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Spatial and temporal dynamics of mangrove cover change in five estuaries along the North Coast of Central Java, Indonesia (2014-2024)

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[2]Disaster Research Center, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret. Jl. Ir. Sutami 36A, Surakarta 57126, Central Java, Indonesia
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Abstract. *Candraningtyas CF, Hafiffah AS, Widowati D, Mardiyanto MB, Saputri AB, Setyawan AD. 2024. Spatial and temporal dynamics of mangrove cover change in five estuaries along the North Coast of Central Java, Indonesia (2014-2024). Intl J Bonorowo Wetlands 15: 40-48.* Mangrove ecosystems are critical coastal habitats that provide essential ecological services, including shoreline protection, carbon sequestration, and biodiversity support, yet they are increasingly threatened by anthropogenic pressures. This study investigates spatial and temporal changes in mangrove cover from 2014 to 2024 across five estuaries along the north coast of Central Java, Indonesia—Sriwulan, Pemali, Comal, Bodri, and Cisanggarung—using Landsat 8 satellite imagery processed via Google Earth Engine and ArcGIS. Mangrove extents were manually digitized and classified into zones of loss, gain, and stability, with field surveys and photographic documentation employed for validation. Results revealed significant mangrove loss in Sriwulan (-47.03%), Cisanggarung (-50.00%), Comal (-11.31%), and Bodri (-1.59%), driven by land conversion for aquaculture and settlements, destructive fishing practices, and hydrological disruptions. In contrast, the Pemali Estuary exhibited a notable 79.83% increase in mangrove cover, primarily due to sediment accretion and community-led restoration efforts, especially silvofishery-based rehabilitation. The study demonstrates that integrating remote sensing with ground truthing is a robust approach for monitoring mangrove dynamics and identifying localized drivers of change. The contrasting trends across estuaries highlight the heterogeneity of coastal ecosystem responses and underscore the importance of site-specific management strategies. While some estuaries face continued degradation, others show promising signs of recovery, illustrating both the challenges and potential in mangrove conservation. These findings emphasize the urgent need for adaptive coastal management that incorporates ecological monitoring, sustainable land-use planning, and active community participation. As mangrove loss continues globally, this research provides important insights into effective restoration and protection strategies for tropical estuarine environments, offering a model for balancing development and conservation in similar socio-ecological settings across Southeast Asia.

Keywords: Central Java, coastal conservation, land use change, mangrove cover change, rehabilitation, remote sensing

INTRODUCTION

Mangrove ecosystems are among the most productive and ecologically significant coastal habitats worldwide. They serve as critical buffers between terrestrial and marine environments, providing a wide array of ecosystem services including shoreline stabilization, carbon sequestration, nursery grounds for fisheries, and habitat for diverse flora and fauna (Nagelkerken et al. 2008; Anu et al. 2024). These intertidal forests occur predominantly in tropical and subtropical regions, thriving in the brackish waters of estuaries, bays, and river mouths where saline and freshwater mix (Godoy and Lacerda 2015). Indonesia holds the largest expanse of mangrove forests globally, estimated at approximately 2.7 million hectares in 2020, accounting for roughly 23% of the world's total mangrove area (Basyuni et al. 2022). This makes the country a critical global hotspot for mangrove conservation and management.

Despite their ecological importance, mangrove ecosystems face increasing threats from anthropogenic pressures. Land-use change driven by urbanization, aquaculture development, agricultural expansion, and infrastructure growth has led to significant mangrove degradation and loss in recent decades (Kusmana 2015; Friess et al. 2019). The conversion of mangrove areas into shrimp ponds and coastal settlements is particularly prevalent in densely populated coastal regions such as Java, Indonesia's most populous island. These activities not only diminish mangrove cover but also disrupt ecosystem functioning and reduce the services these forests provide to coastal communities. However, with these collective efforts, we can mitigate these threats and protect these vital ecosystems. Moreover, environmental stressors such as coastal erosion, sedimentation changes, and pollution further exacerbate mangrove vulnerability (Sanderman et al. 2018).

Monitoring mangrove cover changes is therefore essential to inform effective conservation strategies and policy interventions. Remote sensing technology, especially the use of multispectral satellite imagery, has emerged as a powerful tool for mapping and monitoring mangrove dynamics over time and space (Kuenzer et al. 2011; Pham and Yoshino 2015). Landsat satellites, with their long-term data archives and moderate spatial resolution, have been widely applied in mangrove studies, enabling assessments of deforestation, degradation, and rehabilitation across large geographic extents (Chen et al. 2018; As-Syakur et al. 2023). The integration of cloud computing platforms like Google Earth Engine has further facilitated the efficient processing of large satellite datasets, improving temporal resolution and analytical capability.

The northern coast of Central Java, Indonesia, presents a compelling case for such analyses due to its ecological complexity and intense anthropogenic activity. The region encompasses multiple estuarine systems where mangroves interact with diverse land uses, including fisheries, agriculture, urban development, and industrial zones. This spatial heterogeneity poses challenges for conservation but also opportunities for adaptive management based on detailed spatial data. Past studies in the region have highlighted both losses and gains in mangrove cover, with some estuaries experiencing severe degradation while others show signs of recovery through rehabilitation initiatives (Damastuti and de Groot 2017; Fikriyya et al. 2023).

However, comprehensive assessments spanning multiple estuaries over a decadal period remain limited, particularly for integrating remote sensing data with ground-based observations and socio-environmental context. Understanding the spatial and temporal patterns of mangrove change across several key estuaries along Central Java's northern coast is critical for identifying drivers of change and tailoring management responses. Moreover, evaluating the success of rehabilitation efforts and conservation programs requires consistent and accurate monitoring frameworks.

This study aims to fill these gaps by assessing mangrove cover changes between 2014 and 2024 in five major estuaries along the North Coast of Central Java: Sriwulan, Pemali, Comal, Bodri, and Cisanggarung. Using Landsat 8 imagery processed through Google Earth Engine and ArcGIS, we quantify spatial extents and trends of mangrove cover in each estuary. We further analyze the potential drivers of these changes, including anthropogenic land conversion, natural sedimentation dynamics, and community-based restoration efforts. Complementary field surveys and photographic documentation are integrated to validate remote sensing classifications and provide ground truth.

By examining both losses and gains within this regional context, the study provides insights into the complex dynamics shaping mangrove ecosystems on Java's north coast. The findings are expected to inform targeted conservation strategies, enhance monitoring protocols, and support sustainable coastal management in Indonesia and comparable tropical regions worldwide.

MATERIALS AND METHODS

Study area

Geographic location and climate

The study area covers five major estuaries located along the northern coast of Central Java, Indonesia (Figure 1): Sriwulan, Pemali, Comal, Bodri, and Cisanggarung. These estuaries are situated between approximately 6°50' to 7°20' S and 109° to 110° E, extending from Demak District in the east to Cirebon District in the west. This coastal region forms part of the Java Sea coastline and is characterized by a tropical monsoon climate with distinct wet and dry seasons.

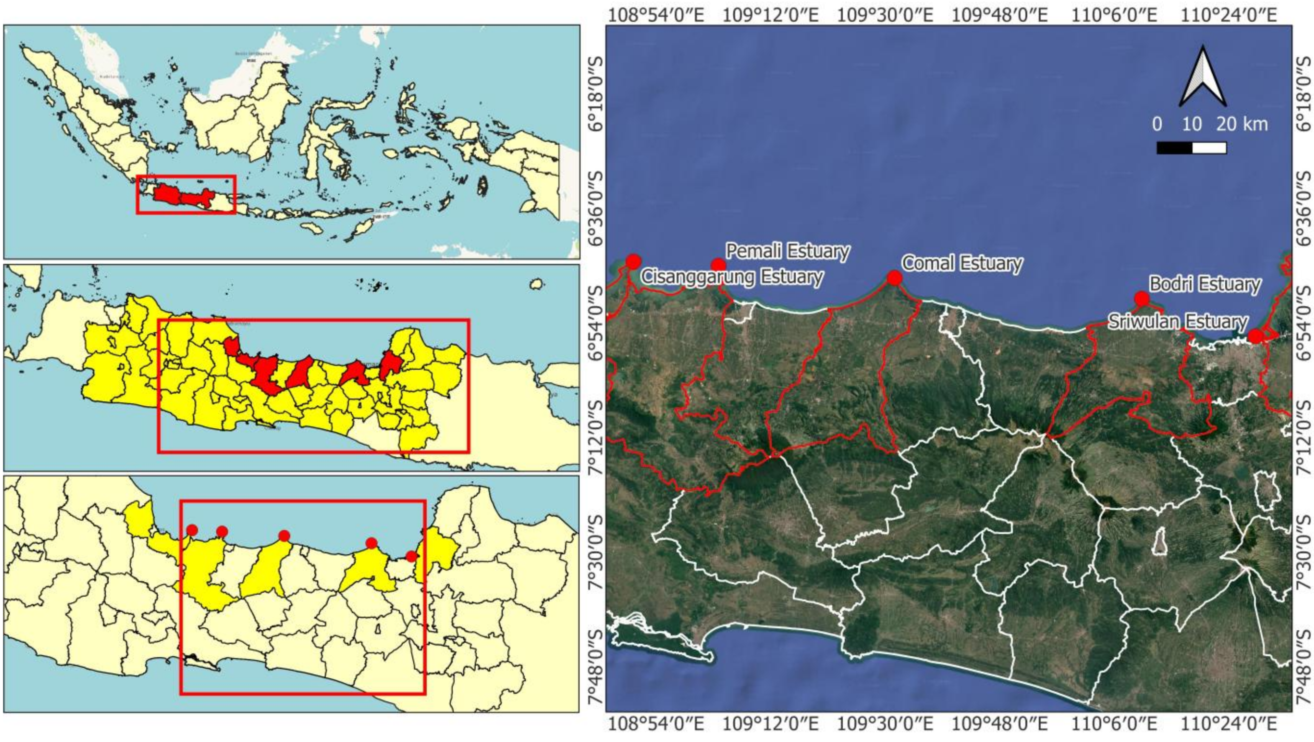


Figure 1. Spatial distribution maps of mangrove cover across the five studied estuaries on the north coast of Central Java, Indonesia

The average annual rainfall ranges from 1,800 to 2,500 mm, predominantly occurring between November and March, while the dry season extends from June to September. Temperatures fluctuate between 24°C and 33°C throughout the year. The tidal regime is semidiurnal with moderate amplitude, influencing the hydrological dynamics and sediment transport in the estuaries. These physical and climatic conditions provide suitable habitats for mangrove forests, which thrive in the intertidal zones of these estuarine systems.

Characteristics of the five estuaries (Sriwulan, Pemali, Comal, Bodri, Cisanggarung)

Each of the five estuaries presents unique geomorphological, ecological, and anthropogenic features:

Sriwulan Estuary is located in Demak District and is characterized by relatively fertile waters with substantial nutrient input, supporting dense mangrove vegetation. The estuary supports local fisheries, settlements, and aquaculture activities. However, increasing urbanization and industrial development have exerted pressure on the mangrove ecosystem, causing fragmentation and degradation.

Pemali Estuary lies in Brebes District and features a delta formed by fluvial and marine sedimentation processes. The region has experienced notable mangrove expansion, attributed largely to successful rehabilitation and silvofishery practices that combine aquaculture and mangrove preservation. The gentle seabed topography facilitates sediment deposition, fostering mangrove growth.

Comal Estuary in Pemalang District serves as an important waterway for fishing and transportation. Recent river diversion efforts to improve navigation have altered hydrodynamics, resulting in localized mangrove loss due to sediment changes and abrasion. Conservation groups have initiated mangrove planting programs, but challenges such as extreme weather reduce seedling survival.

Bodri Estuary is situated in Kendal District and features a dynamic sediment environment with active accretion processes. Despite some industrial and residential development, the mangrove cover has remained relatively stable with minor reductions, mainly due to conversion into salt ponds. The estuary's geomorphology includes sandbars and a sloped riverbed, influencing sediment distribution.

Cisanggarung Estuary is located in Cirebon District, is part of an actively expanding delta with high sedimentation rates forming a bird's foot pattern. While sedimentation facilitates new mangrove habitat formation, the rapid expansion of aquaculture ponds on newly formed land has resulted in significant mangrove loss. Mangroves are also maintained along pond embankments, reflecting complex land use patterns.

Socio-economic and land use context

The northern coast of Central Java is densely populated, with communities heavily reliant on coastal resources for livelihoods, including fishing, aquaculture, agriculture, and small-scale industry. Population growth and economic development have accelerated land conversion, particularly the expansion of shrimp and fish ponds, residential settlements, and industrial zones. These activities frequently encroach upon mangrove areas, leading to habitat loss and fragmentation.

Local knowledge and community participation vary among the estuaries, influencing the success of mangrove conservation and rehabilitation initiatives. For example, in the Pemali Estuary, community-driven silvofishery practices have enhanced mangrove restoration. At the same time, in the Sriwulan and Cisanggarung estuaries, conflicting land uses and regulatory enforcement gaps pose significant challenges.

Land use in the study areas typically includes a mosaic of mangrove forests, aquaculture ponds, agricultural fields, urban settlements, and industrial infrastructure. The balance between these land uses is dynamic and directly affects the spatial distribution and health of mangrove ecosystems. Effective management requires integrating socio-economic considerations with ecological monitoring to ensure sustainable coastal development and conservation outcomes.

Data acquisition

Satellite imagery sources and specifications (Landsat 8)

For this study, multispectral satellite imagery from the Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) was acquired to analyze mangrove cover changes between 2014 and 2024. Landsat 8 imagery is publicly accessible and provides data at a spatial resolution of 30 meters, suitable for regional-scale ecosystem monitoring. The selected bands for this analysis included Band 4 (Red), Band 5 (Near-Infrared), and Band 6 (Shortwave Infrared 1), which are effective in differentiating vegetation types and detecting mangrove vegetation based on their spectral reflectance properties. These spectral bands were processed to generate false-color composites, enhancing the contrast between mangroves, water bodies, and other land covers.

The satellite images were sourced through the Google Earth Engine (GEE) platform, which allows for efficient cloud filtering, atmospheric correction, and batch processing of large datasets. Images with less than 10% cloud cover over the study area were selected for each target year to minimize atmospheric distortion. The temporal window focused on the dry season months (June-September) to reduce phenological variability and water turbidity effects.

Ancillary data (administrative boundaries, hydrology maps)

Aancillary geospatial data were incorporated to delineate study areas precisely and assist spatial analysis. Administrative boundaries for the Central Java districts encompassing the five estuaries were obtained from official government geodata repositories. These boundaries facilitated the accurate extraction and masking of satellite imagery to the study extents.

Hydrological maps and river network data were used to define estuarine zones, tidal influence areas, and river mouths critical for understanding mangrove spatial distribution. Topographic maps and Land Use Land Cover (LULC) data from previous studies and regional planning agencies supplemented satellite imagery for contextual interpretation of land-use dynamics and anthropogenic pressures. The integration of these datasets ensured that mangrove mapping and change detection were spatially accurate and reflected on-the-ground conditions within the administrative and ecological boundaries relevant to management and policy.

Image preprocessing and classification

Selection of spectral bands and false-color composite

To enhance the differentiation of mangrove vegetation from other land covers, the Landsat 8 bands 4 (Red), 5 (Near-Infrared, NIR), and 6 (Shortwave Infrared 1, SWIR1) were selected for analysis. These bands were combined into false-color composite images with Band 5 assigned to red, Band 6 to green, and Band 4 to blue, a configuration that highlights healthy vegetation in bright red tones, facilitating visual identification of mangrove areas. This spectral combination exploits the strong reflectance of vegetation in the NIR band and absorption characteristics in the red and SWIR bands.

Image filtering and cloud masking

Prior to classification, the raw satellite images underwent preprocessing steps to ensure quality and reliability. Images were filtered to exclude scenes with cloud cover exceeding 10% over the study area. Clouds and their shadows were masked using the pixel quality assessment bands available in the Landsat 8 Surface Reflectance dataset, removing artifacts that could confound classification results. Atmospheric corrections embedded in the dataset further refined reflectance values to standardize conditions across different acquisition dates.

Mangrove area delineation and digitization in ArcGIS

Mangrove extents were manually digitized in ArcGIS 10.8 by interpreting the false-color composites alongside ancillary data such as hydrological boundaries and previous land use maps. This manual digitization approach enabled careful delineation of mangrove polygons, especially in areas where spectral confusion with other vegetation or land covers could occur. Polygons were traced along visible mangrove boundaries, considering tidal influence zones and estuarine topography.

Each polygon was attributed with relevant metadata, including estimated area in hectares. The accuracy of the digitized mangrove map was cross-verified through field observations at selected sample points and supplemented by photographic documentation where available. This approach ensured that mangrove boundaries reflected realistic spatial patterns consistent with both satellite imagery and ground truth data.

Change detection analysis

Methodology for comparing 2014 and 2024 mangrove extents

The digitized mangrove polygons from 2014 and 2024 were compared spatially using GIS overlay techniques to quantify changes in mangrove cover over the ten years. The 2014 mangrove layer was subtracted from the 2024 layer to identify areas of loss, gain, and persistence. This spatial comparison allowed for the classification of mangrove change into three categories: deforestation (loss), afforestation or natural regeneration (gain), and stable mangrove cover.

Geoprocessing tools such as 'Erase' and 'Intersect' in ArcGIS were employed to compute the spatial extent and location of these changes at each estuary. The analysis was conducted separately for each of the five estuaries to discern local variation in mangrove dynamics.

Calculation of area changes and percentage differences

The areas of mangrove cover for 2014 and 2024 were calculated in hectares based on the digitized polygons. The absolute change in area (ha) was determined by subtracting the 2014 mangrove extent from the 2024 extent. The percentage change was calculated using the formula:

$$\text{Percentage Change} = \frac{\text{Area}_{2024} - \text{Area}_{2014}}{\text{Area}_{2014}} \times 100\%$$

This metric provided a normalized measure of change, facilitating comparison across estuaries with different initial mangrove extents. The results were tabulated and visualized to illustrate the magnitude and direction of mangrove cover changes spatially and temporally.

Validation and accuracy assessment

Field survey design and data collection

Field validation was conducted at selected sites within the five estuaries to verify the accuracy of mangrove classification derived from satellite imagery. Sampling points were chosen to represent diverse mangrove conditions, including dense, sparse, degraded, and rehabilitated areas. At each point, GPS coordinates were recorded, and detailed observations on vegetation type, canopy cover, and health status were documented. Photographs were taken to provide visual evidence supporting classification accuracy.

Use of photographic documentation and publicly available images

In addition to field surveys, photographic documentation obtained during fieldwork supplemented validation efforts. Where direct field access was limited, publicly available images from platforms such as Google Maps Photos and iNaturalist were used cautiously as supplementary references. These external images helped confirm mangrove presence and conditions in areas not covered during field visits, but were not relied upon as primary validation data due to potential discrepancies in location accuracy and timing.

Limitations of validation data

While efforts were made to ensure robust validation, certain limitations are acknowledged. Field surveys were constrained by accessibility issues, especially in remote or privately owned areas, limiting the spatial coverage of ground truth points. Furthermore, the use of publicly sourced images introduced uncertainties related to metadata accuracy. Despite these challenges, the combination of satellite interpretation, targeted field verification, and supplemental imagery provided a reasonable level of confidence in the mangrove classification and change detection results. Although only 35 validation points were collected, sampling was stratified to capture different vegetation densities and estuarine conditions. Nonetheless, the limited number of ground points may affect the representation of highly fragmented or transitional zones

Data analysis and interpretation

Spatial analysis of mangrove loss and gain

The spatial distribution of mangrove loss, gain, and stable areas was analyzed using GIS tools to identify patterns and hotspots across the five estuaries. Next, overlay maps highlighting areas of significant deforestation and afforestation were generated to visualize spatial trends. These maps facilitated understanding of the geographic context of mangrove dynamics, indicating zones heavily impacted by anthropogenic activities or benefiting from natural regeneration and rehabilitation efforts.

Identification of drivers of change

Integrating spatial analysis results with ancillary land use data, field observations, and a literature review identified key drivers influencing mangrove cover change**.** These included land conversion for aquaculture and settlements, coastal erosion, sediment deposition, and community-led rehabilitation programs. The relative impact of each driver was assessed qualitatively, providing insight into the complex socio-environmental interactions shaping mangrove ecosystems in Central Java.

Integration of remote sensing and field data

The integration of remote sensing data with field validation and socio-environmental context enabled a comprehensive interpretation of mangrove dynamics. This holistic approach enhanced the reliability of change detection and supported the formulation of management recommendations tailored to local conditions. The combined dataset provided a strong evidentiary basis for understanding mangrove ecosystem status and guiding future conservation strategies.

RESULTS AND DISCUSSION

Overview of mangrove cover in 2014 and 2024

Total mangrove area per estuary

The total mangrove area in the five estuaries along the north coast of Central Java showed significant spatial variation in 2014 and 2024. Table 1 presents the total mangrove areas for each estuary at both time points. Overall, the cumulative mangrove area increased from 706.25 ha in 2014 to 838.29 ha in 2024, primarily due to the substantial expansion observed in the Pemali Estuary. Meanwhile, the other estuaries experienced varying degrees of mangrove loss, with the greatest declines noted in the Cisanggarung and Sriwulan estuaries. These contrasting trends highlight the heterogeneous nature of mangrove dynamics along this coastal stretch. Figure 2 illustrates the spatial distribution of mangrove cover in 2014 and 2024, providing a visual comparison of mangrove extent changes across the five estuaries.

Spatial distribution patterns

The spatial distribution of mangrove cover across the five estuaries varied notably between 2014 and 2024. Mangrove patches in the Sriwulan and Cisanggarung estuaries were highly fragmented by 2024, with significant areas converted to aquaculture ponds, built-up land, and bare substrates. However, the Pemali Estuary presented a beacon of hope, exhibiting an expansion of mangrove areas, particularly along deltaic fronts and newly accreted lands, indicating successful sedimentation and restoration efforts.

Figure 2 presents detailed maps showing mangrove spatial patterns for each estuary at both time points, highlighting zones of loss, gain, and stable coverage. The fragmentation observed in the declining estuaries reflects increasing anthropogenic pressures and environmental degradation, underscoring the urgent need for targeted conservation programs. More continuous mangrove coverage in Pemali further emphasizes the importance of such efforts. These spatial trends emphasize the heterogeneity of mangrove ecosystem responses within a relatively small geographic area and underscore the importance of site-specific management and restoration strategies.

Mangrove cover change analysis

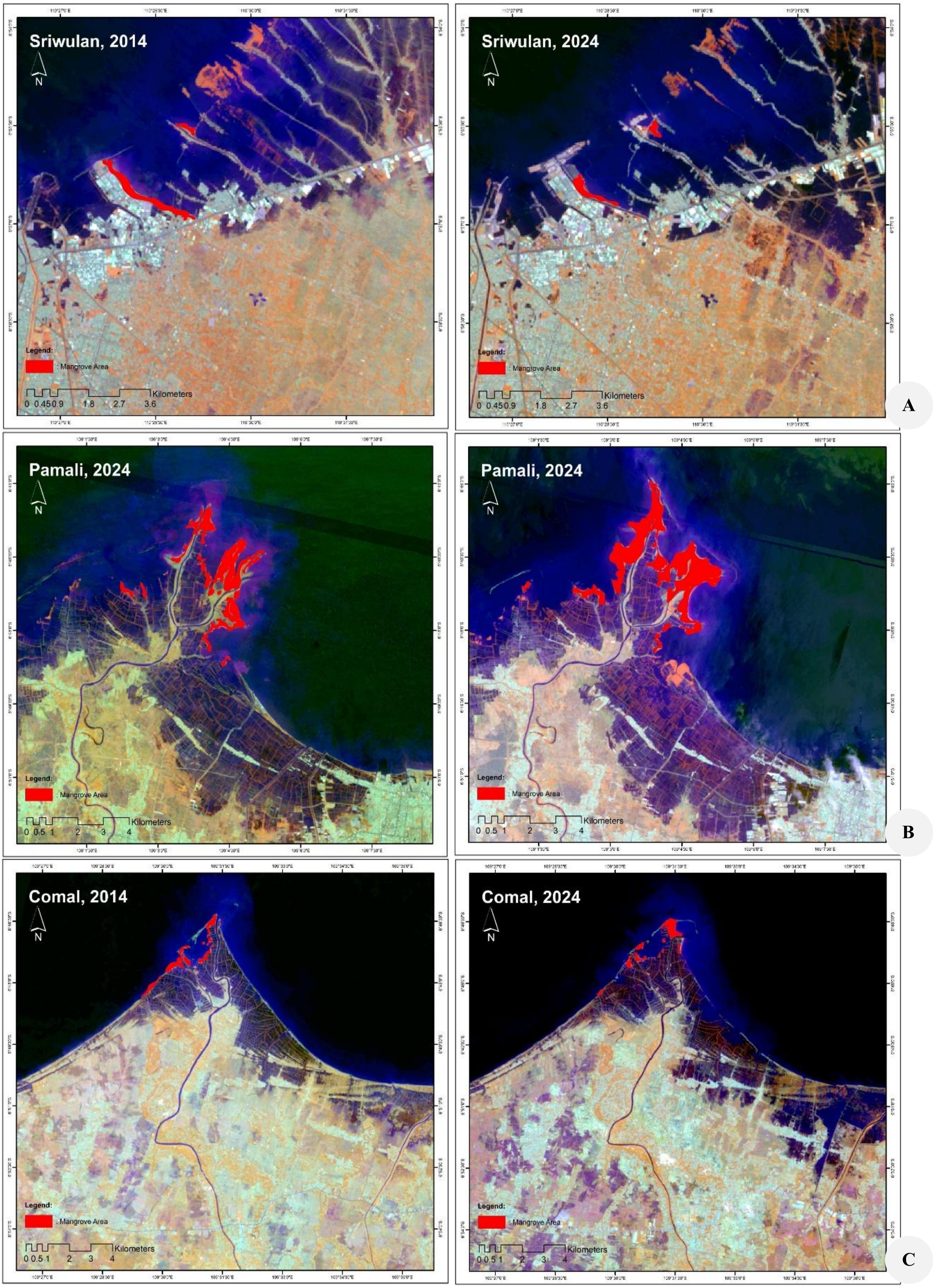
Areas of mangrove loss

Significant mangrove loss was observed in four of the five estuaries between 2014 and 2024. The most extensive losses occurred in the Cisanggarung Estuary, where approximately 99.01 hectares (50%) of mangrove cover were lost, primarily due to conversion to aquaculture ponds and urban development. The Sriwulan Estuary experienced a loss of 26.39 hectares (47.03%), with similar causes including industrial expansion and settlement growth.

Comal and Bodri estuaries also exhibited declines, albeit smaller in scale, with losses of 8.61 hectares (11.31%) and 0.66 hectares (1.59%), respectively. These reductions were largely attributed to abrasion, sediment changes, and localized land conversion.

Table 1. Summarizes the mangrove extent in hectares for each estuary in 2014 and 2024, along with absolute and percentage changes

Estuary	Mangrove area 2014 (ha)	Mangrove area 2024 (ha)	Change (ha)	% change
Sriwulan	56.11	29.72	-26.39	-47.03%
Pemali	334.13	600.85	266.72	79.83%
Comal	76.15	67.54	-8.61	-11.31%
Bodri	41.87	41.20	-0.66	-1.59%
Cisanggarung	197.99	98.98	-99.01	-50.00%



Sriwulan, 2014
N
Legend:
: Mangrove Area
0 0.45 0.9 1.8 2.7 3.6 Kilometers
Sriwulan, 2024
N
Legend:
: Mangrove Area
0 0.45 0.9 1.8 2.7 3.6 Kilometers
A
Pamali, 2024
N
Legend:
: Mangrove Area
0 0.5 1 2 3 4 Kilometers
Pamali, 2024
N
Legend:
: Mangrove Area
0 0.5 1 2 3 4 Kilometers
B
Comal, 2014
N
Legend:
: Mangrove Area
0 0.5 1 2 3 4 Kilometers
Comal, 2024
N
Legend:
: Mangrove Area
0 0.5 1 2 3 4 Kilometers
C

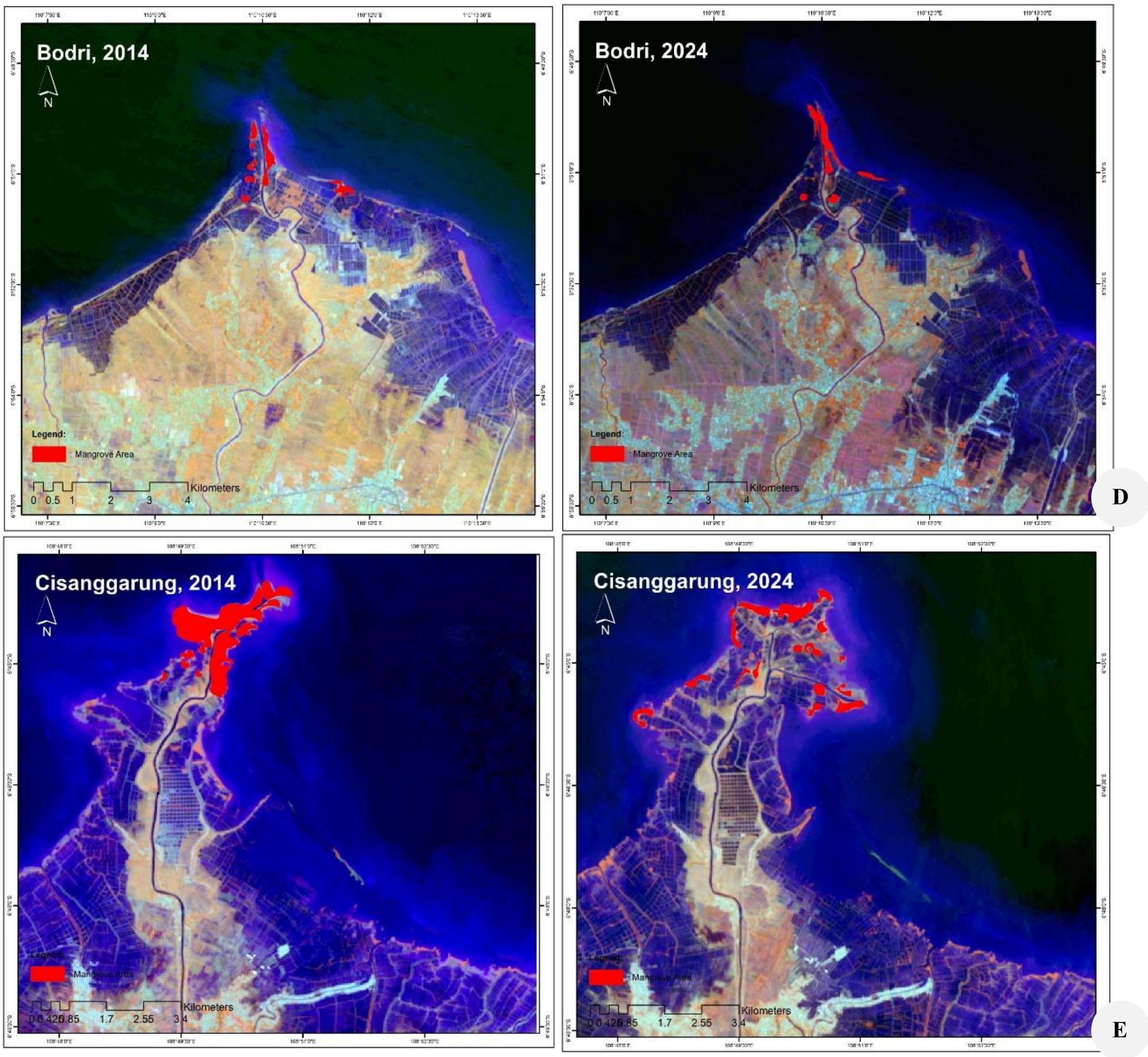


Figure 2. Detailed maps depicting spatial patterns of mangrove loss, gain, and stable areas between 2014 and 2024 for each estuary in the North Coast of Central Java, Indonesia: A. Sriwulan, B. Pemali, C. Comal, D. Bodri, and E. Cisanggarung

Areas of mangrove gain

In contrast, the Pemali Estuary demonstrated a substantial increase in mangrove cover, expanding by 266.72 hectares (79.83%). This gain is attributed to successful mangrove rehabilitation programs and natural sediment accretion, which facilitate mangrove establishment in newly formed land areas. This rapid increase may be attributed to accretion of new land along the delta front, as well as reoccupation of previously abandoned aquaculture zones, which were subsequently revegetated through assisted or natural regeneration.

Stable mangrove zones

Areas where mangrove cover remained relatively stable were identified primarily in the Bodri Estuary, with minimal losses, and in portions of the Comal Estuary where reforestation efforts have helped maintain existing mangrove stands. Table 2 summarizes the magnitude of mangrove loss, gain, and stable areas across the five estuaries, while Figure 3 visually represents these changes spatially.

Estuary-specific mangrove dynamics

Sriwulan Estuary

The Sriwulan Estuary exhibited a significant reduction in mangrove cover, declining by 47.03% from 56.11 hectares in 2014 to 29.72 hectares in 2024. This loss was primarily associated with the expansion of residential and industrial areas and destructive crab fishing practices that damaged mangrove root structures. Field observations indicated poor survival rates of replanted mangrove seedlings, likely due to suboptimal planting periods and environmental stressors. The fragmented mangrove patches are increasingly vulnerable to erosion and habitat degradation (Figure 4.A).

Pemali Estuary

In contrast, the Pemali Estuary experienced a substantial increase in mangrove cover of 79.83%, expanding from 334.13 hectares to 600.85 hectares. This gain is largely attributed to effective community-led rehabilitation programs incorporating silvofishery techniques, which integrate sustainable aquaculture with mangrove conservation. Sediment deposition processes also contributed to the formation of new land suitable for mangrove colonization. The resultant mangrove expansion supports enhanced coastal protection and biodiversity values (Figure 4.B).

Comal Estuary

The Comal Estuary showed a moderate decline of 11.31%, with mangrove area decreasing from 76.15 hectares to 67.54 hectares. Key factors included river diversion works altering hydrodynamics, leading to sediment transport changes and localized erosion. Mangrove restoration efforts have been initiated, but survival rates remain low due to episodic flooding and salinity fluctuations. Patches of stable mangrove are mainly found in less disturbed zones near river mouths (Figure 4.C).

Bodri Estuary

Mangrove cover in the Bodri Estuary remained relatively stable, with a slight decrease of 1.59% (from 41.87 to 41.20 hectares). The estuary features active sediment accretion that supports mangrove persistence despite some conversion of marginal mangrove areas to salt ponds. The relatively continuous mangrove stands contribute to maintaining ecosystem services such as fish nursery habitats and shoreline stabilization (Figure 4.D). The minimal change detected in Bodri may also reflect the spatial scale and detection limits of the 30-meter Landsat resolution, which may underrepresent subtle changes or narrow regeneration zones along accreting riverbanks

Cisanggarung Estuary

The Cisanggarung Estuary suffered the most severe mangrove loss among the studied estuaries, with a 50% decline from 197.99 hectares to 98.98 hectares. The rapid conversion of newly formed deltaic land to aquaculture ponds and urban development drove this loss. Mangrove stands remaining along pond embankments are fragmented and susceptible to further degradation. The estuary represents a critical site for targeted conservation and sustainable land use planning (Figure 4.E).

Validation and accuracy assessment results

Validation of mangrove classification was performed by comparing satellite-based mapping results with ground truth data collected during field surveys and supplemented by photographic documentation. A total of 35 ground truth points were used across the five estuaries, representing a range of mangrove conditions, including dense, sparse, degraded, and rehabilitated areas.

The overall classification accuracy was estimated at 89%, with a Kappa coefficient of 0.86, indicating strong agreement between satellite classification and field observations. The user's accuracy for the mangrove class was 91%, while the producer's accuracy was 88%, demonstrating reliable detection of mangrove areas (Table 3).

Limitations in field data coverage, particularly in inaccessible or privately owned locations, introduced some uncertainty in accuracy estimates. Supplementary validation using publicly available images helped reduce this uncertainty, but could not entirely substitute for comprehensive ground truthing. These results support the robustness of the remote sensing approach used in this study for monitoring mangrove dynamics in the study area.

Table 2. Summary of mangrove loss, gain, and stable areas (hectares) in five estuaries between 2014 and 2024

Estuary	Loss (ha)	Gain (ha)	Stable (ha)
Sriwulan	26.39	0.00	29.72
Pemali	0.00	266.72	334.13
Comal	8.61	0.00	67.54
Bodri	0.66	0.00	41.20
Cisanggarung	99.01	0.00	98.98

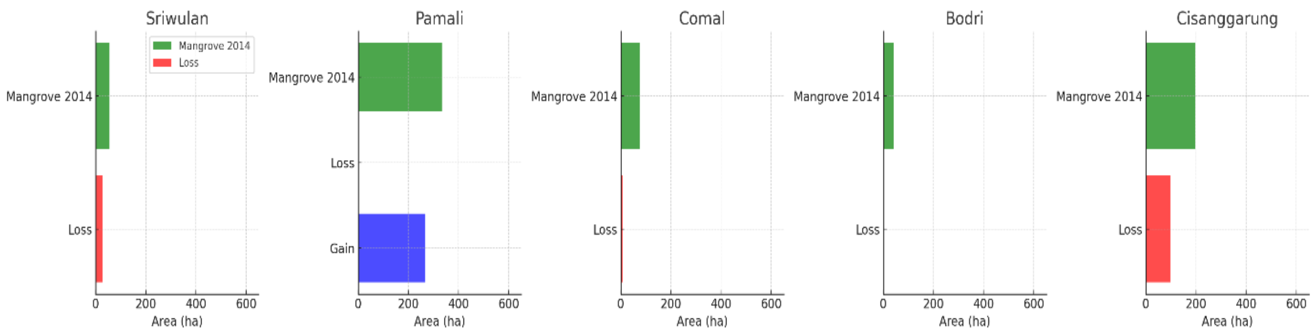


Figure 3. Visualization of mangrove cover change categories (loss, gain, and stable zones) across the five estuaries in the North Coast of Central Java, Indonesia, from 2014 to 2024

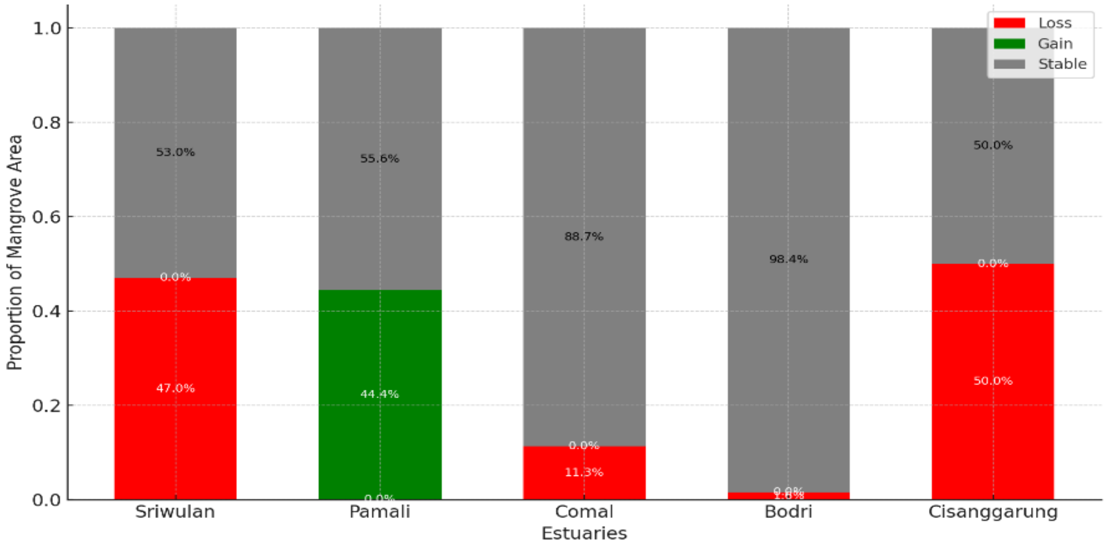


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Figure 4. Estuary-specific mangrove cover change between 2014 and 2024 in the North Coast of Central Java, Indonesia: A. Sriwulan, B. Pemali, C. Comal, D. Bodri, and E. Cisanggarung estuaries

Table 3. Accuracy assessment metrics for mangrove classification in the five estuaries in the North Coast of Central Java, Indonesia

Accuracy metric	Value (%)
Overall accuracy	89
Kappa coefficient	0.86
User's accuracy	91
Producer's accuracy	88

Summary of drivers behind mangrove changes

The analysis identified several key drivers influencing mangrove cover changes across the five estuaries. Anthropogenic factors such as land conversion for aquaculture ponds, urban expansion, and infrastructure development emerged as primary causes of mangrove loss in Sriwulan, Cisanggarung, Comal, and Bodri estuaries. These activities have led to habitat fragmentation and degradation, reducing mangrove extent and ecosystem function. In contrast, natural processes like sediment deposition and accretion played a positive role in mangrove expansion, particularly evident in the Pemali Estuary. Community-led rehabilitation initiatives, incorporating sustainable silvofishery techniques, have also contributed significantly to mangrove recovery in these estuaries.

Environmental stressors such as coastal erosion, changes in hydrology due to river diversion, and destructive fishing practices further impacted mangrove health and regeneration capacity in several estuaries. The interplay between socio-economic pressures and environmental dynamics underscores the complexity of mangrove ecosystem changes in Central Java. Effective conservation and management require integrating these drivers into adaptive strategies tailored to local conditions.

Discussion

Interpretation of mangrove cover changes

Patterns of mangrove loss and gain. The spatial and temporal analysis of mangrove cover from 2014 to 2024 reveals distinct patterns of loss and gain across the five estuaries studied. Overall, four estuaries—Sriwulan, Cisanggarung, Comal, and Bodri—experienced varying degrees of mangrove loss, whereas Pemali Estuary displayed a substantial gain. The losses ranged from minimal (1.59% in Bodri) to severe (50% in Cisanggarung), indicating differential vulnerability influenced by local environmental and anthropogenic factors (Figure 5).

Mangrove loss commonly manifests as fragmentation and ongoing reduction in forest area, often associated with land conversion for aquaculture ponds, urban development, and infrastructure expansion. Such fragmentation not only reduces habitat area but also impairs ecosystem connectivity and resilience, making mangrove forests more susceptible to environmental stressors.

Conversely, the substantial mangrove increases in Pemali Estuary, at nearly 80%, highlights the effectiveness of sediment deposition and successful rehabilitation initiatives. This increase contributed to increased mangrove continuity and expanded coastal protection functions. The presence of new mangrove stands on accreted deltaic land suggests favorable natural conditions synergized with human intervention.

Estuary-specific drivers of change. Each estuary exhibited unique drivers shaping mangrove dynamics over the study period:

Sriwulan Estuary: Rapid urbanization, industrial expansion, and destructive fishing methods, particularly crab harvesting, which damaged root systems, were the primary drivers of mangrove loss. Poorly timed and managed reforestation efforts further hampered natural regeneration.

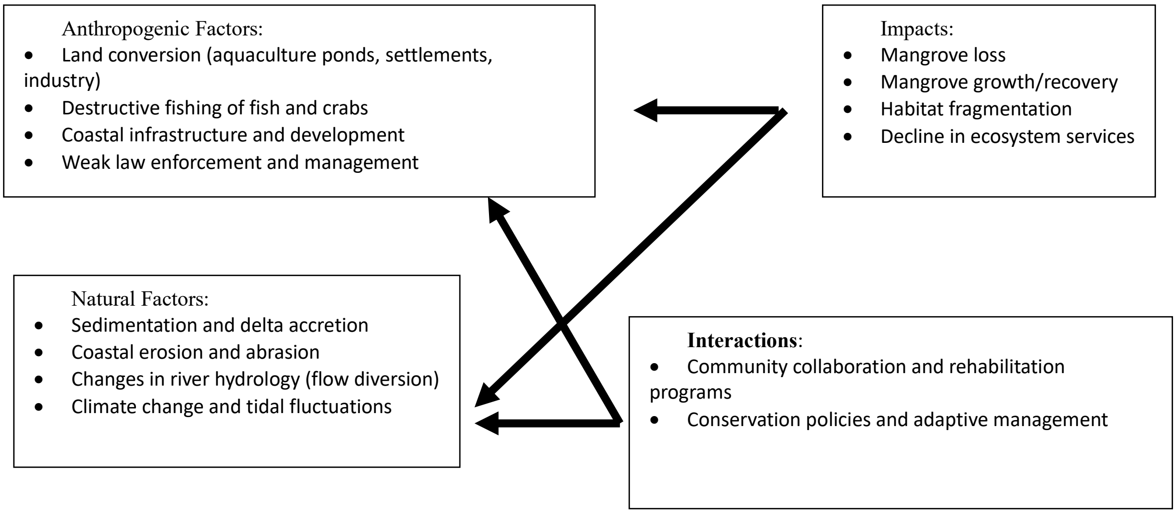

Figure 5. Conceptual diagram summarizing the main anthropogenic and natural drivers influencing mangrove cover changes in the five studied estuaries on the north coast of Central Java, Indonesia

Cisanggarung Estuary: Extensive conversion of deltaic land to aquaculture ponds and settlement development drove the most severe mangrove loss. Rapid land-use change on newly formed sediment posed challenges to sustainable mangrove conservation.

Comal Estuary: Alterations in river flow from diversion projects affected sediment distribution, leading to erosion and localized mangrove degradation. Flooding and salinity fluctuations limited seedling survival despite planting efforts.

Bodri Estuary: Despite active sediment accretion supporting mangrove persistence, marginal conversion to salt ponds caused minor declines. Stable mangrove areas benefit from geomorphological conditions but face encroachment pressures.

Pemali Estuary: Natural sedimentation processes combined with community-driven silvofishery rehabilitation programs facilitated substantial mangrove recovery. Sustainable integration of aquaculture and mangrove conservation has created a positive feedback loop promoting ecosystem resilience.

Understanding these estuary-specific drivers is essential for tailoring conservation and restoration strategies that effectively address local socio-environmental contexts. The interplay of natural and human-induced factors demands integrated management approaches to balance development and ecosystem sustainability.

Comparison with previous studies

Regional and national trends. The mangrove cover changes observed in this study align with broader patterns documented throughout Central Java and Indonesia as a whole. Indonesia has been reported to experience significant mangrove loss, with annual deforestation rates estimated between 1% and 3% over recent decades, largely driven by coastal development, aquaculture expansion, and infrastructure projects (Kusmana 2015; Richards and Friess 2016). The severe losses identified in Sriwulan and Cisanggarung estuaries exceed these national averages, underscoring localized hotspots of intense anthropogenic pressure.

At the regional scale, studies in Java and neighboring islands have similarly reported high rates of mangrove degradation linked to population growth and economic activities (Damastuti and de Groot 2017; Fikriyya et al. 2023). However, pockets of mangrove recovery, as seen in the Pemali Estuary, reflect the growing effectiveness of community-based rehabilitation and sustainable aquaculture practices. These findings corroborate regional efforts to restore mangrove ecosystems while supporting livelihoods.

Global mangrove dynamics. Globally, mangrove ecosystems have undergone dramatic declines in the past century, with approximately one-third of the world's mangroves lost due to deforestation and land conversion (Hamilton and Casey 2016; Friess et al. 2020). Southeast Asia remains a critical hotspot, accounting for a substantial share of this loss. However, recent studies indicate a slow reversal trend in some areas due to improved conservation policies and restoration initiatives.

The contrasting trajectories within this study's five estuaries mirror global patterns of simultaneous loss and gain, driven by a complex mix of natural processes and human interventions (Kuenzer et al. 2011; Alongi 2015). The significant gains in the Pemali Estuary exemplify successful rehabilitation models that have been replicated in other tropical regions, highlighting the potential for recovery under appropriate management. These comparisons emphasize the importance of spatially explicit, long-term monitoring to capture dynamic mangrove changes and inform adaptive management strategies worldwide.

Implications for conservation and management

Effectiveness of rehabilitation programs. The marked increase in mangrove cover observed in the Pemali Estuary highlights the potential success of well-implemented rehabilitation programs. Community-led silvofishery practices, which integrate sustainable aquaculture with mangrove restoration, have proven effective in promoting natural regeneration and increasing forest resilience. These initiatives illustrate how combining ecological restoration with livelihood enhancement can achieve conservation goals while supporting local economies. However, the limited success in other estuaries, such as Sriwulan and Comal, suggests that rehabilitation efforts require careful timing, species selection, and ongoing maintenance to overcome environmental challenges.

Role of community participation. Community involvement emerged as a critical factor influencing mangrove conservation outcomes. In Pemali, the active participation of local stakeholders in planning and managing rehabilitation efforts contributed to improved survival rates and sustainable resource use. Conversely, a lack of community engagement in areas with mangrove decline often correlates with continued degradation and ineffective enforcement of protection measures. Empowering local communities through education, capacity building, and incentives is essential to foster stewardship and long-term conservation success.

Policy and regulatory considerations. Effective mangrove management also depends on robust policy frameworks and regulatory enforcement. The varying degrees of mangrove loss and gain observed among estuaries underscore the importance of coherent land use planning and strict adherence to conservation regulations. Policies facilitating integrated coastal zone management, including habitat protection, sustainable aquaculture zoning, and environmental impact assessments, can mitigate pressures on mangrove ecosystems. Strengthening institutional coordination and monitoring mechanisms is necessary to address illegal encroachment and ensure compliance.

Methodological considerations

Strengths and limitations of remote sensing approach. The use of Landsat 8 satellite imagery and Google Earth Engine provided an efficient and cost-effective means of assessing mangrove dynamics across multiple estuaries over a decade. The multispectral bands selected allowed for reliable discrimination of mangrove vegetation from other land covers, and the temporal availability of data supported consistent change detection. However, the moderate spatial resolution (30 m) of Landsat imagery may limit detection of small-scale changes, edge effects, or sparse mangrove stands. Manual digitization helped address some classification ambiguities but introduced potential subjectivity.

Validation and accuracy challenges. Field validation strengthened confidence in the classification results, yet was constrained by limited accessibility to some sites and the relatively small number of ground truth points. Supplementary use of publicly available imagery helped mitigate these limitations, but cannot fully replace comprehensive field surveys. Temporal mismatches between satellite acquisition and field visits may also affect validation accuracy. Future studies could incorporate higher-resolution imagery (e.g., Sentinel-2, UAV data) and expand field sampling to enhance precision and robustness. Additionally, small-scale mangrove regrowth—particularly scattered seedlings or narrow fringe restoration areas—may not have been captured as 'gain' due to the spatial resolution limits of Landsat imagery or conservative classification criteria

Recommendations for future research and practice. Based on the findings and methodological insights of this study, several recommendations are proposed to strengthen mangrove conservation and research in Central Java and similar tropical coastal areas. Future studies should utilize higher-resolution remote sensing data (e.g., Sentinel-2 or UAVs) to capture fine-scale changes, and expand field validation efforts through systematic ground-truth sampling to enhance classification accuracy. Integrating socio-economic data and local stakeholder perspectives is essential to understand the drivers of change and support more holistic management. Conservation efforts should prioritize community engagement, capacity building, and sustainable livelihoods to ensure long-term success. Additionally, adaptive management strategies informed by ongoing monitoring are needed to respond to emerging challenges. Policymakers must reinforce coastal management policies, enforce environmental regulations, and promote multi-stakeholder collaboration to balance development with ecological preservation.

In conclusion, this study provides a comprehensive assessment of mangrove cover changes between 2014 and 2024 across five estuaries on the north coast of Central Java, Indonesia. This study reveals contrasting dynamics, with significant mangrove losses in Sriwulan, Cisanggarung, Comal, and Bodri estuaries, and a substantial gain in the Pemali Estuary driven by effective rehabilitation and natural sedimentation. These patterns reflect the complex interactions between anthropogenic pressures, environmental processes, and community engagement shaping mangrove ecosystems. The high rates of mangrove loss in some estuaries highlight urgent needs for strengthened conservation efforts, improved land use planning, and enforcement of protective regulations. Conversely, the success in Pemali underscores the value of integrated restoration approaches that combine ecological and socio-economic dimensions. Remote sensing proved a valuable tool for monitoring spatial and temporal mangrove changes, although it requires complementary ground validation to enhance accuracy. Future efforts should prioritize multi-scale monitoring, stakeholder involvement, and adaptive management to ensure the sustainability of these vital coastal ecosystems. This study contributes important insights for policymakers, conservation practitioners, and researchers working towards balancing coastal development and mangrove preservation in Indonesia and similar tropical regions worldwide.

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