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Spatio-temporal changes in mangrove density and cover in Sriwulan and Pasar Banggi-Tireman, Central Java, Indonesia

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Abstract. *Khawarizmi IA, Syahrani LPW, Luthfia, Fadhilah RN, Hapsari KS, Pradhan P, Sutomo, Setyawan AD. 2025. Spatio-temporal changes in mangrove density and cover in Sriwulan and Pasar Banggi-Tireman, Central Java, Indonesia. Intl J Bonorowo Wetlands 15: 121-129.* Mangrove ecosystems play a critical role in maintaining coastal stability and supporting ecological functions in tropical regions. However, mangrove dynamics often involve subtle internal changes that may not be captured by area-based assessments alone. This study analyzed spatio-temporal changes in mangrove density and land cover in Sriwulan Village (Demak District) and Pasar Banggi-Tireman Villages (Rembang District), Central Java, Indonesia, during the period 2019-2024 using Sentinel-2 satellite imagery. Mangrove distribution and density were assessed through Normalized Difference Vegetation Index (NDVI) classification, and changes were quantified by overlaying spatial data from both observation years. Mangrove density was categorized into low, medium, and high classes, and classification accuracy was supported by ground observations. The results show that total mangrove area in Sriwulan Village increased slightly from 16.75762 ha in 2019 to 16.77258 ha in 2024, representing a net gain of 0.01496 ha (0.09%). This change was accompanied by a marked increase in medium-density mangrove, while low- and high-density classes declined. In contrast, total mangrove area in Pasar Banggi-Tireman Villages decreased marginally from 51.13480 ha to 51.05880 ha, corresponding to a net loss of 0.07600 ha (0.15%). Despite this slight decline, medium- and high-density mangrove areas increased, whereas low-density mangrove decreased substantially. These findings indicate that mangrove ecosystems in both study sites remained spatially stable but underwent internal restructuring of canopy density. The study demonstrates that density-based analysis provides critical additional insight beyond total area change and offers a robust approach for evaluating mangrove dynamics and supporting local-scale monitoring and management.

Keywords: Mangrove density, NDVI, remote sensing, Sentinel-2, Spatio-temporal analysis

INTRODUCTION

Mangrove ecosystems are among the most productive coastal habitats in tropical and subtropical regions, providing essential ecological functions and socio-economic benefits. They play critical roles in shoreline stabilization, sediment trapping, nutrient cycling, and carbon sequestration, while also serving as nursery grounds for fish and invertebrates that support coastal fisheries (Alongi 2014; Friess et al. 2019). In densely populated coastal zones, mangroves further contribute to disaster risk reduction by attenuating wave energy and reducing the impacts of coastal erosion and storm surges (Barbier et al. 2011).

Despite their importance, mangrove ecosystems are under persistent pressure from anthropogenic and natural drivers. Coastal development, aquaculture expansion, land conversion, and infrastructure construction have historically contributed to mangrove loss in Southeast Asia (Hamilton and Casey 2016; Richards and Friess 2016). Climate-related factors, including sea-level rise, altered sediment supply, and increasing coastal abrasion, further influence mangrove stability and regeneration (Lovelock et al. 2015; Ward et al. 2016). In Indonesia, which hosts one of the largest mangrove extents globally, patterns of degradation and recovery vary substantially among regions due to differences in geomorphology, management practices, and disturbance regimes (Giri et al. 2011; Ilman et al. 2016; Worthington and Spalding 2018).

Recent studies suggest that large-scale mangrove loss has slowed or stabilized in some coastal areas following rehabilitation initiatives and increased recognition of ecosystem services (Friess et al. 2020). However, stability in total mangrove area does not necessarily indicate ecological resilience, as internal changes in stand structure and canopy condition may still occur (Alongi 2008; Osland et al. 2017). Consequently, reliance on area-based indicators alone may obscure important internal dynamics, highlighting the need for approaches that capture structural change within mangrove stands.

Remote sensing has become a widely used tool for monitoring mangrove distribution, condition, and temporal dynamics across spatial scales. Satellite-based observations enable repeated and consistent measurements of vegetation cover, facilitating the detection of long-term trends and short-term fluctuations (Blasco et al. 2001). Medium-resolution sensors such as Sentinel-2 are particularly suitable for mangrove studies because their spatial resolution and revisit frequency allow effective monitoring of dynamic coastal environments (Li et al. 2011; Pham et al. 2019).

Among vegetation indices, the Normalized Difference Vegetation Index (NDVI) is commonly applied to assess vegetation greenness, canopy density, and photosynthetic activity. NDVI-based analyses have been widely used to classify mangrove density, identify degradation patterns, and evaluate rehabilitation outcomes (Lucas et al. 2007; Kuenzer et al. 2011; Giri and Long 2016; Pham et al. 2019). Changes in NDVI values reflect variations in canopy closure, biomass, and stand maturity, making density-based classification a valuable complement to total area assessments (Zhu and Woodcock 2014). Nevertheless, NDVI interpretation in coastal environments is subject to limitations related to tidal inundation, background reflectance, mixed pixels, and potential saturation in high-density stands (Heumann 2011). These constraints necessitate cautious interpretation and support from ground observations and accuracy assessment (Congalton and Green 2009).

The northern coast of Central Java, Indonesia, exemplifies the interaction between mangrove ecosystems and human activities, including settlement, fisheries, and rehabilitation programs (Setyawan 2005; Kusmana 2011). Sriwulan Village (Demak District) and Pasar Banggi–Tireman Villages (Rembang District) represent contrasting coastal settings shaped by differences in shoreline morphology, exposure to abrasion, and management interventions. Sriwulan Village is characterized by chronic coastal abrasion and shoreline instability, whereas Pasar Banggi–Tireman Villages have experienced more intensive rehabilitation and relatively stable mangrove belts (Fikriyani and Mussadun 2014; Ain et al. 2025). Despite numerous studies documenting mangrove extent and rehabilitation outcomes in Central Java (Sasmito et al. 2019), analyses focusing on spatio-temporal changes in canopy density at the village scale remain limited.

This gap is critical because minor net changes in mangrove area may conceal substantial internal restructuring of mangrove stands, potentially leading to misinterpretation of management effectiveness (Friess and Webb 2014). Therefore, a spatially explicit NDVI-based assessment integrating both total area and density-class changes is required. Based on this rationale, this study hypothesizes that mangrove ecosystems in Sriwulan Village and Pasar Banggi–Tireman Villages exhibit minimal net changes in total area but significant spatio-temporal redistribution among canopy density classes. Accordingly, this study aims to analyze spatio-temporal changes in mangrove density and land cover between 2019 and 2024 using Sentinel-2 imagery, quantify changes in total mangrove area and density classes, and compare mangrove dynamics between the two sites to support local-scale mangrove monitoring and management.

MATERIALS AND METHODS

Study area

This study was conducted in two coastal villages along the northern coast of Central Java, Indonesia, namely Sriwulan Village (6°56′19″S 110°28′48″E) in Demak District and Pasar Banggi (6°42′23″S 111°23′16″E)-Tireman (6°42′30″S 111°22′14″E) Villages in Rembang District (Figure 1). Both locations are situated within low-lying coastal plains that are directly influenced by tidal dynamics, sediment transport, and shoreline processes typical of the Java Sea coast. Mangrove ecosystems in these areas are distributed along estuarine margins and open coastlines, forming narrow to moderately wide belts adjacent to coastal settlements and aquaculture ponds. Field visits were conducted in both villages during late 2024 to support spatial interpretation.

Sriwulan Village is located in a coastal zone that has experienced long-term shoreline changes, including erosion and land subsidence, which have influenced mangrove distribution and stability. In contrast, Pasar Banggi-Tireman Villages represent a coastal setting where mangrove rehabilitation initiatives have been implemented alongside existing natural stands. Differences in coastal morphology, exposure to wave action, and sediment availability contribute to spatial variation in mangrove structure between the two sites.

Both study areas are characterized by mixed mangrove stands dominated by typical Indo-West Pacific species and are subject to ongoing human activities related to fisheries, coastal protection, and settlement expansion. These contrasting environmental and management contexts provide a suitable basis for comparative analysis of mangrove density and land cover dynamics using remote sensing approaches (Alongi 2014).

Data sources and satellite imagery

Mangrove mapping and change analysis were conducted using multispectral satellite imagery acquired from the Sentinel-2 mission of the European Space Agency. Sentinel-2 provides optical imagery with a spatial resolution of 10-20 m and a revisit time suitable for monitoring dynamic coastal environments. In this study, cloud-free Sentinel-2 images representing conditions in 2019 and 2024 were selected to enable multi-temporal comparison of mangrove density and spatial extent.

Satellite data were obtained from publicly accessible archives and processed using standard pre-processing procedures. Images were atmospherically corrected and geometrically aligned to ensure spatial consistency between observation years. To minimize spectral interference from clouds and cloud shadows, only scenes with minimal cloud cover over the study areas were used. The selected images represent comparable acquisition periods to reduce the influence of seasonal variability on vegetation reflectance.

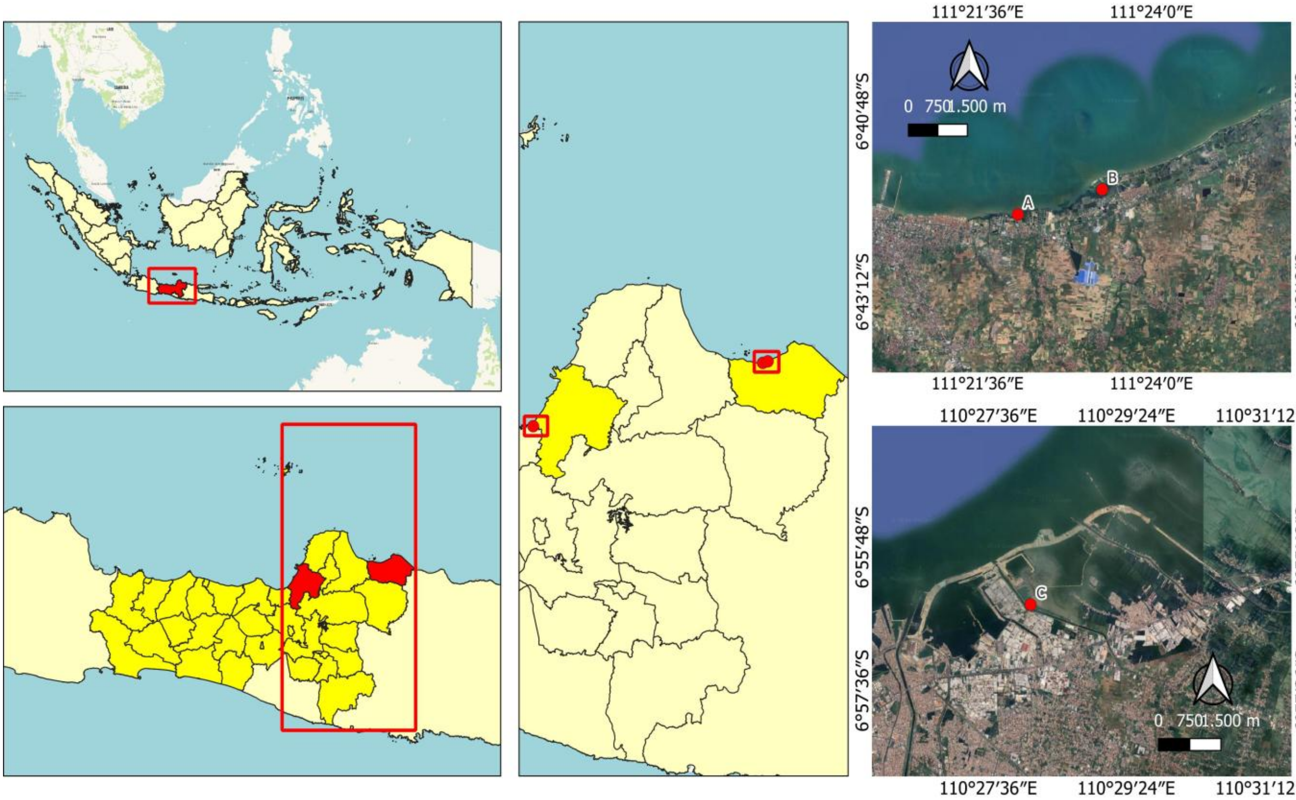

Figure 1. Location of the study area in Pasar Tireman (A)-Banggi (B) Villages, Rembang District, and Sriwulan Village (C), Demak District, Central Java, Indonesia

Sentinel-2 imagery was chosen because its spectral bands in the visible and near-infrared regions are well suited for vegetation analysis, including the calculation of vegetation indices such as NDVI. Previous studies have demonstrated the suitability of Sentinel-2 data for mangrove mapping and condition assessment at local to regional scales (Drusch et al. 2012; Pham et al. 2019). The use of consistent satellite data sources across both time points ensures that observed changes in mangrove density and cover reflect actual spatial dynamics rather than sensor-related differences.

NDVI calculation and density classification

Mangrove vegetation density was assessed using the Normalized Difference Vegetation Index (NDVI), which is widely applied to evaluate vegetation greenness and canopy condition based on spectral reflectance properties. NDVI was calculated from Sentinel-2 imagery using the Near-Infrared (NIR) and red bands according to the standard formula: NDVI = (NIR − Red) / (NIR + Red). Higher NDVI values generally indicate denser and healthier vegetation cover, while lower values correspond to sparse or degraded vegetation.

Following NDVI calculation, mangrove areas were classified into three density classes: low, medium, and high density. The classification thresholds were defined based on NDVI values as follows: low-density mangrove (NDVI 0.30-0.45), medium-density mangrove (NDVI 0.45-0.60), and high-density mangrove (NDVI > 0.60). Classification thresholds were applied consistently across both observation years to ensure comparability of density patterns between 2019 and 2024. This density-based classification approach allows the detection of internal structural changes within mangrove stands that may not be evident from total area measurements alone.

NDVI-based density classification has been widely used in mangrove studies to examine spatial heterogeneity, rehabilitation outcomes, and temporal dynamics of canopy structure (Kuenzer et al. 2011; Pham et al. 2019). However, NDVI interpretation in coastal environments requires caution due to potential influences of tidal inundation, background reflectance, and mixed pixels at mangrove–water interfaces. To address these limitations, NDVI results were evaluated in conjunction with visual interpretation and subsequent accuracy assessment, ensuring that density classes reasonably represented on-ground mangrove conditions (Huete et al. 2002).

Change detection and spatial analysis

Spatial changes in mangrove density and land cover between 2019 and 2024 were analyzed using a post-classification comparison approach. NDVI-based mangrove density maps from each observation year were spatially overlaid to identify changes in both total mangrove area and density-class distribution. This method allows for direct comparison of classified maps from different time periods and is commonly applied in vegetation change analysis due to its conceptual simplicity and interpretability.

For each study site, the spatial extent of mangrove density classes was calculated in hectares based on pixel counts and the spatial resolution of Sentinel-2 imagery. Changes in mangrove cover were quantified as absolute differences in area between the two observation years, while relative changes were calculated with reference to baseline conditions in 2019. This approach enables the identification of both net changes in mangrove area and internal shifts among density classes.

Spatial analysis was conducted using Geographic Information System (GIS) tools to ensure consistent projection, alignment, and area calculation across datasets. By applying identical analytical procedures to both study sites, differences in mangrove dynamics could be attributed to spatial and temporal variation rather than methodological inconsistencies. Post-classification comparison has been widely used in land cover change studies, including mangrove ecosystems, to assess spatio-temporal patterns in vegetation structure and extent (Singh 1989).

Accuracy assessment

The accuracy of mangrove density classification derived from NDVI was evaluated through ground-based validation (Table 1). A total of 30 observation points were collected in each study site, representing different mangrove density conditions. These points were used to verify the correspondence between NDVI-derived density classes and on-site mangrove characteristics. Field observations focused on canopy cover and vegetation condition to ensure consistency with the low-, medium-, and high-density categories identified from satellite imagery.

Classification accuracy was assessed by comparing NDVI-based class assignments with ground observation data. Overall accuracy was calculated to quantify the proportion of correctly classified points, indicating the reliability of the density maps used for subsequent spatial analysis. The classification achieved an overall accuracy of 84.67% with a Kappa coefficient of 0.78, indicating good agreement between NDVI-based density classes and field observations. This validation approach is commonly applied in vegetation mapping studies to assess the performance of remote sensing-based classification, particularly when high-resolution reference data are limited.

The accuracy assessment procedure was integrated into the overall methodological workflow to ensure that mangrove density classification results were sufficiently robust for change detection analysis (Figure 2). Although field sampling was limited in number, the use of evenly distributed observation points across density classes supports the credibility of the classification results (Congalton and Green 2009).

Table 1. Accuracy assessment results of NDVI-based mangrove density classification

Metric	Value
Overall accuracy (%)	84.67
Kappa coefficient	0.78

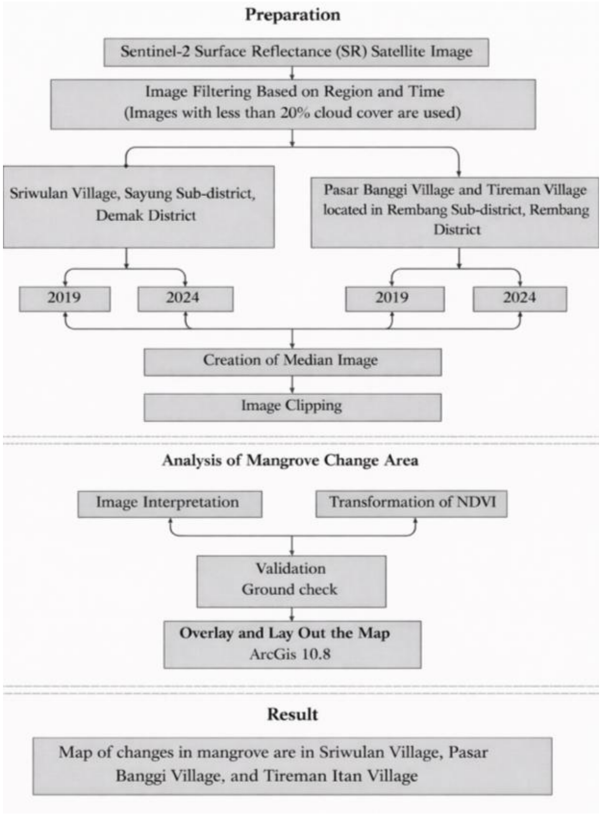

Figure 2. Flowchart of the research methodology for mangrove density and land cover analysis using Sentinel-2 imagery and NDVI classification

RESULTS AND DISCUSSION

Changes in mangrove density and area in Sriwulan Village

Analysis of Sentinel-2 imagery indicates that mangrove cover in Sriwulan Village remained largely stable between 2019 and 2024, with only minor changes in total area and noticeable redistribution among density classes (Table 2; Figure 3.A). In 2019, the total mangrove area in Sriwulan Village was recorded at 16.75762 ha. By 2024, this area increased slightly to 16.77258 ha, representing a net gain of 0.01496 ha or a relative increase of 0.09% over the five-years. Given the validated classification accuracy (Table 1), spatio-temporal changes in mangrove density are considered reliable. Given the satisfactory overall classification accuracy (84.67%) and Kappa coefficient (0.78), these minor net changes are considered robust and not attributable to classification uncertainty.

At the density-class level, contrasting trends were observed. Low-density mangrove area decreased from 2.23652 ha in 2019 to 1.55919 ha in 2024. A similar decline was recorded for high-density mangrove, which decreased from 12.53340 ha to 11.58300 ha. In contrast, medium-density mangrove exhibited a marked increase, expanding from 1.98770 ha in 2019 to 3.63039 ha in 2024. This redistribution among density classes reflects internal structural adjustment within existing mangrove stands rather than artefacts of NDVI-based classification. These changes indicate internal restructuring of mangrove stands rather than substantial spatial expansion or loss.

Spatial patterns derived from NDVI classification show that increases in medium-density mangrove were primarily concentrated adjacent to existing mangrove stands, suggesting gradual changes in canopy condition rather than the establishment of new mangrove areas. Despite reductions in low- and high-density classes, the near-constant total mangrove area suggests that mangrove cover in Sriwulan Village remained relatively stable during the study period. The consistency between spatial patterns, quantitative area estimates, and validated classification accuracy confirms that density-based analysis provides reliable additional insight into mangrove dynamics beyond total area measurements alone.

Table 2. Mangrove area by density class and total change in Sriwulan Village and Pasar Banggi-Tireman Villages, Central Java, Indonesia (2019-2024)

Mangrove density class	Area 2019 (ha)	Area 2024 (ha)
Sriwulan Village		
Low density	2.23652	1.55919
Medium density	1.98770	3.63039
High density	12.53340	11.58300
Total mangrove area	16.75762	16.77258
Net change (2019-2024)		+0.01496
Relative change (%)		+0.09
Pasar Banggi-Tireman Villages		
Low density	11.78290	7.86450
Medium density	16.48810	17.08110
High density	22.86380	26.11320
Total mangrove area	51.13480	51.05880
Net change (2019-2024)		-0.07600
Relative change (%)		-0.15

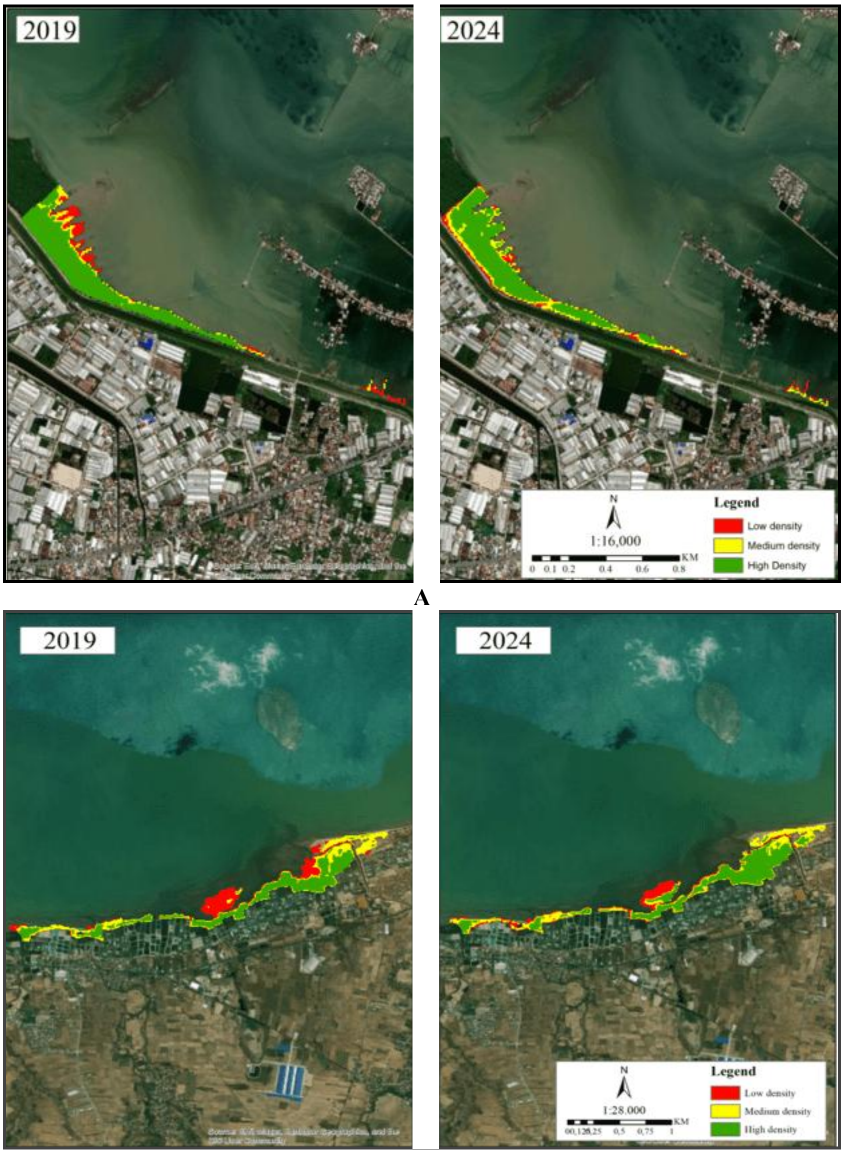

Figure 3. Mangrove density distribution in Central Java, Indonesia. A. Sriwulan Village and B. Pasar Banggi-Tireman Villages in 2019 and 2024 based on NDVI classification

Changes in mangrove density and area in Pasar Banggi-Tireman Villages

Results from NDVI-based analysis indicate that mangrove dynamics in Pasar Banggi-Tireman Villages between 2019 and 2024 differed from those observed in Sriwulan Village, particularly in terms of density-class redistribution (Table 2; Figure 3.B). In 2019, the total mangrove area in Pasar Banggi-Tireman Villages was 51.13480 ha. By 2024, this area decreased slightly to 51.05880 ha, corresponding to a net loss of 0.07600 ha or a relative decrease of 0.15% over the five-years.

At the density-class level, substantial changes were recorded. Low-density mangrove area declined markedly from 11.78290 ha in 2019 to 7.86450 ha in 2024. In contrast, medium-density mangrove increased from 16.48810 ha to 17.08110 ha during the same period. The most notable increase was observed in high-density mangrove, which expanded from 22.86380 ha in 2019 to 26.11320 ha in 2024. These opposing trends among density classes indicate internal structural changes within the mangrove ecosystem rather than large-scale spatial loss.

Spatial distribution patterns show that areas of high-density mangrove were concentrated within existing mangrove belts, suggesting improved canopy closure or stand development in certain zones. Despite the slight reduction in total mangrove area, the increase in medium- and high-density classes highlights localized improvements in mangrove condition. The results demonstrate that mangrove dynamics in Pasar Banggi-Tireman Villages during the study period were characterized by density enhancement accompanied by minimal net area change.

Comparative patterns between study sites

Comparison of mangrove dynamics between Sriwulan Village and Pasar Banggi-Tireman Villages reveals contrasting patterns in density-class redistribution despite similarly small net changes in total mangrove area. In Sriwulan Village, total mangrove cover increased marginally by 0.01496 ha (0.09%) between 2019 and 2024, whereas Pasar Banggi-Tireman Villages experienced a slight net decrease of 0.07600 ha (0.15%) during the same period (Table 2). These values indicate that, at the landscape scale, mangrove extent in both locations remained largely stable over the five-year interval.

At the density-class level, the two sites exhibited different trajectories. Sriwulan Village showed a pronounced increase in medium-density mangrove accompanied by declines in both low- and high-density classes. In contrast, Pasar Banggi-Tireman Villages displayed substantial reductions in low-density mangrove alongside increases in medium- and high-density classes. These patterns suggest that internal structural changes occurred differently across the two sites, even though overall mangrove extent changed only slightly.

Spatially, density-class shifts in both villages were primarily concentrated within existing mangrove areas rather than along new coastal fronts. This indicates that changes were dominated by redistribution among density classes rather than by expansion into previously non-mangrove areas. The comparative results highlight that similar levels of net area stability can be associated with distinct internal dynamics of mangrove density and structure at the local scale.

Discussion

Stability of mangrove cover and implications of minor net changes

The results demonstrate that mangrove cover in both Sriwulan Village and Pasar Banggi-Tireman Villages remained largely stable between 2019 and 2024, with net changes of less than 0.2% of total area. Such minor net changes indicate that, at the landscape scale, neither extensive mangrove expansion nor large-scale degradation occurred during the study period. Similar patterns of relative stability have been reported in several coastal regions where mangrove loss has slowed following rehabilitation efforts or natural stabilization processes (Worthington and Spalding 2018; Friess et al. 2019).

The observed stability contrasts with earlier reports of rapid mangrove decline in parts of Southeast Asia during previous decades (Richards and Friess 2016), suggesting that recent dynamics may reflect shifts in management practices, coastal protection measures, or geomorphological constraints. In Indonesia, regional-scale analyses have shown that mangrove extent can remain stable even under continued anthropogenic pressure, particularly where degradation and recovery processes occur simultaneously in different locations (Giri et al. 2011; Ilman et al. 2016).

Importantly, the small magnitude of net change highlights the limitations of using total area alone as an indicator of mangrove ecosystem condition. Studies have emphasized that stable mangrove extent does not necessarily imply ecological resilience, as internal structural changes, species composition shifts, or canopy degradation may still take place (Alongi 2014; Duke et al. 2017). In this study, density-class redistribution observed in both sites underscores that mangrove dynamics were occurring internally rather than through extensive spatial gain or loss.

From a monitoring perspective, these findings align with research advocating for density- or structure-based indicators to complement area-based assessments (Kuenzer et al. 2011; Pham et al. 2019). Minor net changes, when interpreted alongside density dynamics, can still provide meaningful insights into ecosystem processes and management outcomes. Therefore, the apparent stability of mangrove cover in the study area should be understood as a dynamic equilibrium rather than a static condition, emphasizing the need for continuous, multi-dimensional monitoring approaches.

Density-class shifts as indicators of structural dynamics

Shifts among mangrove density classes observed in both study sites indicate that internal structural dynamics played a more prominent role than net spatial change during the study period. In Sriwulan Village, the expansion of medium-density mangrove alongside reductions in low- and high-density classes suggests gradual canopy reorganization, potentially reflecting transitions between growth stages rather than abrupt disturbance. Similar density-class transitions have been reported in mangrove systems undergoing stand development, where young or recovering stands gradually increase canopy closure before reaching mature structural conditions (Bosire 2008; Duke et al. 2017).

In Pasar Banggi-Tireman Villages, the marked decrease in low-density mangrove accompanied by increases in medium- and high-density classes points to localized improvements in canopy structure within existing mangrove belts. Such patterns are consistent with findings from NDVI-based mangrove assessments that document density enhancement without substantial areal expansion, particularly in areas influenced by rehabilitation or natural regeneration processes (Kuenzer et al. 2011; Pham et al. 2019). These internal shifts may reflect improved vegetation vigor, increased biomass, or enhanced canopy continuity rather than changes in spatial extent.

Density-class analysis provides an important proxy for mangrove structural condition, as canopy density is closely linked to ecological functions such as habitat provision, sediment trapping, and shoreline stabilization (Alongi 2014). However, NDVI-derived density classes should be interpreted as indicators of relative structural change rather than direct measures of biomass or species composition. Factors such as tidal inundation, background reflectance, and mixed pixels may influence spectral responses, particularly at mangrove-water interfaces (Heumann 2011).

The density-class shifts documented in this study reinforce the value of integrating structural indicators into mangrove monitoring frameworks. By capturing internal changes within stable spatial extents, density-based metrics offer a more nuanced understanding of mangrove ecosystem dynamics than total area measurements alone, supporting previous recommendations for multi-dimensional assessments of mangrove condition (Kairo et al. 2001; Simard et al. 2019).

Site-specific processes influencing mangrove dynamics

The contrasting density-class trajectories observed between Sriwulan Village and Pasar Banggi-Tireman Villages highlight the influence of site-specific environmental and anthropogenic processes on mangrove dynamics. Although both locations exhibited minimal net changes in total mangrove area, differences in canopy density redistribution suggest that local conditions play a critical role in shaping mangrove structural development. Such site-dependent dynamics are commonly reported in mangrove ecosystems, where geomorphology, sediment supply, and hydrodynamic exposure interact to influence vegetation structure (Lovelock et al. 2015; Friess et al. 2019).

Sriwulan Village is situated in a coastal zone that has experienced long-term shoreline instability, including erosion and land subsidence, which may constrain mangrove stand development and promote internal restructuring rather than outward expansion. In environments affected by chronic physical stress, mangrove systems often exhibit gradual shifts in canopy density as stands adjust to changing substrate conditions and inundation regimes (Duke et al. 2017). These processes may contribute to the observed redistribution among density classes without substantial changes in overall mangrove extent.

In contrast, Pasar Banggi-Tireman Villages has been the focus of mangrove rehabilitation and coastal protection initiatives, which may have supported improvements in canopy density within existing mangrove areas. Studies have shown that rehabilitation efforts can lead to increased canopy closure and structural maturation without necessarily producing large gains in total mangrove area, particularly in space-limited coastal settings (Kodikara et al. 2017; Worthington and Spalding 2018). At the same time, localized losses may still occur due to natural disturbance or land-use pressures, resulting in overall area stability accompanied by internal structural change.

These site-specific patterns emphasize the importance of localized assessments when evaluating mangrove condition and management outcomes. Even within the same regional coastline, mangrove dynamics may differ substantially depending on physical setting and intervention history, underscoring the need for spatially explicit monitoring approaches tailored to local contexts.

Implications for mangrove monitoring and management

The findings of this study underscore the importance of integrating density-based indicators into mangrove monitoring and management frameworks. The observed stability in total mangrove area, coupled with notable shifts among density classes, demonstrates that area-based metrics alone may be insufficient to capture meaningful ecological changes. Similar conclusions have been drawn in previous studies, which emphasize that structural attributes such as canopy density and stand condition are critical for assessing mangrove ecosystem health and functionality (Alongi 2014; Friess et al. 2019).

From a monitoring perspective, the use of NDVI-derived density classification provides a practical and cost-effective approach for tracking internal changes within mangrove stands over time. Such methods are particularly valuable for local-scale assessments in data-limited contexts, where repeated field-based measurements may be logistically challenging. Remote sensing-based density metrics can support early detection of canopy degradation or recovery by revealing transitions among density classes before substantial changes in total mangrove area become apparent, thereby enabling more responsive and preventive management interventions (Lucas et al. 2007; Giri and Long 2016).

In terms of management, density-based information allows for spatially differentiated rehabilitation strategies. Areas classified as low-density mangrove should be prioritized for targeted rehabilitation actions, such as enrichment planting, improvement of hydrological connectivity, or protection from ongoing physical disturbance. Medium-density stands represent transitional conditions where management efforts should focus on supporting natural growth trajectories and preventing further degradation, rather than introducing excessive planting that may disrupt stand development. In contrast, high-density mangrove areas indicate relatively mature or closed-canopy conditions and should be managed primarily through protection and regular monitoring to maintain long-term stability.

The contrasting density dynamics observed between the two study sites further highlight the need for site-specific management approaches. Locations exhibiting stable mangrove extent but internal restructuring may benefit more from strategies aimed at improving stand quality and resilience than from spatial expansion alone. Accordingly, rehabilitation success should be evaluated not only by increases in mangrove area but also by measurable improvements in canopy density and structural condition, as recommended in recent mangrove management frameworks (Worthington and Spalding 2018).

Integrating spatial extent and density-based indicators provides a more comprehensive basis for evaluating mangrove management outcomes. Such an approach supports adaptive management strategies that are sensitive to local environmental pressures and management histories, ensuring that monitoring and rehabilitation efforts address both the stability and internal dynamics of mangrove ecosystems.

Methodological considerations and limitations

Several methodological considerations should be acknowledged when interpreting the results of this study. NDVI-based classification provides a useful proxy for mangrove canopy density and vegetation condition; however, it does not directly measure biomass, species composition, or structural complexity. Spectral responses in coastal environments can be influenced by tidal inundation, sediment background, and water reflectance, particularly at mangrove–water interfaces, potentially affecting density-class assignment (Heumann 2011).

Beyond these environmental influences, uncertainty in NDVI-based density classification represents an inherent methodological limitation. NDVI values integrate canopy greenness but may overlap across density classes due to variations in canopy structure, species composition, understory exposure, and substrate conditions. In abrasion-prone coastal settings, sparse canopies and exposed sediments can produce intermediate NDVI values that blur the distinction between low- and medium-density classes. Nevertheless, the satisfactory overall classification accuracy (84.67%) and substantial Kappa coefficient (0.78) obtained in this study indicate that such spectral overlap is unlikely to substantially bias the observed spatio-temporal patterns of mangrove density change.

The moderate spatial resolution of Sentinel-2 imagery may also limit the detection of fine-scale changes in narrow or fragmented mangrove stands. Mixed pixels can obscure subtle transitions between density classes, particularly along mangrove edges and in heterogeneous canopy patches. Although these limitations are inherent to medium-resolution satellite data, the use of ground-based validation and accuracy assessment supports the overall reliability of the classification results for comparative and change detection purposes. Some degree of uncertainty nevertheless remains inherent in satellite-based analyses and should be considered when interpreting localized density changes (Congalton and Green 2009).

Temporal resolution represents an additional limitation. The use of two observation years, while sufficient for identifying medium-term trends, may not capture short-term disturbances, episodic events, or seasonal variability in mangrove canopy condition. Tidal stage differences at the time of image acquisition may further influence NDVI responses by altering the proportion of exposed substrate and inundated vegetation surfaces. Long-term monitoring using multi-year time series and complementary field data would improve the robustness of change detection and support more detailed assessments of mangrove dynamics (Friess et al. 2019). Despite these limitations, the applied methodology provides a consistent, validated, and replicable framework for local-scale mangrove monitoring, particularly when results are interpreted as indicative spatial patterns rather than exact measurements of mangrove structural attributes.

In conclusion, this study demonstrates that mangrove ecosystems in Sriwulan Village and Pasar Banggi–Tireman Villages between 2019 and 2024 exhibited a high degree of spatial stability, with only minor net changes in total mangrove area. Mangrove cover in Sriwulan Village increased marginally from 16.76 ha to 16.77 ha (net gain of 0.015 ha; 0.09%), while Pasar Banggi-Tireman Villages experienced a slight decrease from 51.13 ha to 51.06 ha (net loss of 0.076 ha; 0.15%). Despite these minimal net changes, pronounced redistribution among mangrove density classes was observed at both sites, indicating that meaningful internal structural dynamics can occur without substantial spatial expansion or loss. The application of NDVI-based density classification proved effective for capturing these internal changes in canopy structure. By distinguishing shifts among low-, medium-, and high-density classes, this approach provided critical additional insight into canopy reorganization and stand development that would not have been evident from total area metrics alone. Density-based indicators therefore offer a practical and complementary tool for local-scale mangrove monitoring in dynamic coastal environments. From a management perspective, the findings suggest that mangrove conservation and rehabilitation efforts should not be evaluated solely on the basis of areal gain. Improvements in canopy density and structural condition within existing mangrove stands represent important indicators of ecosystem recovery and functionality. Several limitations should be acknowledged, including the indirect nature of NDVI as a proxy for canopy structure and the use of two observation years, which may not capture short-term disturbances or seasonal variability. Future research should prioritize longer-term, multi-temporal monitoring and integration of field-based measurements to strengthen the assessment of mangrove dynamics and support adaptive, evidence-based coastal management strategies.

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