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Research Article

Identification of Changes in Extent and Density of Mangrove Vegetation Cover in Ambon Bay Using PlanetScope Satellite Imagery

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ABSTRACT

Mangrove forests represent a coastal ecosystem located in the transitional zone between land and sea. This ecosystem thrives in the intertidal zone, where seawater naturally rises and falls daily. Mangrove forests face serious degradation threats due to development activities and land conversion, including in Ambon Bay. This study utilized high-resolution PlanetScope imagery at 3 m resolution and the NDVI algorithm to analyze mangrove vegetation extent and density. The results indicate a consistent decline in mangrove vegetation area in Ambon Bay, from 55.79 ha in 2016 to 53.75 ha in 2020 and further to 49.87 ha in 2026, representing a total loss of 5.92 ha (10.6%) over the decade. NDVI analysis from 3 m PlanetScope imagery reveals the complex dynamics of mangrove density in Ambon Bay, with low-density area increasing from 3.05 ha (2016) to 4.23 ha (2020) and 5.51 ha (2026), medium-density area fluctuating from 11.15 ha (2016) to 10.38 ha (2020) and then 12.81 ha (2026), while high-density area experienced progressive degradation from 39.00 ha in 2016 to 37.16 ha (2020) and 29.87 ha in 2026. The Ambon City regional government must establish strict mangrove conservation zones in Ambon Bay through comprehensive revisions to the Regional Spatial Plan, prohibiting mangrove land conversion for unsustainable industrial or residential development, and promoting community participation through economic incentives such as mangrove ecotourism and sustainable fisheries, which will strengthen socio-ecological resilience, where local residents are trained as area managers to periodically monitor vegetation density.

Keywords: Ambon Bay, mangrove, NDVI, PlanetScope

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INTRODUCTION

Mangrove forests represent a coastal ecosystem located in the transitional zone between land and sea. This ecosystem thrives in the intertidal zone, where seawater naturally rises and falls daily (Wei et al. 2025). Mangrove trees possess specialized pneumatophores that enable survival in oxygen-poor muddy soils (Sofue et al. 2025). Indonesia boasts the world's largest mangrove forest area, accounting for about one-quarter of global mangroves, with exceptionally high species diversity (Basyuni et al. 2025).

Ecologically, mangrove forests serve as natural protectors of coastlines against wave erosion and tropical storms. This ecosystem also prevents seawater intrusion into agricultural lands and absorbs large quantities of carbon dioxide from the atmosphere, thereby contributing to climate change mitigation (Rivera-Solís et al. 2025).

Mangroves provide essential habitats, foraging grounds, and breeding sites for various fish, crab, and coastal bird species, supporting biodiversity and local livelihoods (Rachman and Hanifa, 2024).

However, mangrove forests face serious degradation threats from human activities such as logging and land conversion. Globally, approximately one-third of mangrove area has been lost in recent decades at a rate of 1-2% per year. In Indonesia, pressures from land conversion for shrimp ponds, settlements, and agriculture have diminished the ecosystem's capacity to protect coasts and store carbon (McNulty et al. 2025).

In the Maluku region, including Ambon Bay, mangrove land conversion to shrimp ponds and settlements has increased significantly, with over half of the original mangrove area logged in the past two decades (Latumahina et al. 2024). These changes disrupt coastal ecosystem balance and heighten community vulnerability to flooding and coastal abrasion. Monitoring changes in mangrove vegetation extent and density is urgently needed for sustainable management (Salakory and Rakuasa, 2022).

Remote sensing technology using high-resolution 3 m PlanetScope satellite imagery has proven effective for monitoring mangrove dynamics (Purnamasari et al. 2021). The Normalized Difference Vegetation Index (NDVI) calculated from PlanetScope imagery enables accurate detection of mangrove cover extent and density levels (Sahitya et al. 2026). Previous studies in Maluku relied on moderate-resolution imagery like Landsat, but PlanetScope offers daily updates and superior spatial detail for temporal change analysis (Liu et al. 2026).

Research in Ambon Bay remains limited to moderate-resolution imagery and lacks focus on vegetation density analysis using PlanetScope-derived NDVI. Combining 3 m PlanetScope imagery with NDVI algorithms can precisely identify changes in mangrove extent and health (Mahardhika and Kamal, 2020). This study is essential to support conservation decision-making in degradation-prone Ambon Bay, preserving its ecological functions for coastal communities.

METHODS

This study was conducted in the inner Ambon Bay area, Ambon Island, Indonesia, focusing on the mangrove ecosystem. The study location is shown in Figure 1. The research utilized PlanetScope satellite imagery data and ArcGIS Pro software for spatial analysis. PlanetScope satellite imagery data was officially downloaded from the website **https://www.planet.com/explorer/**. PlanetScope is a remote sensing satellite constellation owned by Planet Labs, comprising hundreds of small Dove CubeSats (10x10x30 cm in size) orbiting at 475 km altitude with daily global revisit, covering up to 200 million km² of Earth's surface per day (Sahitya et al. 2026). The multispectral sensor provides 3-meter spatial resolution per pixel with 4 basic bands (blue, green, red, and NIR) and optional 8 bands (including red edge for vegetation), a 12-bit dynamic range, and surface reflectance products harmonized with Landsat/Sentinel-2 for accurate time-series analysis since 2016 ideal for mangrove change monitoring such as NDVI and deforestation detection (Purnamasari et al. 2021).

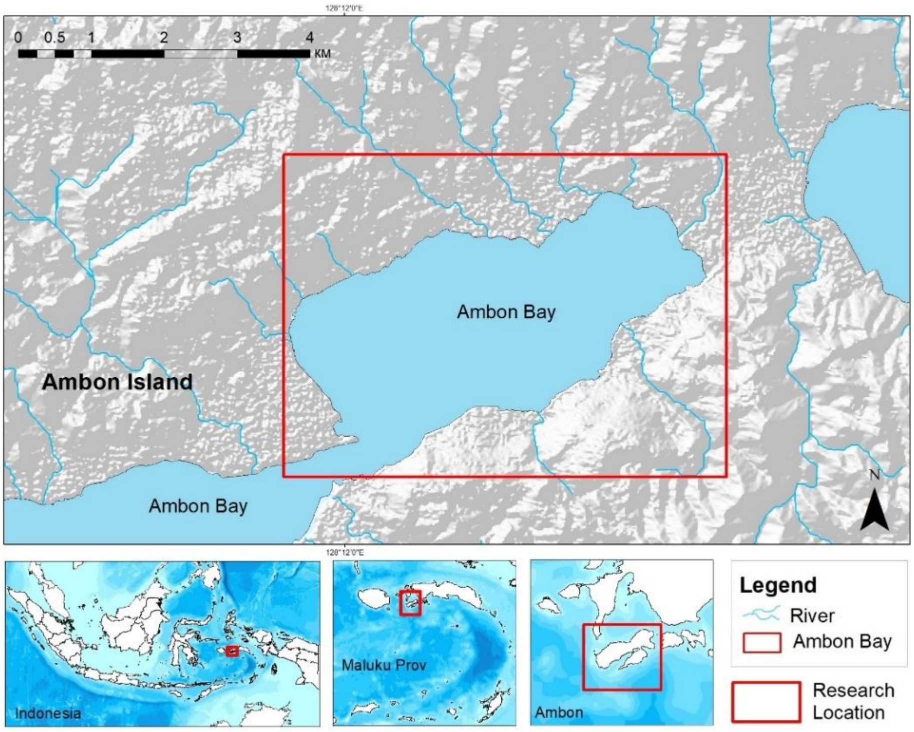

Figure 1. Research location, Ambon Bay, Indonesia

In greater detail, the PlanetScope data used in this study consisted of PlanetScope Ortho Scene Product (Level 3B) from acquisition dates 10/01/2016, 10/01/2020, and 10/01/2026. Level 3B PlanetScope indicates that the imagery has undergone geometric and radiometric corrections, making it ready for subsequent analysis, including NDVI. Thus, the preprocessing steps applied in this study were limited to converting pixel values (Digital Number) to Radiance and masking objects that could introduce bias in vegetation density index transformation results (Baloloy et al. 2018).

Processing and analysis began by clipping the satellite imagery to the study area, followed by visual interpretation to assess mangrove extent for the periods 2016, 2020, and 2026. To analyze mangrove density, this study employed the Normalized Difference Vegetation Index (NDVI). NDVI is one of the most commonly used vegetation indices for mangrove density mapping due to its ability to detect green biomass through the contrast between high near-infrared (NIR) reflectance in healthy leaves and low red band absorption due to chlorophyll (Pietersz et al. 2024). This index is highly effective for mangroves in Ambon Bay, where tidal conditions and sedimentation influence vegetation density, enabling precise spatial mapping at a 3 m scale with PlanetScope (Sahitya et al., 2026). The locations of change and density analysis are shown in Figure 2.

NDVI can be applied to various imagery types with diverse spatial resolutions, provided the imagery includes red and near-infrared channels. Based on these two channels, vegetation density using NDVI can be obtained through Equation 1:

$$NDVI = \frac{(NIR - Red)}{(Nir + Red)}$$

Caption: NIR = Near-Infrared band (channel 8 on PlanetScope) and Red = red wavelength channel (channel 6 on PlanetScope).

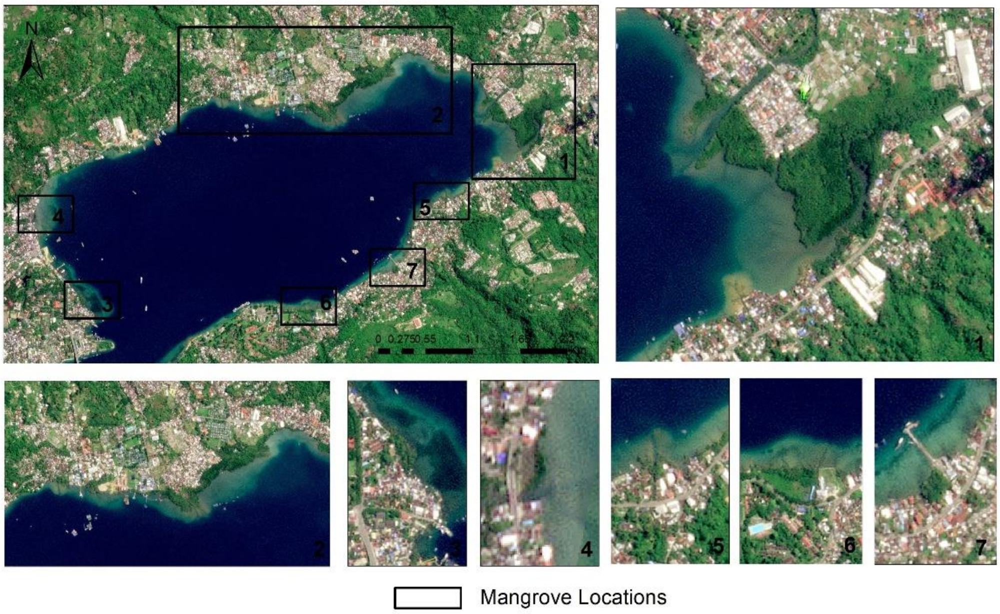

Figure 2. Mangrove locations in Ambon Bay based on PlanetScope Satellite Imagery

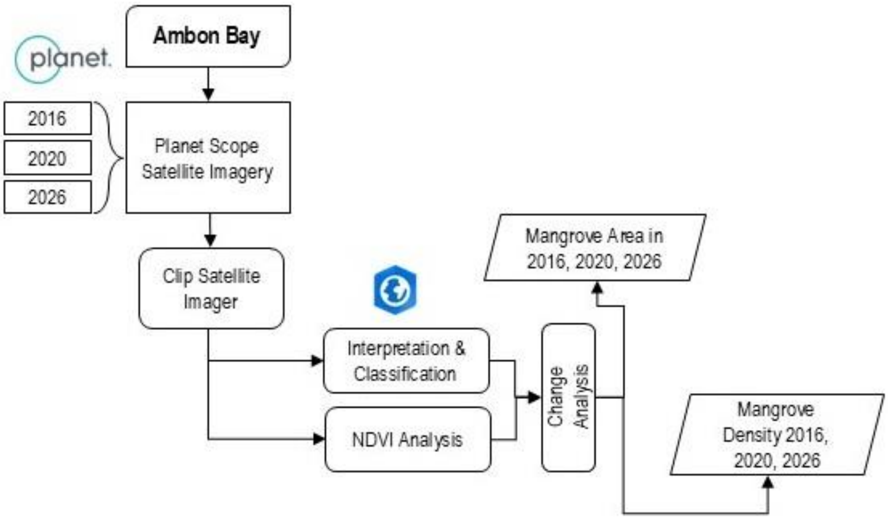

Figure 3. Research workflow

The resulting transformation was subsequently classified into four vegetation density classes: low, medium, and high. The mangrove density classes derived from NDVI transformation were then validated using true-color and false-color composite PlanetScope imagery. Validation was conducted directly by comparing the vegetation density class results with the actual appearance in the imagery. Direct comparison was feasible using high-resolution imagery (in this case, 3 meters) because mangrove objects appear clearly and are easily identifiable visually. The complete workflow is shown in Figure 3.

RESULTS AND DISCUSSION

Changes in mangrove extent in 2016, 2020, and 2026

PlanetScope imagery analysis shows that mangrove vegetation extent in Ambon Bay experienced a consistent decline from 55.79 ha in 2016 to 53.75 ha in 2020 and further to 49.87 ha in 2026, representing a total loss of 5.92 ha (10.6%) over the decade. The primary causes of mangrove extent reduction were settlement expansion and commercial facilities such as cafes in the Ambon Bay coastal zone, particularly in Poka, Passo, and Waiheru Villages, where development directly converted mangrove areas into concrete infrastructure (Rihulay and Papilaya, 2022; Rifai et al. 2025). Spatial changes in mangrove extent are shown in Figure 4, while mangrove extent is depicted in Figure 5.

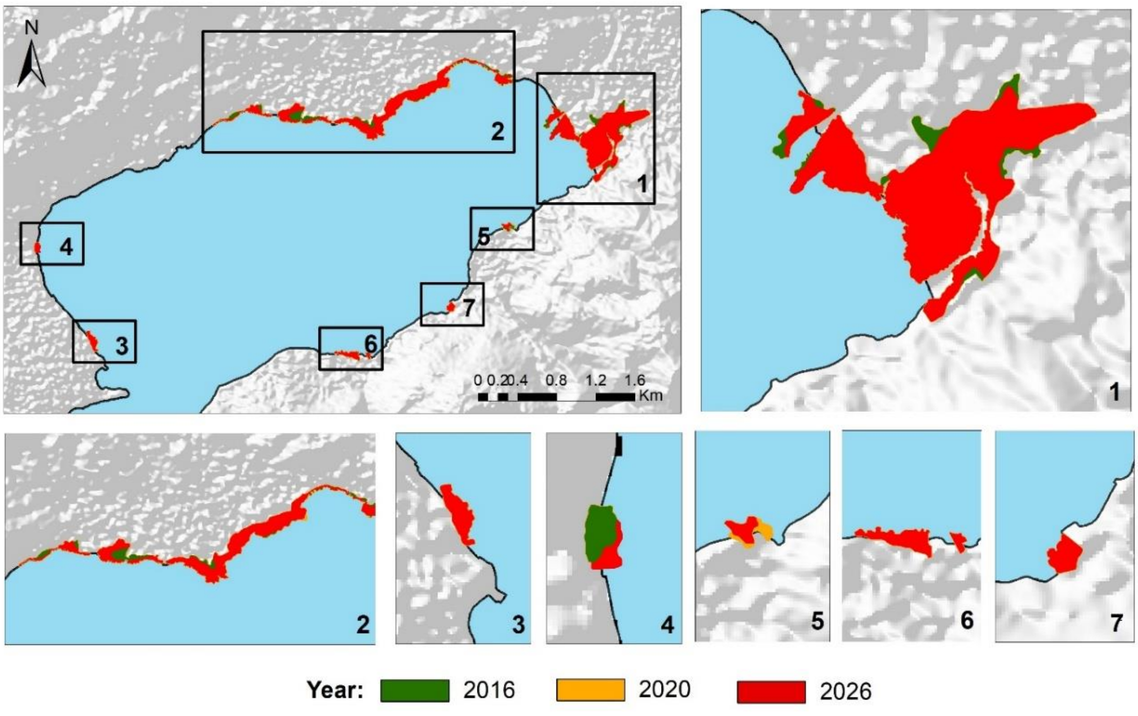

Figure 4. Mangrove extent changes in the periods 2016, 2020, and 2026

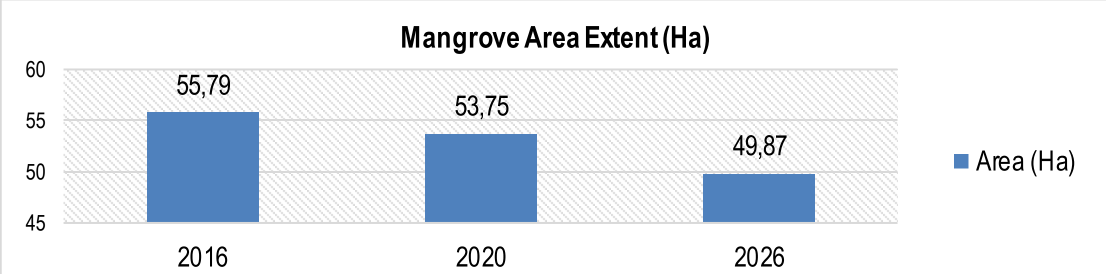

Figure 5. Changes in mangrove area extent for the periods 2016, 2020, and 2026 (Ha)

Massive sedimentation from deforestation of Ambon Island's steep slopes represents the second most important factor, with sediment accumulation in Galala and Tantui reaching 18.96 ha in 2018 due to mudflows from highland settlement land clearing (Meirina, 2021). This sediment buildup buries mangrove roots and alters salinity, causing mass mortality, particularly among dominant *Rhizophora* and *Sonneratia* species in Ambon Bay (Suyadi, 2012). Industrial waste pollution, especially from the Poka Diesel Power Plant operated by PT PLN, has led to mangrove drying and tree death, as documented by the Pulau Kalesang Community's protests against coastal ecosystem damage (Meirina, 2021).

Land use conversion for shrimp ponds and port infrastructure also contributed significantly, with OBIA studies showing mangrove conversion to ponds and footpaths as the primary cause of land cover change in Inner Ambon Bay. Pietersz et al. (2024), confirmed mangrove area damage from pollution activities and land conversion reaching 48.94% of the remaining total extent. Increasing ship traffic in Ambon Bay contributed to mud, waste, and plastic debris accumulation trapped in the mangrove ecosystem, significantly degrading forest quality over a decade (1998-2008). Tapilatu & Pelasula, (2012), documented a decline in extent from 49.5 ha (1987) that became less significant by 1991 due to port activity pressures.

Sea level rise exacerbated by sedimentation alters intertidal zone hydrodynamics, forcing mangroves to retreat to ecologically less suitable zones (Rondon et al. 2023). This combination of anthropogenic factors and climate change creates an unconducive environment for natural mangrove regeneration in Ambon Bay. Overall, Ambon Bay mangrove degradation represents a complex interaction of urban expansion (35%), sedimentation (30%), industrial pollution (20%), and aquaculture conversion (15%), necessitating satellite data-based restoration interventions to identify degradation hotspots and design targeted rehabilitation strategies (Moh Ponting, 2023).

Mangrove density changes in 2016, 2020, and 2026

NDVI analysis from 3 m PlanetScope imagery reveals complex mangrove density dynamics in Ambon Bay, with low-density area increasing from 3.05 ha (2016) to 4.23 ha (2020) and 5.51 ha (2026), medium-density fluctuating from 11.15 ha (2016) to 10.38 ha (2020) then 12.81 ha (2026), while high-density experienced progressive degradation from 39.00 ha (2016) to 37.16 ha (2020) and 29.87 ha (2026), a total decline of 9.13 ha, or 23.4%, in the dense canopy class. The significant decline in high density (>0.6 NDVI) was primarily caused by chronic sedimentation from upstream land clearing (ULC) on Ambon Island, increasing at 203.8 ha/year during 2001-2020, burying root systems of *Rhizophora apiculata* and *Sonneratia alba* and reducing light penetration to <20% (Tapilatu & Pelasula, 2012; Salakory et al., , 2019; Pietersz et al., 2024). Mangrove extent is shown in Table 1.

Table 1. Mangrove density extent in the periods 2016, 2020, and 2026

Mangrove Density	Area (Ha)		
	2016	2020	2026
Low	3.05	4.23	5.51
Medium	11.15	10.38	12.81
High	39.00	37.16	29.87

Urban expansion in the coastal zones of Poka, Passo, and Waiheru created edge effects from fragmentation that expanded low-density areas (+80%), where settlement and cafe conversion transformed homogeneous canopy into degraded patches with NDVI 0.1-0.3 (Alimudi et al. 2023). These edge effects facilitate seagrass invasion and salinity stress, reducing ecosystem connectivity and natural regeneration of climax mangrove species.

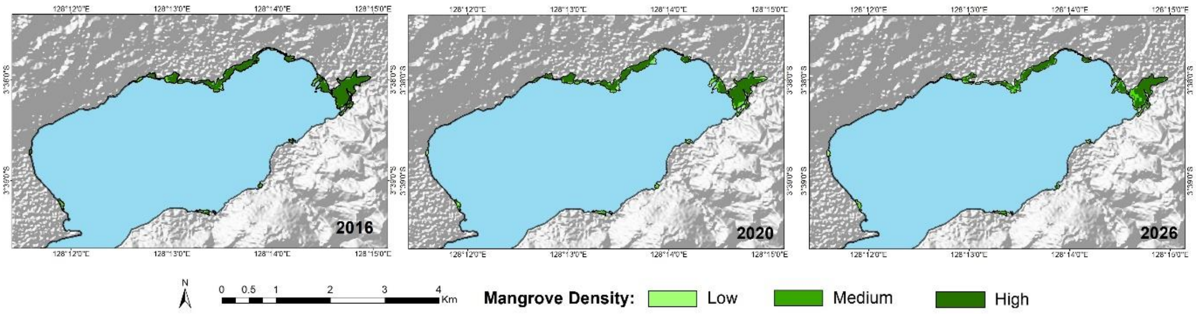

Figure 6. Mangrove Density in the Periods 2016, 2020, and 2026

The increase in medium density (+14.9%) in 2026 reflects partial rehabilitation efforts in Lateri and Passo (5 Ha planting), but seedlings failed to develop into dense canopy due to contaminated hydrology and persistent anthropogenic pressures (Herman, 2025). Planting without watershed management improvements failed to shift NDVI structure from medium to high density. Industrial pollution from the Poka Diesel Power Plant (diesel spills) caused chronic physiological stress in mangrove canopy, with hydrocarbon waste reducing chlorophyll indices and increasing 15-20% mortality in mature trees, particularly in core high-density zones (Belseran and Waas, 2022). Mangrove density in Ambon Bay is shown in Figure 6.

Policy Recommendations

The Ambon City regional government needs to establish strict mangrove conservation zones in Ambon Bay through a more comprehensive revision of the Regional Spatial Plan, prohibiting the conversion of mangrove land for unsustainable industrial or residential development. This policy must be supported by an integrated restoration program, including the replanting of native mangrove species using a community-based approach, as well as the implementation of a Pigovian tax on industrial polluters to fund long-term monitoring using high-resolution satellite imagery NDVI technology and UAVs. In addition, cross-sectoral collaboration with the Ministry of Environment and Forestry as well as international non-governmental organizations is necessary to build local capacity in ecosystem management so that changes in mangrove vegetation area and density can be effectively restored.

Increasing regional budgets for mangrove conservation must be prioritized through village fund allocations and regional revenue and expenditure budgets, with a target recovery of at least 10-20 ha per year based on annual economic damage data reaching billions of rupiah due to ecosystem degradation. Encouraging community participation through economic incentives such as mangrove ecotourism and sustainable fisheries will strengthen socio-ecological resilience, where local residents are trained as area managers to periodically monitor vegetation density (Kolengsusu et al. 2024). This policy aligns with the national mangrove management strategy that emphasizes conservation as the top priority for coastal disaster mitigation.

CONCLUSION

PlanetScope imagery analysis reveals significant degradation of mangrove vegetation in Ambon Bay, with the area declining from 55.79 ha (2016) to 49.87 ha (2026), or a 10.6% loss, accompanied by a 23.4% degradation in high-density areas due to urban expansion (35%), sedimentation from upstream deforestation (30%), industrial pollution such as from the Poka Diesel Power Plant (20%), and aquaculture conversion (15%), which disrupt intertidal hydrodynamics and natural regeneration of dominant species like Rhizophora and Sonneratia. Partial rehabilitation efforts in Lateri and Passo failed to achieve dense canopy due to inadequate watershed management and persistent anthropogenic pressures; thus, recommended conservation policies, including strict RTRW zones, community-based restoration, Pigovian taxes, and increased APBD funding for a 10-20 ha/year recovery target, are crucial for ecosystem restoration, enhancing coastal resilience to climate change, and supporting local economies through ecotourism and sustainable fisheries.

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AUTHOR CONTRIBUTIONS

Field data collectors (Ahmat Rifai & Stewart Pertuack), Data & Method Verification (Halim), Editor (Heinrich Rakuasa)

CONFLICTS OF INTEREST

The authors declare no conflict of interest

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