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Quantifying Decadal Recovery in Small Scale Community-Based Mangrove Management (SSCM) in East Java, Indonesia, using Integrated Remote Sensing and Ecological Assessments

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ABSTRACT

This study examines ecological outcomes of small-scale community-based mangrove management (SSCM) in three locations in East Java: Clungup Mangrove Conservation (CMC, south coast), Penunggul (north coast) and Hijau Daun (small island). The primary objective is to evaluate the impacts of local community initiatives on mangrove ecosystem recovery over the past decade. Methodology combined remote sensing and field-based approaches. Machine learning google earth engine (GEE) was applied to assess past decade vegetation recovery using Normalized Difference Vegetation Index (NDVI), while raster analysis processed using R software to obtain net value change. To ensure compatibility between datasets, spatial harmonization was performed by resampling and aligning Sentinel-2 imagery to match Landsat 7 resolution using QGIS software. Field observations were conducted to assess the current ecological metrics, and descriptive analysis was carried out to connect restoration outcomes with management practices. Research findings indicate notable increases in net value change, with CMC showing the most substantial recovery (0.2-0.3), shifted from predominantly open or sparse areas to moderate or dense vegetation. Mangrove in Daun and Penunggul have ΔNDVI of 0-0.1, reflecting mild improvement in vegetation cover. Ecological assessments further revealed variation among sites. In Penunggul, diameter at breast height (DBH) of mangrove ranged from 2-16 cm (mean 7.70±3.34 cm), with average tree density of 2,300 ind/ha. CMC has mangrove density from 1,200-3,600 ind/ha and mean DBH 5.70±2.20 cm (range from 3.00-10.00 cm). Hijau Daun exhibited the lowest average density at 1,333 ind/ha, with DBH range from 2.00-37.00 cm (mean 9.27±7.24 cm).

HIGHLIGHTS

Small scale community-based initiatives (SSCM) are creating sustainable mangrove management models. GEE-based NDVI analysis and net value change indicate increasing vegetation cover and density in restored areas, while field surveys show enhancements in terms of mangrove ecological quality. However, lacks of seaward expansion in most restoration sites despite decadal consistent management, highlights limitations in biophysical support. This should be considered by government and stakeholders when proposing mangrove restoration programs.

1. INTRODUCTION

Indonesia has 3.44 Mha of mangrove (Ministry of Forestry, 2021), representing one-fifth global mangrove areas, as well as the most diverse mangrove species (Arifanti et al., 2022b). This ecosystem provides at least 26 ecosystem services: supporting, provisioning, regulating, and cultural services (Bimrah et al., 2022). Mangrove also plays an important role in carbon sequestration in marine systems (Kathiresan and Bingham, 2001; Donato et

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al., 2011; McLeod et al., 2011), forming the foundation of "Nature-based Solutions (NbS)" (Cohen-Shacham et al., 2016).

East Java has 27,221 ha of mangrove (Ministry of Forestry, 2021), making it the largest in Java, most populated Island in Indonesia. Majority mangrove in East Java categorized as converted mangrove, located in high intensity use of coastal areas. North coast of East Java provides an ideal habitat for mangrove, dominated by *Avicennia* and *Sonneratia* spp. (Asadi et al., 2019; Saputra et al., 2022b). South coast is geologically uplifted region dominated by sand and carbonate deposits. Lagoon mangrove in this region are found in river mouths affected by tides, behind sandy coastlines, protecting vegetations from high wave energy of the Indian Ocean (Saputra et al., 2020; Winarso et al., 2023; Sidik et al., 2025). Mangrove in East Java are utilized in various ways, providing a range of services that can be categorized into provisional, regulatory, and socio-cultural functions.

- Provisional function: mangrove-associated fish (Harahab, 2009; Saputra et al., 2022a) and various derivative products (functional-food, medicine and natural dyes for clothing) (Hardoko et al., 2015; Hardoko et al., 2020).
- Regulatory function: blue carbon ecosystem (Donato et al., 2011; Alongi, 2012; Asadi et al., 2018), protect coastal settlements and aquaculture from damaging storm, waves, and floods (Bimrah et al., 2022).
- Socio-cultural function: recreational sites (Hakim et al., 2017; Harahab and Setiawan, 2017; Arsad et al., 2021; Intyas et al., 2021; Abidin et al., 2023).

In contrast, mangrove ecosystems are among the most vulnerable habitats in Indonesia, with total net deforestation or the net loss of mangrove forest area from 2001-2020 at 193.37 ha (Sasmito et al., 2023), contributing CO_2 emission factor (EF) of 24.0±5.4 - 92.3±15.7 Mg CO_2e/ha/year (Arifanti et al., 2022a). Over decades, mangrove deforestation is estimated at around 637,000 ha or 10-33% of total mangrove area (Arifanti et al., 2022b), including mangrove in East Java (Saputra et al., 2022a).

Local communities play a pivotal role in the success of sustainable mangrove management (Susilo et al., 2015; Arifanti et al., 2022b; Quevedo et al., 2023). In East Java (outside national parks), existing mangrove stands outside national parks largely result from local conservation and restoration initiatives by local community (Susilo et al., 2015; Hakim et al., 2017). Mangrove in East Java is the prime examples of how small scale community-based mangrove management (SSCM) efforts become backbone to mangrove existence. SSCM is closely related to community based mangrove management terms (Tacconi, 2007), aimed at restoring important services and conserving biodiversity, with heavy involvement of local communities in various forest activities such as planting, monitoring and nursery establishment. Despite these promising results, there is a research gap in understanding the impacts of SSCM on the ecological and socio-economic outcomes of mangrove ecosystems. Comprehensive research focusing specifically on East Java is still lacking.

The advancement of technology provides new opportunities to evaluate SSCM initiatives. Combination of ecological assessment (plot-based field measurement) and remote sensing provides key information related to SSCM results. This study aims to (1) Quantify current mangrove condition after more than one decade of restoration, (2) Identify long-term changes in mangrove cover using multi-temporal satellite data, and (3) Integrate both approaches to evaluate SSCM effectiveness in East Java.

2. METHODOLOGY

This research covers primary SSCM areas, representing all geomorphological regions in East Java. South coast of East Java represented by CMC (Clugup Mangrove Conservation) in Malang, north coast of East Java represented by Penunggul in Pasuruan, while small islands represented by Mangrove Hijau Daun in Bawean Island, 60 nautical miles from Gresik Regency (Figure 1). A total of 15 plots 10×10 m were deployed using stratified random sampling to obtain community structure data. Field observations carried out in 2023-2024 for each location.

2.1 Temporal analysis of mangrove cover

Change in mangrove cover within last decade (2012-2024) processed using google earth engine (GEE), which supports geospatial processing, cloud computing and provides vast number of satellite datasets (Gorelick et al., 2017). Landsat 7 Collection 2 Level-2 imagery was filtered for the period Jan 1 - Dec 31, 2012, while Sentinel-2 Surface Reflectance imagery was filtered for the period Jan 1 - Dec 31, 2024. Both satellite imageries prepared with a max cloud cover of 20%. Median composite imagery was generated to minimize the influence of atmospheric conditions and

ensure high data quality. Due to Landsat 7 SLC failure (which affecting up to 22% results), gap filling algorithms were implemented during median composite processing (Chen et al., 2011).

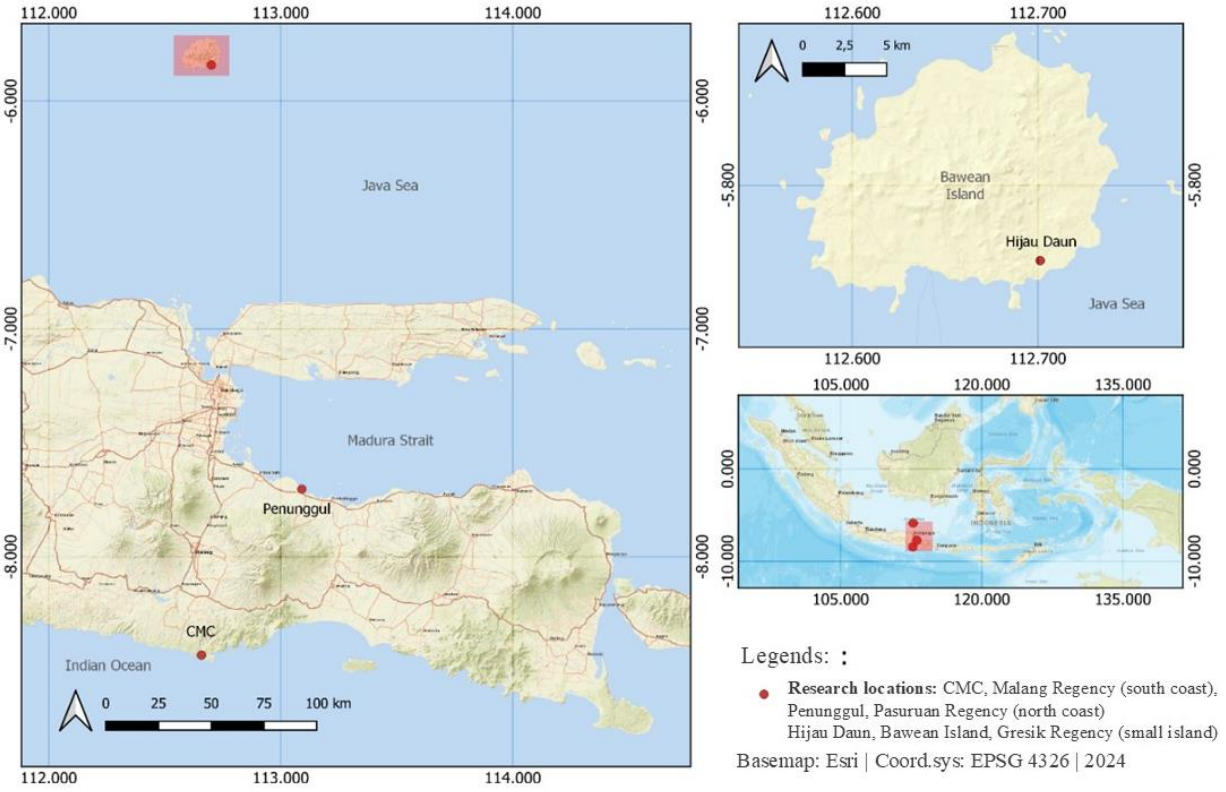


Figure 1. Map of research locations

NDVI values were computed using the (normalized Difference) function in GEE. NIR represents the near-infrared reflectance (Landsat 7: Band 4, Sentinel-2: Band 8), and RED represents the red reflectance (Landsat 7: Band 3, Sentinel-2: Band 4). Normalized Difference Vegetation Index (NDVI) was calculated for each year using the following formula (Pettorelli et al., 2005):

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

NDVI rasters derived from Landsat 2012 and Sentinel 2024 satellite imagery. To ensure compatibility between datasets, spatial harmonization were performed to obtain comparable pixels. Sentinel-2 NDVI raster was resampled and aligned to Landsat 7 (30 m resolution) using Qgis software. The NDVI values for 2024 and 2012 then compared on a pixel-by-pixel basis to assess temporal changes in vegetation cover. This comparison was performed using the QGIS raster calculator, with the net NDVI value change (ΔNDVI) calculated as:

$$\Delta\mathrm{NDVI} = \mathrm{NDVI}_{2024} - \mathrm{NDVI}_{2012}$$

Positive values of ΔNDVI represent increase in vegetation cover, while negative values suggest a decrease. The resulting raster file was exported in GeoTIFF format and imported into R software using Terra package (Hijmans, 2020). ΔNDVI was derived by subtracting baseline from recent NDVI, which theoretically ranges between -2 and 2. For classification and visualization, ΔNDVI values were normalized to a 0-1 scale. ΔNDVI values were further reclassified into predefined ranges (0-1) to facilitate a deeper understanding of vegetation dynamics as a result of rehabilitation efforts.

2.2 Present ecological mangrove condition

Mangrove ecological quality consists of mangrove density, important value index (IVI) and mangrove health index (MHI). Field data collection was carried out at three locations, namely Penunggul, CMC and Hijau Daun. Primary variable of community structure represented by mangrove DBH size (cm) at 1.3 m height, mangrove density (ind/ha) and IVI. IVI

is widely used to explain ecological dominance of a species within forest community (Darmawan and Pramudji, 2017). It is calculated using the relative density (RD), relative frequency (RF) and relative dominance (RD), as explained from following equations:

$$RD_i = \left(\frac{N_i}{N_{tot}}\right) \times 100$$

$$RF_i = \left(\frac{F_i}{F_{tot}}\right) \times 100$$

$$RDom_i = \left(\frac{BA_i}{BA_{tot}}\right) \times 100$$

$$BA_i = \pi\left(\frac{DBH_i}{2}\right)^2$$

$$IVI = RD_i + RF_i + RDom_i$$

MHI model was generated by combination of vegetation indices algorithms (NBR, GCI, SIPI, and ARVI) (Nurdiansah and Dharmawan, 2021). Mangrove health index (MHI) represents the condition of healthy and productive mangrove ecosystem, supported by adequate natural regeneration to ensure the sustainability of the mangrove community. It calculated from canopy cover, sapling density and sapling-tree diameter (Nurdiansah and Dharmawan, 2021). MHI categorized mangrove condition into three categories: Poor (MHI ≤ 33.33%), Moderate (33.33% < MHI ≤ 66.67%) and Excellent (MHI > 66.67%). MHI values were used to determine the placement of sampling plots for field sampling, representing the poor, moderate, and excellent categories.

2.2 Stakeholder analysis

Semi-structured interviews were conducted with key local stakeholders in the study areas to obtain information related to motivations, activities and challenges of their initiatives. A descriptive analysis was performed to understand the impact of SSCM activities on mangrove ecosystem quality. This analysis can inform the development of strategies for mangrove conservation and restoration.

3. RESULTS AND DISCUSSION

3.1 Results

3.1.1 Temporal changes of mangrove cover

In the 1980s, coastal area of Penunggul Village experienced significant degradation due to land conversion. In response, local community initiated voluntary mangrove replanting in 1985, using propagules of *Rhizophora* spp. (Sofian et al., 2012). Restoration site focused in abandoned farms and sedimentation zone surrounding Lewean rivermouth. This initiative marked the beginning of small-scale, community-based mangrove restoration in East Java.

Existing mangrove area in Penunggul Village spans approximately 31 ha, with a stable shoreline trend observed in the restored mangrove area, while the Lewean rivermouth continues to expand seaward. Temporal analysis using NDVI over the past decade (Figure 2) shows increase in maximum NDVI values (from 0.42 in 2012 to 0.60 in 2024) and a reduction in open areas, particularly in former abandoned farms. This reflects improvement in vegetation cover, driven by both replanting efforts and natural mangrove regeneration.

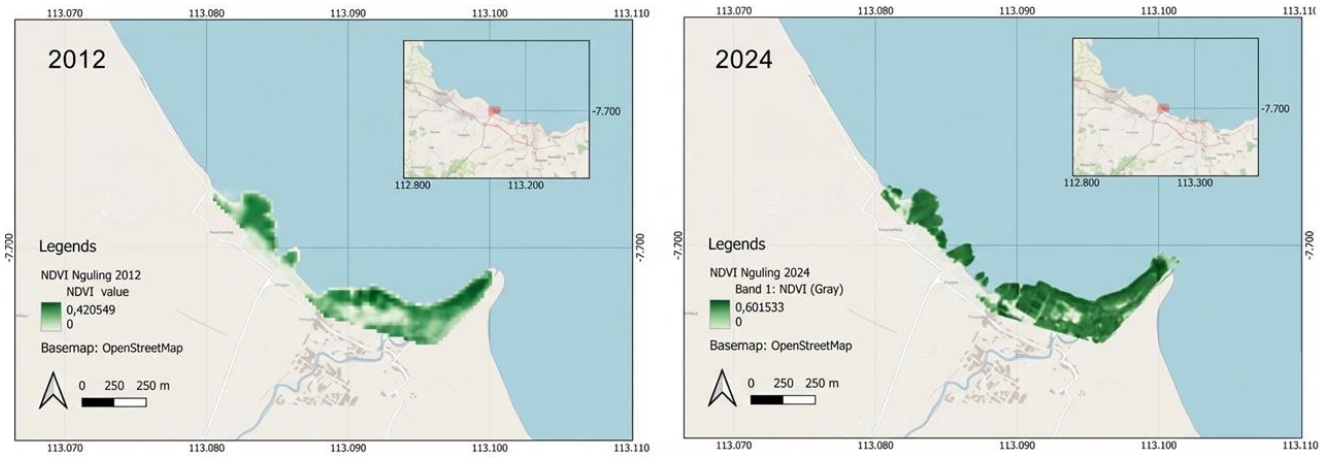


Figure 2. Temporal change of mangrove area in Penunggul, Pasuruan

Clungup mangrove conservation (CMC) represents inland mangrove in uplifted region, south coast of Malang. This area experienced severe deforestation from 1998 to early 2000s. Started in 2012, small-scale restoration initiatives were initiated voluntarily by local community (Antyo et al., 2018). The establishment of the Supervisory Community Group (POKMASWAS) GOAL played a pivotal role in enhancing the restoration efforts. From 2012-2024, CMC gradually experienced significant improvements in mangrove cover. NDVI analysis revealed notable changes. In 2012, NDVI scores ranged from 0-0.4, representing majority of open areas and sparse transitioned into moderate vegetation cover. By 2024, NDVI values mostly range between 0.3-0.6, indicates moderate to dense vegetation cover (Figure 3).

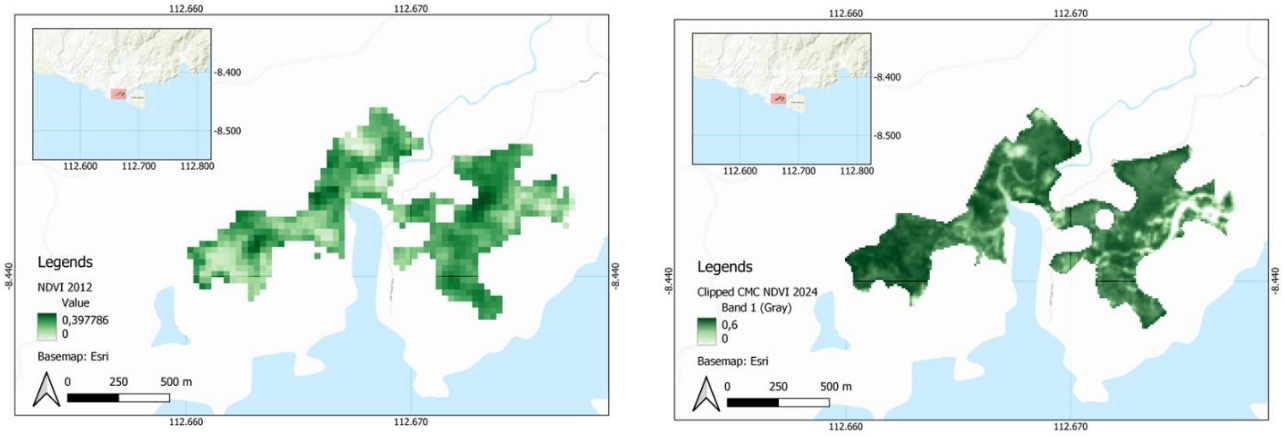


Figure 3. Temporal change of mangrove area in CMC, Malang

Hijau Daun in Bawean Island has a coastal area dominated by fringing mangroves, with a tidal inlet that drains the tides into the back mangroves, protecting vast area of rice fields behind mangrove stands. In the 1990s, mangrove along the coast of Hijau Daun, Bawean, suffered extensive damage due to overharvesting for firewood and the use of destructive fishing. These activities led to 43 ha coastal erosion in 2004, inundating productive rice-fields and severely affected the village's economy (Saputra et al., 2024). In response, a local youth group in 2008 initiated voluntary activities to restore mangrove ecosystem. Temporal analysis using NDVI revealed significant shifts in vegetation cover classes during last decade. In 2012, NDVI values ranged from 0-0.44, indicating the dominance of sparse to moderate vegetation cover. By 2024, NDVI values had shifted to 0.30-0.66, signifying a majority of moderate to dense categories (Figure 4). However, there has been no significant seaward mangrove expansion due to the characteristics of small island beaches, which receive minimal sediment input from terrestrial sources.

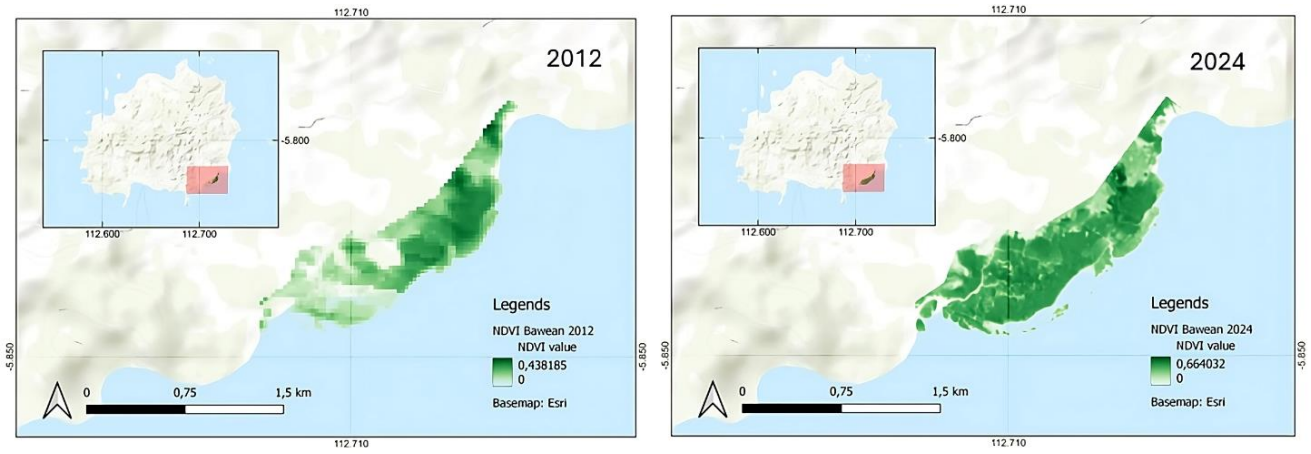


Figure 4. Temporal change of mangrove cover in Hijau Daun, Bawean Island

Analysis of NDVI value change (ΔNDVI) performed by reclassifying pixel value 0-1, divided into equal interval. With the temporal observation spanning over one decade, value ΔNDVI less than 0.3 can be categorized as mild improvement in mangrove cover, while more than 0.4 considered as significant change. Based on pixel count of ΔNDVI, Bawean and Penunggul has the highest pixel count within 0-0.1 class, while CMC has the most value in 0.2-0.3 class. This difference can be attributed to the varying starting points of rehabilitation efforts. Penunggul began its rehabilitation activities since 1980s, allowing ample time for vegetation to recover and establish in early decade of restoration. Similarly, Hijau Daun in Bawean Island initiated its rehabilitation efforts in 2008, benefiting from over a decade of both replantation and natural regeneration. Moreover, both locations using fast growing *Rhizopora* spp. as primary replanted species, which will produce significant canopy density after five years of plantation. In contrast, CMC started rehabilitation initiatives in 2012, which consequently, temporal analysis spanning last 10 years reflects significant changes in vegetation cover, encompassing almost entire CMC area (Figure 5).

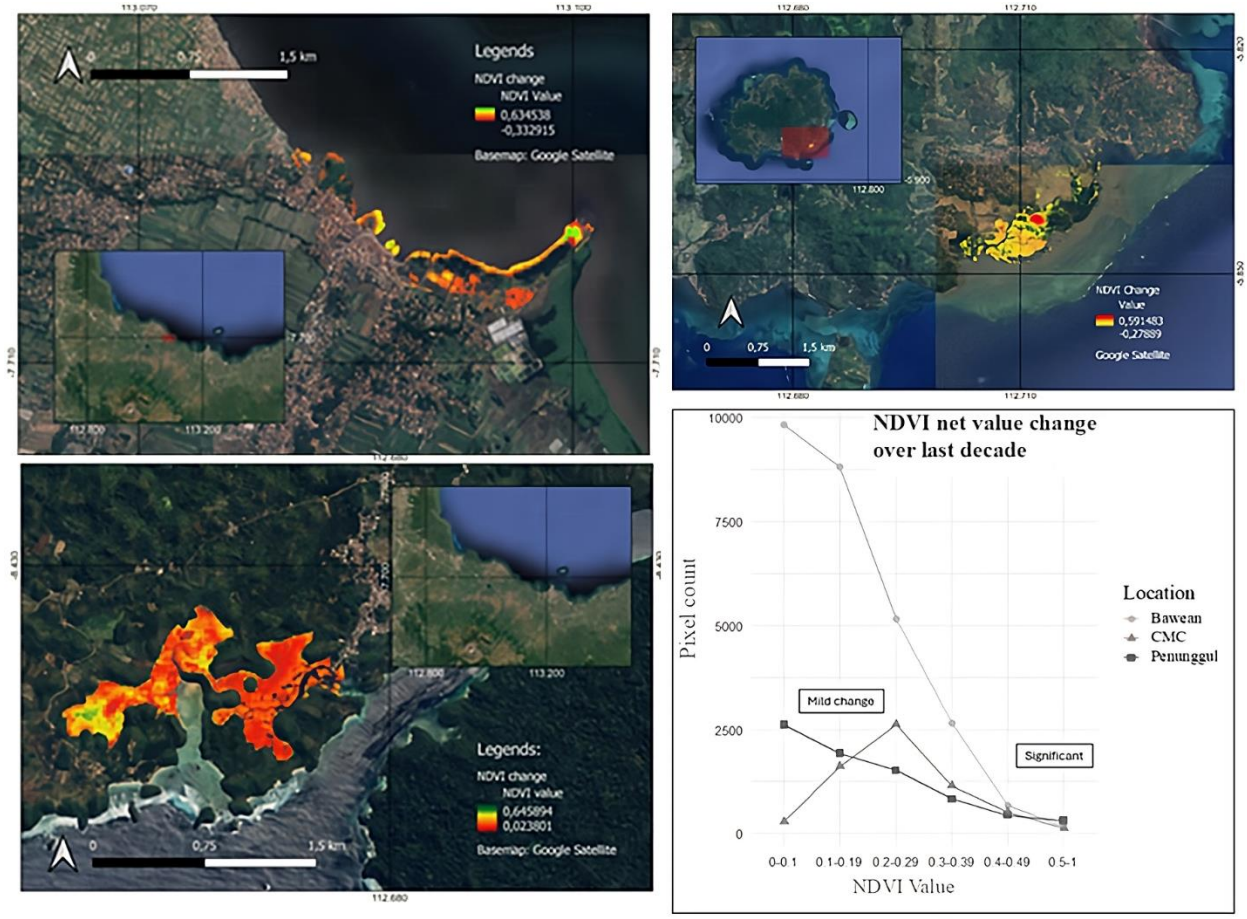


Figure 5. Net change of NDVI values (ΔNDVI) from each location over the last decade

Mangrove in Penunggul supported by favorable coastal characteristic that naturally promote mangrove growth (muddy substrate and high sediment input, particularly surrounding Lewean rivermouth in Penunggul). In contrast, CMC (uplifted south coast) and Hijau Daun (carbonate small island) tend to stable. These two locations faces biophysical limitations due to its predominantly sandy substrate and the lack of organic matter input from terrestrial sources.

3.1.2 Present ecological status of mangrove

After more than one decade, restoration inititatives by local communities shows clear ecological recovery. Sampling plots in Penunggul dominated by tree category (mean DBH 7.70±3.34 cm), dominated by *Rhizopora* spp. In CMC, restoration in the karstic environment produced diverse species and mangrove stands. There are eight species recorded within plot, with mean DBH is

5.70±2.20 cm. Plots in Hijau Daun, Bawean, consists of six mangrove species with various DBH size. Mixed replanted Rhizoporaceae combined with old natural *Sonneratia* stands contribute wide DBH range (2-37 cm) with mean of 9.27±7.24 cm. All three sites has average density more than 1,000 ind/ha, categorized as moderate to good condition, according to Ministry of Forestry standard (Darmawan and Pramudji, 2017). DBH distribution and mangrove density presented in Figure 6.

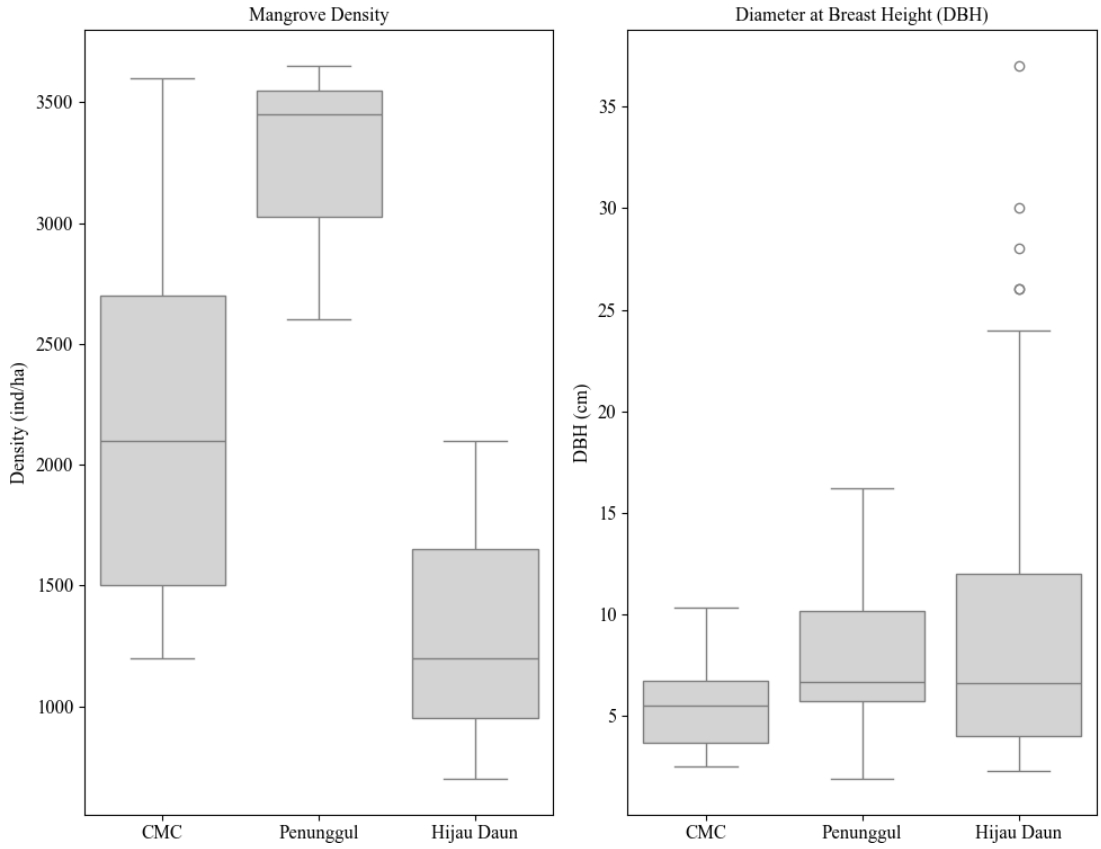


Figure 6. DBH distribution and mangrove density from each location

Most of mangrove area in CMC categorized as excellent MHI (38.4 ha, represents 69.3% of total area), while most of mangrove areas in Penunggul and Hijau Daun, dominated by moderate class of MHI. Penunggul has 12.5 ha of mangrove in moderate category (represents 57.5% of total area), while Hijau Daun has 61.5 ha of mangrove within moderate category (62.2% of total area). All three locations have less than 10% of "poor" category MHI (Figure 7).

Present ecological condition of the three SSCM sites are summarized in Table 1. Ecological variables determine mangrove status under Min. Decree of Indonesia No. 201/2004.

Table 1. Present ecological condition as resulted from SSCM initiatives

RestorationSite	Dominant species (IVI)	DBH (cm)/ mean±SD	% Trees (DBH≥5 cm)	Density (ind/ha, mean±range)	Category
Penunggul (Pasuruan)	*R. mucronata* (155.63), *R. apiculata* (144.37)	2-16/7.70±3.34	87.5%	2,300 (low variability)	Good
CMC (Malang)	*R. apiculata* (196.99-231.66), *C. tagal* (208.81-300), *S. alba*, *B. gymnorrhiza*	3-10/5.70±2.20	66.7%	2,155 (1,200-3,600)	Good
Hijau Daun (Bawean Island)	*R. stylosa* (151.94), *A. marina* (91.84), *S. alba* (123.58)	2-37/9.27±7.24	70.9%	1,333 (700-2,100)	Moderate

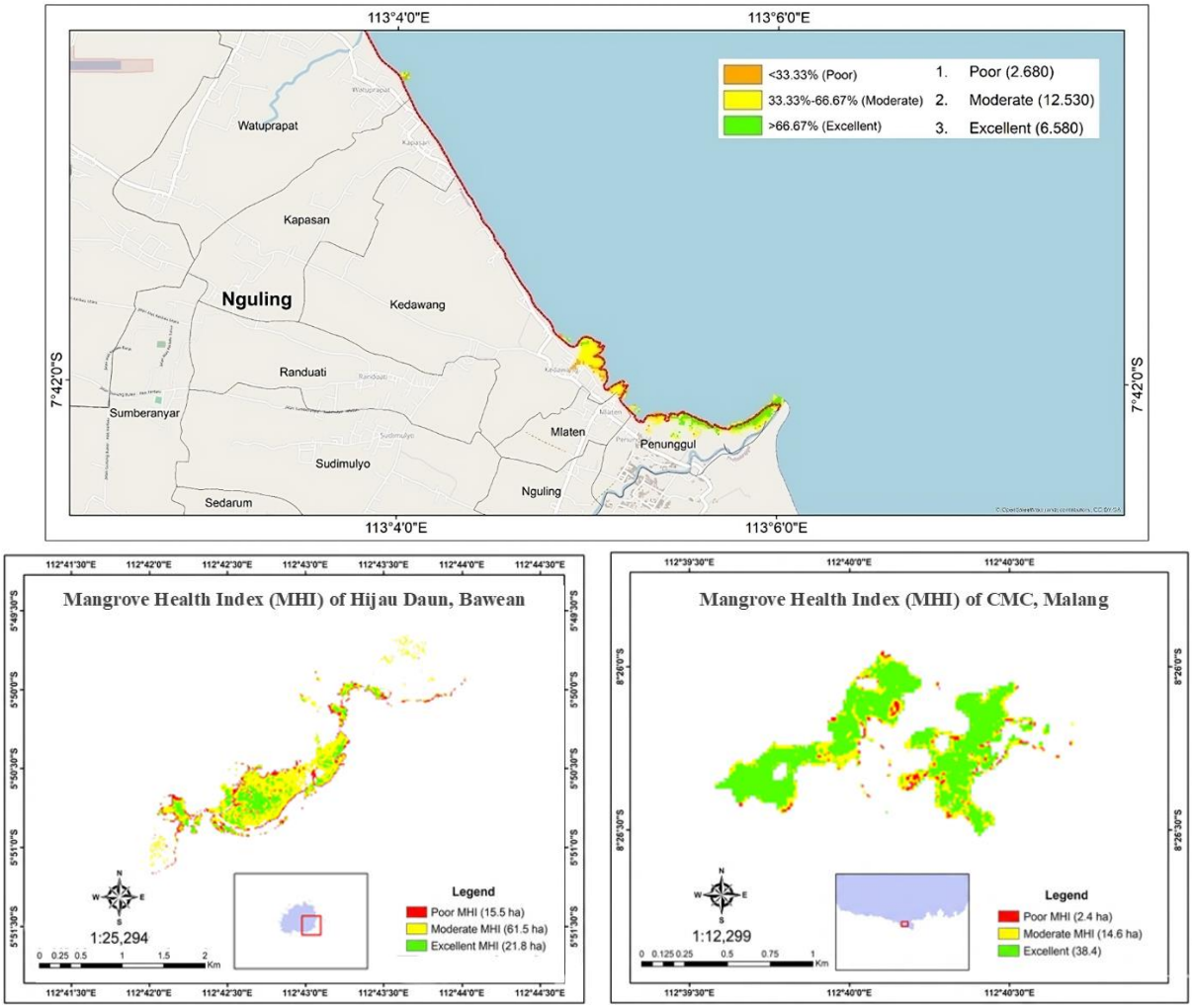


Figure 7. MHI value shows good condition of restored mangrove areas

4. DISCUSSION

ΔNDVI analysis confirms that SSCM increased canopy cover significantly at all sites. CMC, rehabilitated since 2012, has the highest ΔNDVI (0.2-0.3), which suggests rapid change due to fast-growing *Rhizophora* spp. Penunggul (since the 1980s) and Bawean (since 2008) both have small ΔNDVI (0-0.1). Penunggul indicates old stable maturity stands, where biophysical constraints in Bawean limit the mangrove growth. Restoration age thus controls canopy dynamics considerably, such that early-stage restoration exhibits fast increases, whilst older systems register stability more than growth (Lovelock and Brown, 2019; Sasmito et al., 2019; Sasmito et al., 2023; Howard et al., 2023).

A single NDVI reading can't solely determine restoration effectiveness. Negative results can signify conversion for agriculture or aquaculture uses. Static change in NDVI values can be a sign of location-specific biophysical constraints, and drastic NDVI improvement can sometimes be indicative of invasive species growth. Other algorithms (Baloloy et al., 2020; Nurdiansah and Dharmawan, 2021; Winarso et al., 2023) and in-field ecological information are needed for proper assessment.

Stakeholder interviews highlight community motivation as the key driver for long-term success. Many villagers who, since childhood, had witnessed mangrove decline, were deeply motivated to restore them. Early restoration efforts were carried out voluntarily, despite social tensions, lack of funding and technological constraints. Sustained efforts over more than five years led to ecological recovery, the return of bird populations, and increased productivity of mangrove crab and fisheries. This strong community incentive distinguishes SSCM from large-scale restoration programs, which are often driven by regulatory objectives (Arifanti et al., 2022b; Friess et al., 2022; Quevedo et al., 2023). On the densely inhabited coast of Java, there is very limited space

available for large-scale restoration (Worthington and Spalding, 2018), as many biophysically suitable areas area already used for fisheries and coastal activities (Saputra et al., 2022b; Saputra, 2023). Tenure conflicts regarding the land contribute to another barrier (Lovelock and Brown, 2019). In contrast, small-scale conservation of existing mangrove stands is often more feasible and cost-effective. SSCM, when adapted to the local conditions, provides pragmatic and sustainable solutions (Sasmito et al., 2023).

Another benefit of SSCM is a strong connection with local livelihoods. Ecotourism and aquaculture activities generate income that complements conservation efforts. For example, Penunggul and CMC programs promote ecotourism (Sofian et al., 2012; Harahab and Setiawan, 2017), while in Bawean, restoration with crab aquaculture (Saputra et al., 2024). Such activities help alleviate poverty while strengthening local ownership of conservation outcomes.

5. CONCLUSION

This study reveals that SSCM has effectively enhanced mangrove canopy cover and ecosystem quality over the past decade. Change detection analysis using ΔNDVI shows positive trends across all three sites, with CMC recording the most ΔNDVI values in the 0.2-0.3 range, reflecting rapid recovery due to its early restoration phase. In contrast, Penunggul and Hijau Daun-both with longer restoration histories-display smaller ΔNDVI changes (0-0.1), reflecting their mature and stable ecosystems. However, ΔNDVI alone cannot fully capture restoration success, as it is shaped by factors such as biophysical conditions, invasive species, and land-use changes. All sites demonstrated improved ecological quality, indicated by increased mangrove density and mangrove health index (MHI) values. Our findings demonstrate strong relations between SSCM interventions and the observed improvements in vegetation cover and ecological quality. The temporal alignment between restoration activities and positive ΔNDVI trends, combined with field evidence of improved mangrove condition, supports this interpretation. Overall, the results highlight the value of SSCM as a practical and adaptive approach to mangrove conservation and recovery.

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AUTHOR CONTRIBUTIONS

The contribution of each author as follow, DKS; collected the data, performed data processing and analysis and drafted the manuscript. SS, AT, ES, HH, UZ, MM, AS, YEP; devised the main conceptual ideas and critical revision of the article. AY, SSR, MAA, MAZF; concepting, provide additional data and supervising of the analysis. All authors discussed the results and contributed to the final manuscript.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest.

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