representing three main density classes:

- Low (0.10–0.30) – degraded or recently converted zones.
- Moderate (0.30–0.50) – regenerating or mixed stands.
- High (>0.50) – dense, mature mangrove canopies.

High NDVI values (>0.55) were consistently observed in Sungsang IV, confirming its ecological stability. Meanwhile, Muara Sungsang and Sungsang I–III exhibited declining NDVI trends, corresponding to intensified land conversion. In 2024, Marga Sungsang showed no measurable mangrove vegetation, corresponding to a complete loss of canopy cover due to extensive land conversion into aquaculture ponds and open fields. This area was therefore recorded as n/a (no mangrove cover) in Table 4. The correlation between NDVI decline and ANN-predicted change underscores the effectiveness of NDVI as an early indicator of disturbance.

Moderate NDVI values in Marga Sungsang suggest areas suitable for assisted natural regeneration (ANR), aligning with findings in similar deltaic systems where intermediate canopy density zones respond well to community-based restoration [22].

Table 4 Vegetation Density in Tanjung Carat Area (2016–2024)

Village	Vegetation Density					
	2016	2017	2019	2021	2023	2024
Marga Sungsang	0.34 – 0.57	0.28 – 0.53	0.30 – 0.45	0.25 – 0.54	0.30 – 0.49	n/a
Muara Sungsang	0.12 – 0.59	0.17 – 0.56	0.26 – 0.49	0.30 – 0.59	0.19 – 0.55	0.20 – 0.50
Sungsang I	0.16 – 0.57	0.15 – 0.54	0.16 – 0.47	0.16 – 0.56	0.14 – 0.53	0.17 – 0.56
Sungsang II	0.30 – 0.58	0.24 – 0.56	0.22 – 0.51	0.16 – 0.57	0.15 – 0.53	0.16 – 0.57
Sungsang III	0.21 – 0.56	0.23 – 0.54	0.17 – 0.49	0.18 – 0.60	0.12 – 0.54	0.22 – 0.59
Sungsang IV	0.12 – 0.60	0.19 – 0.57	0.27 – 0.53	0.20 – 0.58	0.17 – 0.56	0.30 – 0.58

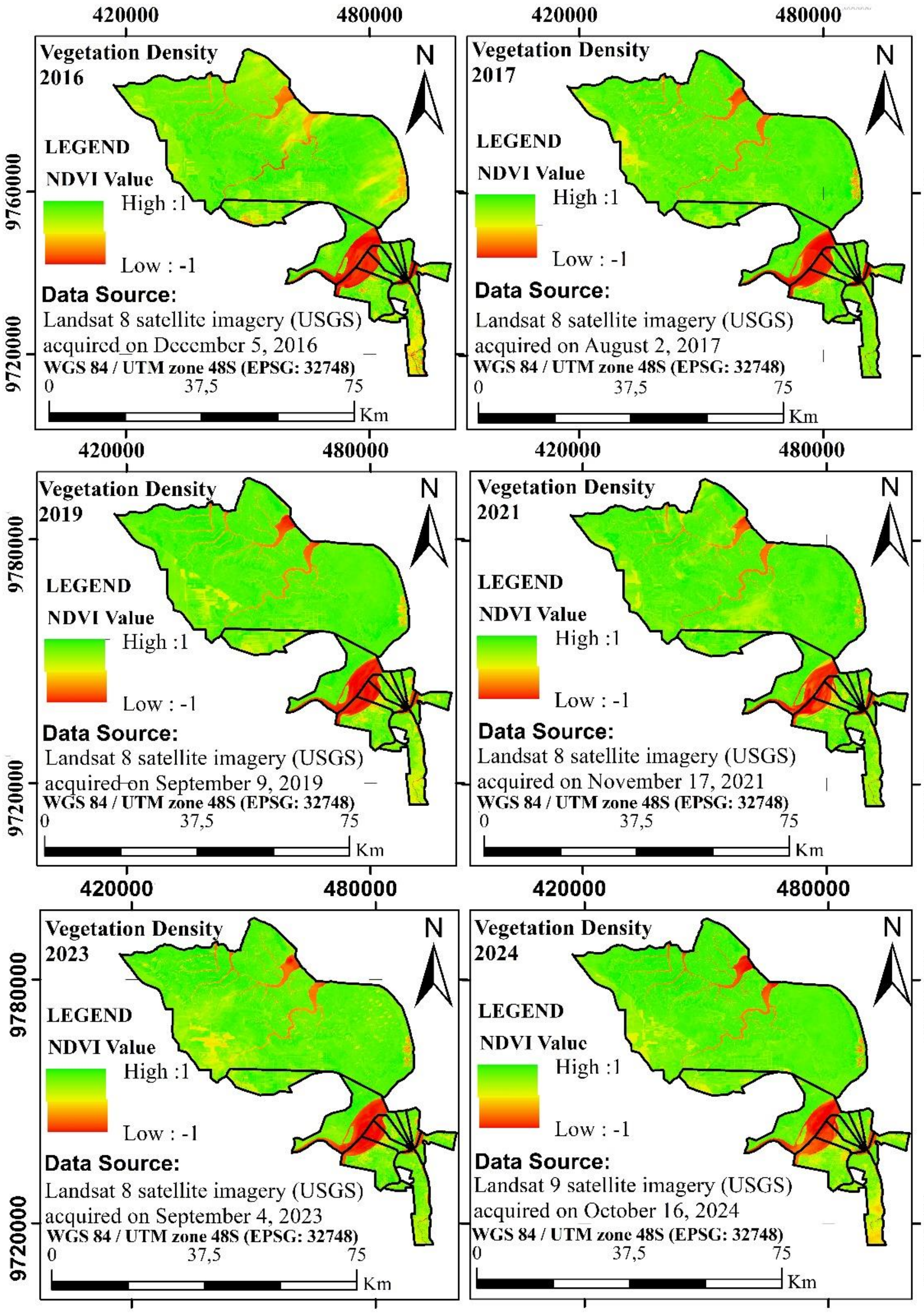

Fig. 4 Spatial distribution of mangrove vegetation density in Tanjung Carat Area, South Sumatra (2016–2024)

4.4 Integrated Implications under the Nature-based Solutions (NbS) Framework

The integration of land cover, ANN projections, and NDVI analysis provides a clear foundation for NbS-driven management zoning in Tanjung Carat. Three priority management zones are identified:

1. Conservation Core Zone (Sungsang IV): Maintain ecological integrity through strict protection, monitoring, and hydrological preservation.
2. Restoration Priority Zone (Muara Sungsang, Sungsang I–III): Implement replanting, tidal flow rehabilitation, and community-managed buffer plantations.
3. Adaptive Buffer Zone (Marga Sungsang): Promote ANR and agroforestry-based livelihood programs to balance economic and ecological objectives.

By combining predictive modeling with empirical remote sensing data, this study demonstrates that Artificial Neural Networks (ANNs) can serve as effective decision-support tools for anticipating land use transitions and prioritizing restoration investments. This integrated spatial approach supports the implementation of NbS for coastal resilience [23], particularly in rapidly developing delta regions like Tanjung Carat.

5. CONCLUSION

This study quantified mangrove changes in Tanjung Carat, South Sumatra (2016–2024), revealing a net loss of 5,446 ha (−5.6%), mainly from conversion to aquaculture (46.8%), settlement and infrastructure (32.4%), and agriculture (20.6%). While Sungsang IV showed relative resilience (−1.4%), Muara Sungsang and Sungsang I–II underwent severe degradation. The ANN model projects an additional 4.6 % decline (≈4,195 ha; ≈0.58% yr^{-1}) by 2032 if current trends persist, consistent with predictive modelling results in other mangrove landscapes using multi-temporal satellite data [24].

Given Indonesia's coastal development trajectory, a balanced management strategy is essential. Spatial results suggest designating 30–35% (≈27,000–30,000 ha) of remaining mangroves as strict conservation zones, prioritizing Sungsang IV and its buffers; 40% (≈36,000 ha) for hydrological rehabilitation and community restoration in Sungsang I–III and Muara Sungsang; and the remainder as adaptive-use zones integrating eco-aquaculture and sustainable port infrastructure. Such spatially informed zoning aligns with successful applications of Landsat-based mangrove monitoring used to guide conservation and land-use planning in other tropical deltas [25].

Effective implementation requires annual remote-sensing composites and community-based monitoring (e.g., CIFOR–ICRAF SMART framework) to guide adaptive, evidence-based management. This study establishes a spatially explicit NbS framework integrating NDVI and ANN modeling for sustainable delta management. Limitations include the moderate Landsat resolution and short temporal baseline (2016–2024); future work should employ higher-resolution imagery, hydrodynamic-socioeconomic models, and policy evaluation to refine restoration and resilience planning.

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8. REFERENCES

1. Lovelock C.E., Bennion V., de Oliveira M., Hagger V., Hill J.W., Kwan V., Hayes M.A., Rogers K., Duke N.C., Mangrove Ecology Guiding the Use of Mangroves as Nature-Based Solutions. Journal of Ecology, 112(11), 2024, pp.2510–2521. https://doi.org/10.1111/1365-2745.14383
2. Food and Agriculture Organization of the United Nations (FAO), Global Forest Resources Assessment 2020 – key findings. FAO, Rome, 2020, pp.1–48. https://www.fao.org/interactive/forest-resources-assessment/2020/en/
3. Ju C., Fu D., Lyne V., Xiao H., Su F., Yu H., Global Declines in Mangrove Area and Carbon-Stock from 1985 to 2020. Geophysical Research Letters, 52(8), 2025, pp.e2025GL115303–e2025GL115303. https://doi.org/10.1029/2025GL115303
4. Ministry of Environment and Forestry (MoEF),

National Mangrove Map 2021. MoEF, Jakarta, 2021, pp.1–120. https://pdasrh.menlhk.go.id/vo/download.php?id=59&token=gWBCAzL6ACrzQ9GlgO35AljlLpXwRdgK

5. Zhang J., Liu W., Chen J., Zhang W., Xu J., Zhang Y., Zhou T., Chen L., Li M., A Global Assessment of Mangrove Soil Organic Carbon Sources and Implications for Blue Carbon Credit. Nature Communications, 15(1), 2024, pp.8994–8994.
6. Kospa H.S.D., Natul A.S., Haidir H., Puspasari S., Mapping Physical and Environmental Vulnerabilities for Port Development in Tanjung Carat, South Sumatra. Environmental and Ecological Research, 12(6), 2024, pp.601–619. https://doi.org/10.13189/eer.2024.120604
7. Tran T.V., Reef R., Zhu X., Long-term Changes of Mangrove Distribution and Its Response to Anthropogenic Impacts in the Vietnamese Southern Coastal Region. Journal of Environmental Management, 370, 2024, pp.122658–122658. https://doi.org/10.1016/j.jenvman.2024.122658
8. Sunkur R, Kantamaneni K, Bokhoree C, Ravan S., Mangroves' Role in Supporting Ecosystem-Based Techniques to Reduce Disaster Risk and Adapt to Climate Change: A Review. Journal of Sea Research, 196, 2023, pp.102449–102449. https://doi.org/10.1016/j.seares.2023.102449
9. Paxton A.B., Riley T.N., Steenrod C.L., Puckett B.J., Alemu J.B., Paliotti S.T., Theuerkauf S.J., Pollack J.B., Evidence on the Performance of Nature-Based Solutions Interventions for Coastal Protection in Biogenic, Shallow Ecosystems: A Systematic Map. Environmental Evidence, 13(1), 2024, pp.28–28. https://doi.org/10.1186/s13750-024-00350-5
10. Yang X., Liu Y., Liu Q., Chen B., Wang Z., Li S., Zhou T., Huang H., Tracking Mangrove Condition Changes Using Dense Landsat Time Series. Remote Sensing of Environment, 315, 2024,pp.114461–114461. https://doi.org/10.1016/j.rse.2024.114461
11. Casal G., Trégarot E., Cornet C.C., McCarthy T., van der Geest M., A Cost-Effective Method to Map Mangrove Forest Extent, Composition, and Condition in Small Islands Based on Sentinel-2 Data: Implications for Management. Ecological Indicators, 159, 2024, pp.111696–111696. https://doi.org/10.1016/j.ecolind.2024.1116
12. Priyono K.D., Saifuddin A., Nugroho F.S., Jumadi J., Identification of Mangrove Changes in the Mahakam Delta in 2007–2017 Using ALOS/PALSAR and Landsat. International Journal of GEOMATE, 23(96), 2022, pp.77–84. https://doi.org/10.21660/2022.96.3312
13. Alimin, Rozirwan, Wildayana E., Riswani, Mangrove Wetland Ecotourism Development Potential in the Sungsang-Sembilang Region, South Sumatra. AACL Bioflux, 17(1), 2024, pp.207–218.
14. Sarno S., Hidayat A., Pratama R., Lestari N., Sustainable Environmental Conservation Through Planting of Mangrove Arboretum in Sungsang IV Village, Banyuasin, South Sumatera. Asian Journal of Community Service, 4(5), 2025, pp.435–444. https://doi.org/10.55927/ajcs.v4i5.159
15. Gao B., NDWI—A Normalized Difference Water Index for Remote Sensing of Vegetation Liquid Water From Space. Remote Sensing of Environment, 58(3), 1996, pp.257–266. https://doi.org/10.1016/S0034-4257(96)00067-3
16. Rouse J.W., Haas R.H., Schell J.A., Deering D.W., Monitoring the Vernal Advancement and Retrogradation (Green Wave Effect) of Natural Vegetation. Progress Report RSC, 1978-1, 1973, pp.112–112. https://ntrs.nasa.gov/citations/19740008955
17. Chaiklang P., Karthe D., Babel M., Giessen L., Schusser C., Reviewing Changes in Mangrove Land Use Over the Decades in Thailand: Current Responses and Challenges. Trees, Forests and People, 17, 2024, pp.100630-100630. https://doi.org/10.1016/j.tfp.2024.100630.
18. Jia M., Wu Z., Wang C., Zhang Y., Huang H., Zhou Z., Li X., Mapping Mangrove Functional Traits From Sentinel-2 Imagery Based on Hybrid Models Coupled With Active Learning Strategies. International Journal of Applied Earth Observation and Geoinformation, 130, 2024, pp.103905–103905. https://doi.org/10.1016/j.jag.2024.103905
19. Zhang H., Xia Q., Dai S., Zheng Q., Zhang Y., Deng X., Mangrove Forest Mapping from Object-Oriented Multi-Feature Ensemble Classification Using Sentinel-2 Images. Frontiers in Marine Science, 10, 2023, pp.1243116–1243116. https://doi.org/10.3389/fmars.2023.1243116
20. Wardhani M.K., Rosyid D.M., Armono H.D., Land Use Change of Mangrove Forest for Eco-Tourism in the South Coastal, Bangkalan, East Java-Indonesia. International Journal of GEOMATE, 23(98), 2022, pp.136–146. https://doi.org/10.21660/2022.98.1221
21. Mahmood R., Zhang L., Li G., Assessing effectiveness of Nature-based Solutions with big earth data: 60 years' mangrove plantation program in Bangladesh coast. Ecological Processes, 12, Article 11 (2023). https://doi.org/10.1186/s13717-023-00419-y
22. Wang Y., Wang X., Khan S., Zhou D., Ke Y. Evaluation of Mangrove Restoration

Effectiveness Using Remote Sensing Indices – A Case Study in Guangxi Shankou Mangrove National Natural Reserve, China. Frontiers in Marine Science, 10, 2023, pp.128037–128037. https://doi.org/10.3389/fmars.2023.128037

23. Ayassamy P. Mangroves as a Nature-Based Solution and a Tool for Coastal Resilience. Wetlands, 45, 2025, pp.89–89. https://doi.org/10.1007/s13157-025-01971-3
24. Seydi S.T., Ahmadi S.A., Ghorbanian A., Amani M. Land Cover Mapping in a Mangrove Ecosystem Using Hybrid Selective Kernel-Based Convolutional Neural Networks and Multi-Temporal Sentinel-2 Imagery. Remote Sensing, 16(15), 2024, pp. 2849–2849. https://doi.org/10.3390/rs16152849
25. Vásquez J., Acevedo-Barrios R., Miranda-Castro W., Guerrero M., Meneses-Ospina L. Determining Changes in Mangrove Cover Using Remote Sensing With Landsat Images: A Review. Water, Air, & Soil Pollution, 235, 2024, pp. 18–18. https://doi.org/10.1007/s11270-023-06788-6