

# Mangrove Cover Changes In The Coastal Area Of Sorong City: A Spatio-Temporal Study Using Satellite Imagery And Geographic Information System

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## **Abstract**

Mangrove ecosystems play a vital ecological and economic role, yet they are often threatened by various human activities and environmental changes. This research aims to analyze the land cover changes of mangrove ecosystems in the coastal areas of Sorong City between 2017 and 2025, utilizing Landsat satellite imagery and manual digitization techniques within a Geographic Information System (GIS). The research stages included downloading Landsat satellite imagery, band compositing, clipping the imagery to the Sorong City Area of Interest (AoI), and creating a 5-6-4 band composite for mangrove visualization. Mangrove ecosystems were then manually digitized based on visual interpretation of the imagery. The mangrove cover area was calculated and overlaid with thematic maps of administration boundaries and forest areas. The research findings indicate an aggregate increase in mangrove cover in Sorong City from 782.1 hectares in 2017 to 791.27 hectares in 2025, with a total increase of 9.17 hectares. The overall rise in mangrove cover suggests the presence of effective conservation and restoration efforts, coupled with environmental conditions more conducive to mangrove growth. Besides their natural recovery capabilities, Sorong City's mangrove ecosystems are also being restored through human-assisted rehabilitation activities. Further analysis identified Klamana Village as the area with the largest reduction in mangrove cover, decreasing by 10.23 hectares (6.8%) from 158.6 ha in 2017 to 148.4 ha in 2025. These findings indicate heterogeneity in the effectiveness of mangrove conservation at the village level, underscoring the need for local governments in Sorong City to review the effectiveness of mangrove management policies at the village level to ensure the sustainability of coastal ecosystems.

**Keywords:** Mangrove, Sorong City, Temporal-Spatial Analysis, GIS.

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## **INTRODUCTION**

Mangrove ecosystems are one of the coastal ecosystems that have a fundamental role in maintaining environmental balance and providing significant socio-economic benefits to the community. Located in the transition zone between land and sea, mangrove forests serve as coastal protectors from abrasion and storm surges, become habitats for various species of marine flora and fauna (such as fish, shrimp, and crabs), and play an important role in carbon cycling and CO<sub>2</sub> sequestration (Alongi, 2008; Duke et al., 2007). Indonesia, as the largest archipelago in the world, has a very long coastline and is the center of global mangrove biodiversity, with the second largest mangrove area in the world after Brazil (Bengen, 2002; Spalding et al., 2010).

However, mangrove ecosystems in Indonesia, including in the coastal area of Sorong City, Southwest Papua Province, continue to face various threats of land degradation and conversion. The rapid development of the development sector, both for settlements, transportation infrastructure, fisheries (such as ponds), and industry, often sacrifices mangrove areas. Global data shows that about 35% of the world's mangrove ecosystems have been lost in the last five decades, with a significant rate of loss in Southeast Asia (Osman et al., 2021; Friess et al., 2019). Coupled with the impact of global climate change such as rising sea levels and increasing frequency of extreme weather events, which can affect the survival and spatial distribution of mangrove ecosystems (IPCC, 2021).

Sorong City, as one of the main coastal cities in the Bird's Head of Papua Island, has a coastal landscape dominated by mangrove ecosystems. The dynamics of mangrove land cover in this region are very important to be monitored and understood because they affect the surrounding marine ecosystem, coastal resilience, and the sustainability of livelihoods of communities that depend on mangrove resources. An in-depth understanding of patterns of change, area area, and the factors that affect them is crucial for the formulation of effective and sustainable coastal management policies.

Although there are several studies that examine coastal ecosystems in the Papua region, including those that may touch mangroves around Sorong City, there is a significant research gap related to in-depth and up-to-date spatial-temporal analysis of mangrove land cover changes specifically in Sorong City for the period 2017-2025, using manual digitization techniques based on Landsat and ArcGIS imagery. The

majority of previous studies may have focused on a different time period, used lower image resolution, or applied classification methods that were not as detailed as the visual interpretation you had planned. This study aims to fill this gap by providing accurate quantitative and spatial data on the condition of mangroves in Sorong City, as well as identifying critical areas that require special attention in conservation and restoration efforts.

The objectives of this study are:

1. Analyzing changes in land cover of mangrove ecosystems in Sorong City based on Landsat satellite imagery data and manual digitization techniques for the period 2017-2025.
2. Identify spatial and quantitative patterns of mangrove land cover changes in Sorong City for the period 2017-2025.
3. Factors that have the potential to affect changes in mangrove land cover in Sorong City.

## METHOD

This study uses a quantitative approach with a spatial-temporal analysis method using remote sensing data and Geographic Information Systems (GIS). This approach was chosen for its ability to accurately map and analyze land cover changes over a wide geographic scale and a specific time span.

### 1. Research Location and Time

This research was carried out in the coastal area of Sorong City, Southwest Papua Province. The city of Sorong is located in the southwestern province of Papua, geographically located at coordinates of about 5°40' - 6°00' South Latitude and 130°40' - 131°10' East Longitude. The coastal area of Sorong City is characterized by the existence of a vast mangrove ecosystem, which is the main focus of the analysis of land cover changes.

The data used in this study includes Landsat satellite imagery for the time period from 2017 to 2025. The selection of this period was based on the availability of relatively accessible satellite imagery data with adequate resolution, and included a sufficient time span to identify trends in land cover change.

### 2. Data Used

The main data used in this study are:

1. **Landsat Satellite Imagery:** Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) satellite imagery will be used. Landsat 8 was chosen for its availability, 30-meter spatial resolution for multispectral bands, and the ability to distinguish different types of land cover, including mangroves. The data will be downloaded from a trusted source such as USGS EarthExplorer. For this analysis, we will focus on the multispectral bands relevant for mangrove mapping, namely band 5 (SWIR1), band 4 (NIR), and band 3 (Red) to form a corresponding color composite.
2. **Administrative Vector Data:** The administrative map of Sorong City (city boundaries, sub-district boundaries, and sub-district boundaries) will be used as a spatial reference to limit the analysis area (clipping) and map the findings based on administrative units. This data is usually available from relevant government agencies such as the Central Statistics Agency (BPS) or the National Land Agency (BPN).
3. **Other Thematic Data:** Other thematic data such as the Sorong City Administrative Boundary Map, Sorong City Spatial Pattern Plan Map, protected area/forest map, or historical land use data can be used as supporting data for the analysis of factors causing change.

### 3. Research Stages

This research process is carried out systematically through several main stages:

1. **Landsat Satellite Image Download:** Landsat 8 OLI/TIRS satellite imagery covering the Sorong City area for 2017 and 2025 will be downloaded from the USGS EarthExplorer portal. Image selection will take into account minimal cloud cover conditions (ideal <10%) to ensure optimal visualization and interpretation quality.
2. **Pre-processing of Satellite Imagery:**
  1. **Radiometric Correction:** The downloaded image will be radiometrically corrected to convert the digital value to the surface reflectance value. It is important to compare data from different times accurately.
  2. **Geometric Correction (if needed):** Ensuring that each pixel in the image has the correct geographic position according to the coordinate system used.
    - o **Clipping:** Corrected satellite images will be clipped according to the administrative boundaries of Sorong City using administrative vector data. It aims to limit the area of analysis to only the study area.

#### 1. **Band Composite Formation and Mangrove Digitization:**

1. **5-6-4 Band Combination:** To optimally visualize the mangrove ecosystem, the Landsat 8 imagery will be combined with the sequence of band 5 (SWIR1) - 4 (NIR) - 3 (Red). This combination highlights the spectral characteristics of mangroves, where healthy mangrove vegetation will appear blackish-red or dark brown, distinct from water bodies (dark blue) and other terrestrial vegetation.

2. **Manual Digitization:** Based on the composite image of the 5-6-4 band that has been cut, the mangrove ecosystem cover will be digitized manually using the spatial editing feature in ArcGIS. The digitization process will be carried out carefully, identifying the appearance of mangroves based on their distinctive colors, textures, and spatial patterns. Each area identified as a mangrove will be drawn as a polygon. This process will be carried out separately for the 2017 and 2025 images.

#### 1. **Wide Calculation and Change Analysis:**

1. **Area Calculation:** After digitization is completed for both time periods, the mangrove area area for each polygon will be calculated using the area calculation function in ArcGIS. The total area of mangroves per year will be summed up.

#### 2. **Overlay with Thematic Map:**

Digitized mangrove polygons will be overlaid with administrative maps (village boundaries) to calculate the area of mangroves per village. If relevant, overlays with forest area maps can also be done to see the status of mangrove areas.

o **Change Detection:** Changes in mangrove land cover will be analyzed by comparing the results of manual digitization from 2017 and 2025. This will involve identifying areas that are experiencing mangrove loss (degradation or conversion) and areas that are undergoing mangrove additions (if any, e.g. from restoration or natural growth to areas that were previously not mangroves). Calculation of the percentage change and identification of specific areas that change will be carried out.

2. **Identification of Potential Factors:** Based on the results of spatial and quantitative change analysis, as well as by referring to previous research and available supporting data (e.g., land use maps, demographic data if accessed), a discussion will be held on factors that have the potential to affect mangrove land cover change in Sorong City, such as urban expansion, fishery activities, or rehabilitation programs.

#### 4. **Software Used**

The main software used in this study are:

1. **ArcGIS Pro (or other relevant version of ArcGIS):** Used for all stages of image processing, digitization, and spatial analysis and broad calculations.

2. **Microsoft Excel:** Used for tabular data processing, statistical calculation, and summary table creation.

## RESULTS AND DISCUSSION

### **Mangrove Dynamics in Sorong City**

Mangrove dynamics in Sorong City refers to the Spatial Dynamics (Changes in Area and Distribution) that occur in the mangrove forest ecosystem over time. These changes can be caused by internal and external factors, natural or influenced by human activities, and occur on various scales (spatial and temporal). Understanding the dynamics of mangroves is essential to design an effective and sustainable management strategy. Mangrove dynamics research was conducted in the city of Sorong, Southwest Papua Province.

In more detail, mangrove dynamics include several key aspects:

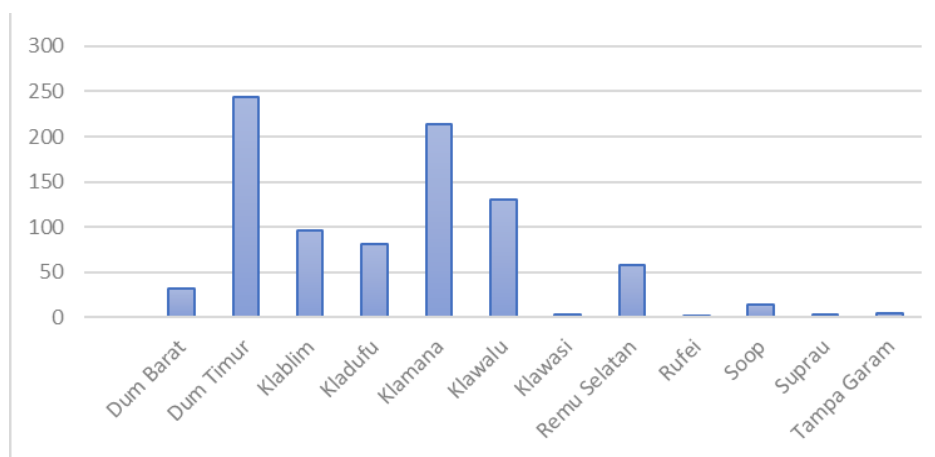
#### 1. **Mangrove area of Sorong city**

The area of mangrove forests in Sorong City in 2025 will be 791.27 hectares (ha). can be seen on the following map:



**Figure 1. Map of Mangrove Forest Ecosystem Distribution in Sorong City in 2025**

The mangrove ecosystem in Sorong City is spread across 12 villages. The distribution of mangrove area per village in Sorong City can be seen in table 1 below:



**Table 1. Distribution of Mangrove Area by Village in Sorong City**

Based on the table above, the distribution of urban mangrove forests in Sorong City shows that East Dum Village has the largest mangrove forest area, which is 243.39 Ha, or around 30.76% of the total Mangrove forest in Sorong city. Followed by: Klamana: 148.44 Ha (18.76%) Klawalu: 128.46 Ha (15.98%) Klabilim: 95.14 Ha (12.02%) Kladufu: 74.68 Ha (9.44%). These five areas account for 86.96% of the total mangrove area in Sorong City. This shows that mangrove forest areas are highly concentrated in these 5 villages.

Rufei Village has the smallest area, only 0.01 Ha while other Villages with a small area: Suprau: 2.53 Ha, Klawasi: 3.70 Ha, Tampa Garam: 3.71 Ha. These four villages have insignificant mangrove forest areas. This condition can show two things: Geographically, the village does not support mangrove growth. Or existing mangroves have been significantly reduced due to land conversion, reclamation, or environmental degradation.

Five villages with large mangrove areas have historical and current land use characteristics that are more conducive to the existence of mangroves. The mangrove areas in these five branches have not been converted massively. In contrast, the very small areas in Rufei, Suprau, Klawasi, and Tampa Garam are very likely the result of intensive land conversion. This area initially developed into the center of Sorong. Urbanization, port infrastructure development, coastal reclamation for housing or industry, and unsustainable agricultural or fisheries practices are the main drivers of land change dynamics that lead to coastal wetland loss (Lambin et al., 2001; Seto et al., 2012). The economic and social appeal of alternative land use is more financially profitable in the short term, which often ignores the ecological value and environmental services of mangroves (Alongi, 2008). These findings are in line with numerous global

studies that show that anthropogenic stress is the main cause of mangrove degradation, especially in densely populated and rapidly developing coastal areas (Giri et al., 2011; Richards & Friess, 2016). From the perspective of Coastal Ecology Theory and Physical Environmental Factors, this disparity in mangrove area can also be influenced by geographical and hydrodynamic suitability. Five villages with large mangroves may have substrate characteristics suitable for mangrove growth, such as nutrient-rich mud deposits, as well as supportive hydrological conditions, including adequate tides and appropriate salinity. In contrast, villages with significantly smaller mangrove areas (Rufei, Suprau, Klawasi, Tampa Garam) may inherently have less supportive physical conditions, such as overly sandy substrates, steep coastal slopes, or exposure to high waves that inhibit germination and growth of mangrove saplings (Duke, 2007)

Critically, a comparison of these findings with the global literature shows a pattern that is common in many tropical coastal regions. Study in Southeast Asia, such as in Vietnam (Nguyen et al., 2018), the Philippines (Primavera et al., 2015), and Indonesia (Badje & Wouthuyzen, 2020), often report mangrove concentrations in certain areas and significant degradation in other areas due to development. However, the uniqueness of the findings in Sorong City lies in the very high concentration scale (86% in 5 villages) and the very small scale of the village in some areas (Rufei 0.01 Ha). Contextual factors such as the history of urban development, specific coastal spatial policies, and the unique geomorphological characteristics of Sorong City can explain these similarities and differences (Bunting et al., 2018). These findings expand the boundaries of knowledge by highlighting how the dynamics of urban development can create highly concentrated distributions of mangroves and very small fragments on a relatively small regional scale.

## 2. Mangrove Cover Dynamics of Sorong City

Mangrove forest cover dynamics data require at least 2 different time periods. The interval to be taken is between 2017 and 2025. The results of monitoring mangrove cover in Sorong City using Sentinel 2A satellite imagery in 2017 can be seen on the following map:

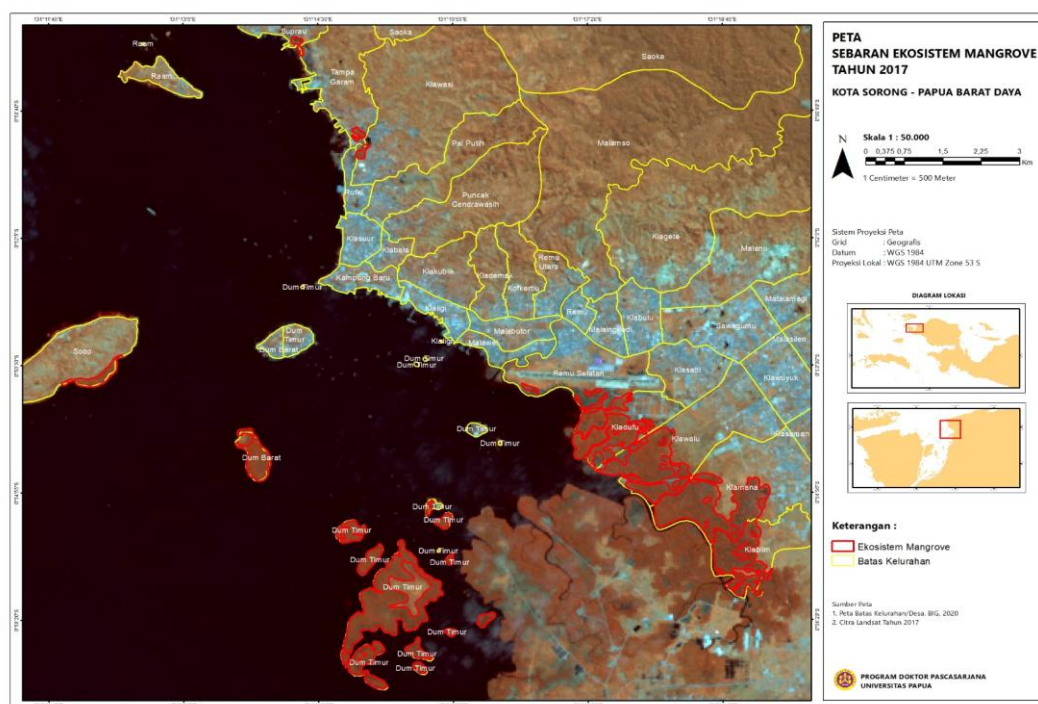


Figure 2. Map of Mangrove Forest Distribution in Sorong City in 2017

The results of monitoring mangrove cover in Sorong City using Sentinel 2A satellite imagery show that in 2017 it was 782.1 ha. Meanwhile, in 2025 there will be a mangrove cover of 791.27 hectares. Mangrove Forest Cover in 2025 will increase by 9.17 Ha from the area in 2017. Although there has been an increase in the overall mangrove cover area, if you look at it based on the totality, there are several villages that have a reduced mangrove area by 2025.

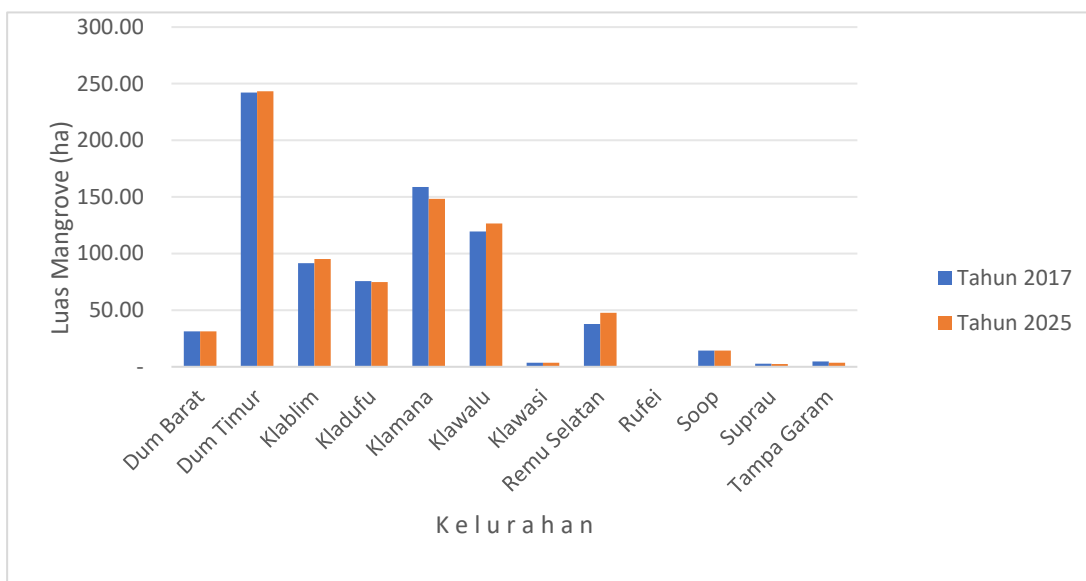


Table 2. Comparison Chart of Mangrove Area in 2017 and 2025 Based on Villages in Sorong City  
 The findings of this study, which indicate an increase in mangrove cover in aggregate in Sorong City from 782.1 hectares in 2017 to 791.27 hectares in 2025, also highlight a specific decline in Klamana Village. Klamana Village is the village that has the largest decrease in mangrove cover. In 2017, Klamana Village had a mangrove area of 158.67 ha, but in 2025 the mangrove area will decrease to 148.4 ha or decrease by 10.23 ha (6.8%).

The increase in overall mangrove cover in Sorong City shows that conservation and restoration are accompanied by changes in environmental conditions that are more conducive to mangrove growth. Apart from the ability to recover on its own, the mangrove ecosystem of Sorong City is also restored with human assistance through mangrove rehabilitation activities. Mangrove ecosystem restoration was carried out by the Peat and Mangrove Restoration Agency (BRGM) in Sorong City in 2021 covering an area of 53 ha. (UNIPA 2021) (UNIPA 2021)

The paradoxical phenomenon in Klamana Village, where significant mangrove deforestation occurs, requires a more in-depth analysis. From the perspective of Sustainable Resource Management Theory, the decline in Klamana can be interpreted as a failure to manage mangrove resources sustainably. The mechanisms underlying this phenomenon can vary, ranging from anthropogenic pressures such as land conversion for coastal development, land acquisition, to fishing practices that damage mangrove habitats, which are often driven by short-term economic needs (Agrawal, 2010). Conversely, the aggregate increase may reflect the successful implementation of conservation and restoration policies in other areas of Sorong City, in line with the principles of Environmental Governance Theory which emphasizes the importance of strong institutional frameworks, stakeholder participation, and law enforcement to ensure ecosystem sustainability (Ostrom, 1990).

Further, we can analyze these findings through the lens of Vulnerability Theory and Ecological Adaptation. The increase in overall mangrove cover may indicate that most of the mangrove ecosystems in Sorong City have an adequate level of resilience or have successfully adapted to environmental changes, including the potential for climate change (Turner et al., 2016). However, the decline in Klamana underscores the specific vulnerabilities that the area may experience. Factors such as increase intensitas badai, kenaikan muka air laut yang ekstrem, or more drastic changes in salinity in the region can trigger mangrove degradation, even if conservation efforts elsewhere are successful (Duke et al., 2007). The underlying mechanism of the decline in Klamana could be a complex interaction between physical environmental pressures and local socio-economic dynamics that have not been effectively addressed.

The implications of these findings on existing theories are significant. These findings reinforce the argument that the effectiveness of mangrove conservation and management efforts is heterogeneous, even within a single administrative area. It challenges the unifying view of successful mangrove management and emphasizes the need for a more decentralized and context-sensitive approach. Regenerative ecosystem theory needs to be enriched with an understanding of how specific factors at the local level can disrupt or accelerate the regeneration process. Similarly, sustainable resource management theory should consider

that failures at a single location can occur despite aggregate successes, highlighting the importance of nested analysis in natural resource management studies (Berkes & Folke, 1998).

These findings are relevant to the global literature on mangrove cover dynamics that show a global downward trend due to anthropogenic pressures (Alongi, 2008). However, this study is also in line with studies that report increases in mangrove cover in some areas, often as a result of intensive restoration programs or policy changes that support conservation (Friess et al., 2019; Giri et al., 2015).

Critically, these findings need to be compared with other studies using similar methodologies in the Southeast Asian region. For example, a study in Vietnam by Tran et al. (2021) showed a decline in mangroves in some coastal areas due to aquaculture expansion, while in others there was an increase thanks to mangrove forest rehabilitation programs. Similarly, a study in Malaysia by Jamil et al. (2020) identified factors such as coastal reclamation and infrastructure development as the main drivers of mangrove deforestation, in contrast to successful conservation efforts in some coastal national parks. A study in Indonesia by Adnyana et al. (2022) on the North coast of Java showed significant mangrove degradation due to urbanization and industry, a pattern that appears to be different from the general trend in Sorong, but may have similarities with specific declines in Klamana.

The contextual factors that explain the similarities and differences between these findings and the existing literature are crucial. The level of economic development, population density, the dominant type of economic activity (agriculture, fisheries, tourism, industry), the effectiveness of spatial planning policies, and the existence and sustainability of conservation or restoration programs, all play a role in shaping the dynamics of mangrove cover (MacKinnon et al., 2019; Valiela et al., 2008). The difference between the aggregate increase and the decrease in Klamana can be explained by the variation in these factors at the sub-district level in Sorong City. Urban villages that experience improvements may have stricter protection policies, higher community participation in mangrove management, or lower development pressures. Instead, Klamana Village may face more intensive development pressures, a lack of law enforcement, or the negative impact of activities in the surrounding area that affect the local mangrove ecosystem.

The uniqueness of these findings in the corpus of literature lies in their ability to demonstrate quantitatively that positive trends in aggregate can hide significant negative patterns at the local level. It highlights the importance of granular spatial analysis in land cover studies, particularly for dynamic ecosystems such as mangroves. These findings expand the boundaries of knowledge by showing that the success of mangrove management programs in general does not automatically mean that all mangrove areas within the study area are safe from degradation. This is driving a paradigm shift from aggregate evaluation to more detailed location-based analysis. Research by Simanova et al. (2024) on mangrove mapping at various scales shows that village-level analysis is crucial.

These findings have theoretical implications that can be refined through conceptual models that integrate spatial heterogeneity in mangrove dynamics. This model can visualize how factors such as development pressures (e.g., urbanization, aquaculture), conservation policies (e.g., protected areas, restoration programs), and local environmental conditions (e.g., sedimentation, salinity) interact across different spatial units (urban areas) to produce different mangrove cover patterns. This model will show that successful management in one unit does not guarantee success in another, and that interventions should be tailored to the specific characteristics of each unit.

The methodological implications for subsequent research are crucial. This study underscores the need for the use of high-resolution remote sensing data combined with multi-scale spatial analysis to identify not only general land cover changes, but also specific shifts at smaller administrative levels. Further research should use more sophisticated classification methods, such as deep learning (e.g., Convolutional Neural Networks - CNNs) that are able to distinguish different types of mangrove cover and detect subtle changes (Li et al., 2023). In addition, the integration of remote sensing data with ground truth data as well as socio-economic and policy data at the village level will provide a more comprehensive understanding of the drivers of change.

This finding requires local governments to review the effectiveness of mangrove management policies at the sub-district level. Identifying Klamana Village as a declining area requires special attention, further investigation into the causes, and the development of targeted intervention strategies. A zoning approach to mangrove management that is more adaptive to local conditions needs to be considered.

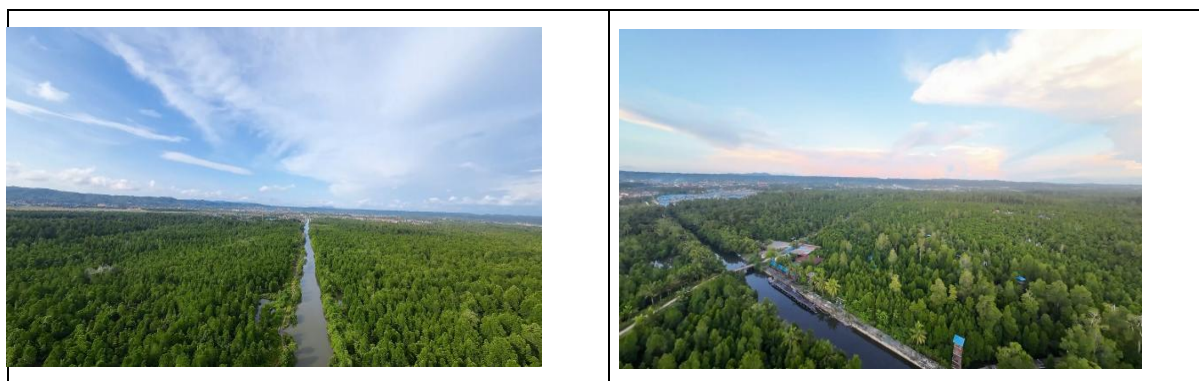


Figure 3. The Expanse of Mangrove Ecosystem in Sorong City

### 3. Mangrove Transition in Sorong City

The Mangrove Forest of Sorong city is undergoing a transition that refers to spatial and temporal changes that occur in the area, density, and physical structure of mangrove forest stands. These changes are the most obvious indicator of the condition of the mangrove ecosystem and how it interacts with environmental factors and human activities. An overview of the transition that occurred in the Mangrove forest of Sorong city is presented on the following map.

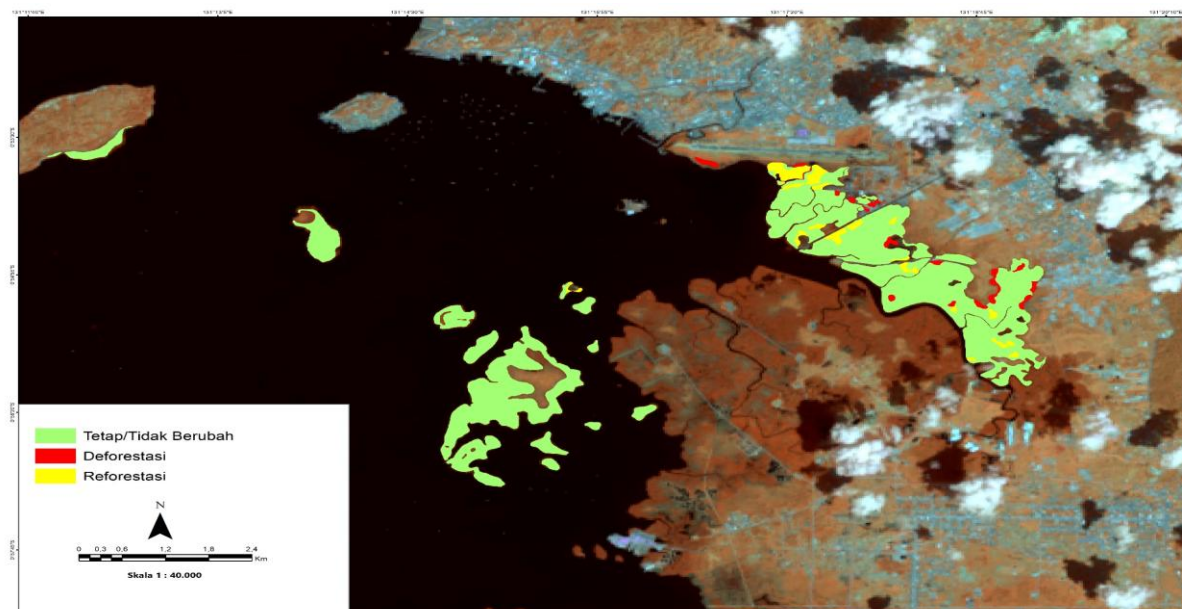


Figure 4. Mangrove Ecosystem Transition Map 2017-2025

The map above shows that areas that experience deforestation occur in mangrove ecosystems that are directly adjacent to urban areas/centers. Disturbances in the form of deforestation are not found in mangrove areas found on small islands on the coast of Sorong city. Furthermore, the extent of deforestation and afforestation that occurs per sub-district is presented in table 3.

Table 3. Deforestation and Reforestation of Mangroves in each Village in Sorong City

Kelurahan	Transisi Mangrove 2017-2025			Grand Total (Ha)
	Deforestasi	Reforestasi	Tidak Berubah	
Dum Barat			31,24	31,24
Dum Timur		1,32	242,07	243,39
Klablim	0,76	4,28	92,38	95,90
Kladufu	3,53	5,37	72,84	74,68
Klamana	64,87	2,49	210,82	148,44
Klawalu	2,09	11,09	117,37	126,45

Klawasi			3,70	3,70
Remu Selatan	5,00	19,83	32,83	47,66
Rufei			0,01	0,01
Soop			14,32	14,32
Suprau			2,53	2,53
Tampa Garam			3,71	3,71
<b>Grand Total</b>	<b>76,25</b>	<b>44,38</b>	<b>823,82</b>	<b>791,27</b>

This table presents data on mangrove cover changes in several villages in Sorong City during the 2017-2025 period. The data were classified based on three categories of change: deforestation (loss of mangrove cover), reforestation (increase in mangrove cover), and unchanged (mangrove cover remained stable).

The total deforestation in all villages during the period was 76.25 ha. Klamana Village experienced the most significant deforestation (64.87 ha), which shows that there is great pressure on the mangrove ecosystem in the area. South Remu Village also experienced significant deforestation (5.00 ha). Kladufu, Klwalu, and Klalim villages are experiencing deforestation on a smaller scale.

Some villages (West Dum, East Dum, Klawasi, Rufei, Soop, Suprau, Tampa Garam) showed no deforestation during this period.

also The total reforestation in all villages during the period was 44.38 ha. South Remu Village showed the most significant reforestation (19.83 ha), Klwalu (11.09 ha), and Kladufu (5.37 ha) showed reforestation. Klamana Village shows relatively small reforestation (2.49 ha), despite experiencing very large deforestation. Some villages do not show reforestation.

Most of the mangrove areas in all villages remained stable (unchanged) during the period (823.82 ha). East Dum Village has the largest unchanged mangrove area (242.07 ha). The total area covered in the data is 944.45 ha.

From the data on deforestation and forestation that occurred per village, a very heterogeneous pattern was revealed. The total deforestation in all villages reached 76.25 hectares, inversely proportional to the total reforestation of 44.38 hectares. Although this reforestation was able to cover most of the mangrove loss, a net deficit of 31.87 hectares still occurred.

The net increase in overall mangrove cover can be interpreted through the lens of Ecosystem Regeneration Theory (Odum, 1971). This increase is most likely facilitated by conservation efforts, successful restoration in some areas, or changes in environmental conditions that are more conducive to mangrove growth. However, the significant deforestation phenomenon in Klamana (-64.87 ha) and South Remu (-5.00 ha) sub-districts demands a more in-depth analysis from the perspective of Sustainable Resource Management Theory. The decline in Klamana, which is the most significant deforestation, can be interpreted as a failure to manage mangrove resources sustainably in the region. The mechanisms underlying this phenomenon can be diverse, including land conversion for coastal development, urbanization, reclamation, or uncontrolled informal economic activities, often driven by short-term economic needs (Agrawal, 2010). On the other hand, the reforestation observed in South Remu (19.83 Ha), Klwalu (11.09 Ha), and Kladufu (5.37 Ha) villages can reflect the successful implementation of conservation policies, effective restoration programs, or active community participation in restoring mangrove ecosystems. This is in line with the principles of Environmental Governance Theory which emphasizes the importance of strong institutional frameworks, stakeholder participation, and law enforcement to ensure ecosystem sustainability (Ostrom, 1990).

Further, we can analyze these findings through the lens of Vulnerability Theory and Ecological Adaptation. The increase in overall mangrove cover, which is largely contributed by the unchanged area (823.82 ha), may indicate that most mangrove ecosystems in Sorong City have adequate levels of resilience or have successfully adapted to environmental changes (Turner et al., 2016). However, the drastic decline in Klamana underscores the specific vulnerabilities experienced by the area, which may be triggered by a combination of more intense environmental physical stresses (e.g., increased intensity of erosion or uncondusive sedimentation) and local socio-economic dynamics that have not been effectively addressed. The natural reforestation observed in some villages, as mentioned in the study by Gandhi et al. (2008) in Bintuni Bay, shows the inherent capacity of mangroves to recover when supporting factors such as substrate conditions, climate, and canopy structure are adequate. However, the relatively small scale of

reforestation in Klamana Village (2.49 Ha) compared to deforestation (-64.87 Ha) confirms that natural regeneration alone is not enough to overcome the high rate of degradation.

The implications of these findings on existing theories are significant. These findings reinforce the argument that the effectiveness of mangrove conservation and management efforts is heterogeneous, even within a single administrative area. It challenges the unifying view of successful mangrove management and emphasizes the need for a more decentralized and context-sensitive approach. Regenerative ecosystem theory needs to be enriched with an understanding of how specific factors at the local level can disrupt or accelerate the regeneration process. Similarly, sustainable resource management theory should consider that failures at a single location can occur despite aggregate successes, highlighting the importance of nested analysis in natural resource management studies (Berkes & Folke, 1998). These data also provide strong empirical evidence to support studies on the resilience of mangrove ecosystems to anthropogenic stresses and environmental changes.

These findings have theoretical implications that can be refined through conceptual models that integrate spatial heterogeneity in mangrove dynamics. This model can visualize how factors such as development pressures (e.g., urbanization, aquaculture), conservation policies (e.g., mangrove area designation, restoration programs), and local environmental conditions (e.g., sedimentation, salinity) interact across different spatial units (urban villages) to produce different mangrove cover patterns. This model will show that successful management in one unit does not guarantee success in another, and that interventions should be tailored to the specific characteristics of each unit.

This once again requires local governments to review the effectiveness of mangrove management policies at the sub-district level. The identification of Klamana Village as an area experiencing massive decline (-64.87 Ha) requires special attention, in-depth investigation of its causes (e.g., land use permits, law enforcement), and the development of targeted intervention strategies, including a moratorium on mangrove land conversion there. A zoning approach to mangrove management that is more adaptive to local conditions needs to be considered.

#### 4.Land Functions of Mangrove Areas

Mangrove ecosystem land cover data will provide an overview of the zoning and distribution of land use in the Sorong City area that intersects with the mangrove ecosystem. The function of mangrove land cover can be seen from the image below.

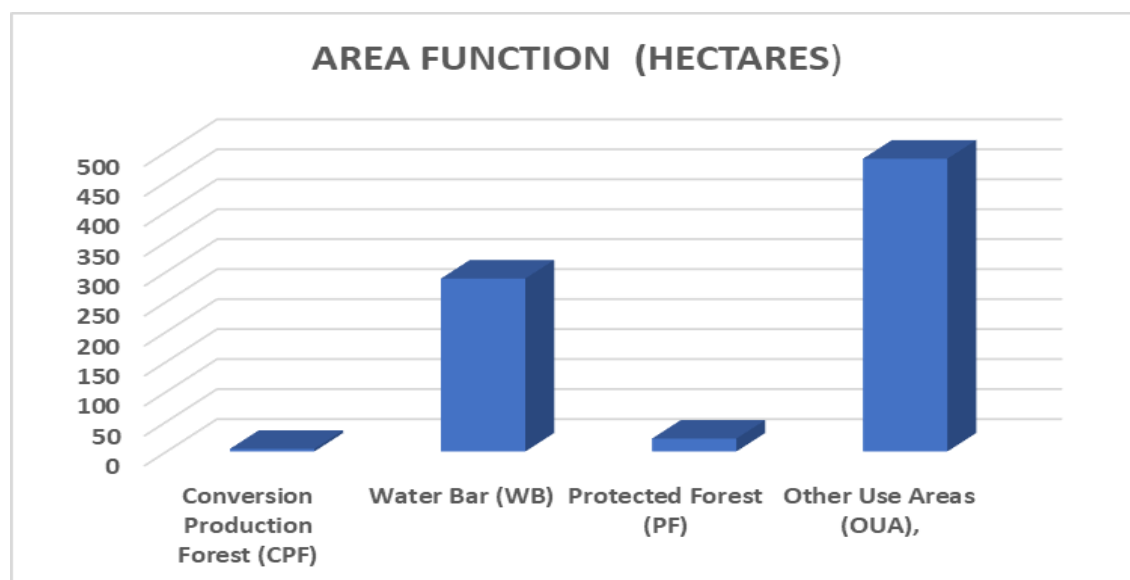


Table 5. Distribution of Mangrove Ecosystems in Area Functions

The mangrove land cover data presented (Total 802.97 Ha) shows that mangrove land covering an area of 488.47 ha is included in the land function as Other Use Areas (OUA), covering around 60.83% of the total mangrove land area.

The dominance of this OUA generally shows the presence of significant anthropogenic pressures on the coastal landscape of Sorong City. OUA often includes residential, industrial, dryland farms, plantations, or commercial areas.

Increasing land needs for OUA can encourage the conversion of mangrove land, both legally and illegally, for the expansion of settlements, industries, or other economic activities. This is a direct threat to mangrove forest cover and health.

In addition, activities that occur in OUA, such as domestic waste from settlements, industrial waste, or agrochemical residues from agriculture, have the potential to pollute coastal waters that are mangrove habitats. This pollution can interfere with mangrove growth, reduce biodiversity, and degrade the quality of ecosystems.

The expansion of OUA can fragment mangrove ecological corridors, isolate mangrove populations and the organisms that live in them, and disrupt genetic flow and movement of animals.

However, OUA can also include synergistic uses: If OUA includes areas managed for mangrove ecotourism, environmental information centers, or sustainable fisheries cultivation that are integrated with mangroves, then their existence could provide indirect benefits to mangrove conservation.

The Protected Forest Area (PF) ranks second largest with an area of 288.54 ha (35.93%). The significant presence of PF in the coastal landscape of Sorong City provides a great opportunity for conservation and mitigation of the negative impacts of OUA (Appelgren et al., 2018). The function of HL as a buffer zone is very important:

**Protection from External Stress:** The dense vegetation in the Protected Forest (PF) can help absorb some pollutants, reduce soil erosion, and limit the expansion of human activities into core mangrove areas.

Protected Forests are the basis for the preservation of the diversity of mangrove species and related biodiversity. Therefore, the effective management of Protected Forest areas must be a top priority. Mangrove management strategies that integrate or collaborate with Protected Forests management can improve overall conservation effectiveness.

**Water bodies (21.53 Ha / 2.68%):** The existence of water bodies (rivers, estuaries, coastal waters) is an integral component of mangrove ecosystems, becoming a tidal medium, nutrient transport, and habitat for aquatic biota (Krauss et al., 2014). Although the area is relatively small in this data, the quality of water in these water bodies is greatly influenced by the surrounding land cover, especially the OUA.

**Conversion Production Forest (CPF) (4.44 Ha / 0.55%):** The very small area of CPF suggests that the potential for mangrove forest land conversion facilitated by CPF status does not appear to be the dominant issue in this analysis. However, the status of Conversion Production Forest inherently has the potential to be converted, so it still requires continuous monitoring and policy evaluation to prevent it from becoming a threat to mangrove land conversion (Suryanto et al., 2020). Implications for Mangrove Sustainability and Management Strategies

The composition of this land cover indicates that the mangrove ecosystem of Sorong City operates in a landscape dominated by human activities but protected by conservation areas. A high proportion of Other Use Areas (OUA) (>60%) is a significant sustainability challenge, as it increases the risk of degradation, fragmentation, and pollution.

In this context, management strategies that refer to SWOT (Strengths-Opportunities) analysis become very relevant. The main strength is the existence of large protected forest areas that can function as buffer zones and conservation areas. Existing opportunities include the potential for community-based ecotourism development and blue carbon utilization, which can provide economic incentives for conservation (Sasmito et al., 2019; Buckley, 2012).

Management strategies should focus on optimizing the function of Protected Forests as an effective buffer zone through access restrictions and strict enforcement of rules.

**Managing the Pressures of the OUA** Through strong law enforcement against the conversion of mangrove land in the OUA, better waste management, and the development of clear zoning that separates economic activities from mangrove ecosystems.

**Developing Synergy** by integrating the development of mangrove ecotourism and the use of blue carbon with the conservation function of PF, as well as ensuring the economic benefits of these activities can support conservation efforts and community empowerment (Mappatoba, 2021) However, a very large proportion (more than 60%) tends to lead to the dominance of non-conservation functions Findings on the dominance of mangroves in cultivation areas, especially OUA and CPF, as well as its susceptibility to functional switching, can be interpreted through a rich theoretical lens.

First, Institutional Theory is very relevant here. Institutions, in the broad sense as defined by Scott (2008), encompass the formal rules (laws, regulations) and informal (norms, culture) that shape human behavior. The determination of the function of forest areas by the state is an example of a formal institution that directly affects land allocation. However, the effectiveness of these formal institutions is highly dependent on law enforcement, supervision, and adaptation to socio-economic dynamics. The presence of mangroves in Other Use Areas, which has by definition been released for cultivation activities, indicates that the existing formal institutions have not been fully able to withstand the pressure for conversion, especially when short-term economic interests are prioritized (Ostrom, 1990). The mechanism underlying this phenomenon is the existence of a "loose coupling" between the determination of forest area zoning and implementation in the field, where interpretation or even abuse of rules can occur.

Second, the Common-Pool Resource Theory, popularized by Elinor Ostrom, also provides important insights. Although mangrove forests are technically managed by the state, their characteristics as a resource accessible to many parties (fishermen, local communities to take firewood or non-timber forest products) make it relevant to be analyzed through this framework. However, in the context of OUA and CPF, the pressure for conversion often comes from actors who have greater economic and political power, such as property developers or industry. Mangrove vulnerability in OUA can be seen as a failure in resource governance mechanisms, where existing rules are not strong enough to prevent overexploitation by certain individuals or groups for personal gain, ultimately undermining ecosystem sustainability (Agrawal, 2005). Third, Environmental Economic Theory, especially the concept of negative externality and the tragedy of common ownership, can explain why mangroves in Other Use Areas (OUA) and HPK are vulnerable. The conversion of mangroves into developed land or agriculture generates direct benefits for landowners, but the environmental costs (loss of coastal protection, degradation of water quality, loss of habitat) are borne by the wider community and the ecosystem itself. These external costs are often not taken into account in conversion decisions, causing a tragedy of shared ownership when natural resources that should be kept together are overexploited for individual benefit (Hardin, 1968). The underlying mechanism is the failure of the market to internalize the ecological value of mangroves and the inability of regulatory mechanisms to fully compensate for such externalities.

The implications of these findings on existing theories are significant. This reinforces the argument that the designation of forest area functions alone is not enough to guarantee conservation, but rather must be followed by effective governance, stakeholder participation, and strong law enforcement, as emphasized in studies on the success of shared resource management (Agrawal & Gibson, 2001). These findings also highlight that economic models that ignore the ecological value and environmental services of ecosystems such as mangroves will continue to drive environmental degradation, in line with criticism of development approaches that are solely oriented towards economic growth (Daly & Farley, 2011).

These findings on the distribution and vulnerability of mangroves need to be contextualized with the extensive current literature. Research by Alongi (2009) and Duke et al. (2014) has consistently shown that mangrove ecosystems globally face significant threats due to human activities, including land conversion for aquaculture, agriculture, and urban development. Case studies in Southeast Asia, such as those reported by Kristensen (2008) in Thailand and Primavera (2000) in the Philippines, are particularly relevant because they show a similar pattern in which coastal mangroves are often converted into shrimp ponds or farmland, eroding their ecological function and coastal protection.

Critically, these findings are in line with research that identified OUA and production areas as critical zones for mangrove loss (e.g., Adame et al., 2018; Friess et al., 2019). Adame et al. (2018) found that more than 50% of global mangrove loss between 1990-2015 occurred due to aquaculture and agriculture, mostly in convertible zones or other uses. Friess et al. (2019) also highlight that although protected forests tend to be safer, areas intended for economic development are often the primary targets for conversion. However, specific findings regarding the proportion of mangroves in Other Use Areas (61.39%) and Conversion Production Forest (4.44%) and Protected Forest (38.62%) in Sorong city offer important nuances. Comparisons with studies in other regions show significant variations. For example, in some regions of Brazil, the proportion of mangroves in protected areas may be higher due to stricter conservation policies (Schaeffer-Novelli et al., 2000). On the other hand, research in Vietnam shows that the conversion of mangroves to aquaculture is very massive in areas that were previously designated as production forests (Nam et al., 2014).

Contextual factors that explain the similarities and differences include: (1) Spatial and Forestry Policy: The level of fragmentation of forest area designation, the flexibility of CPF conversion, and the

effectiveness of OUA zoning vary widely between countries and regions. (2) Local Economic Pressures: Communities' economic dependence on activities that require land conversion, such as large-scale agriculture or coastal development, will increase the risk of mangrove conversion (Blicharska & Mikusiński, 2014). (3) Ecological Characteristics: Coastal land drainage, soil type, and accessibility also influence motivation for conversion (Krauss et al., 2014). (4) Governance and Law Enforcement: The effectiveness of environmental management and law enforcement agencies against zoning violations is a crucial factor (Agrawal, 2005).

The uniqueness of the findings in the corpus of literature lies in the specific quantification of the proportion of mangroves based on the function of the forest area determined in this study area, as well as the identification of OUA as the most vulnerable area. Although the general trend of mangrove loss in cultivated areas has been widely reported, detailed spatial data such as this allow for a more focused analysis of the effectiveness of forest area management regimes in the context of mangrove conservation. These findings expand the boundaries of knowledge in the field by providing strong empirical evidence on how the determination of forest area functions can be a double-edged sword: on the one hand, the determination of PF provides protection, but on the other hand, the presence of mangroves in OUA and CPF underscores high-risk areas that require more intensive conservation attention. This suggests the need for a review of forest area management strategies that are more adaptive and responsive to ecological and socio-economic dynamics in transition zones such as OUA (Hamilton & S for example, 2008).

The findings regarding mangrove vulnerability in OUA and HPK have broad implications, both theoretically, methodologically, practically, and policyly.

**Theoretical Implications:** These findings can be used to refine conceptual models of the interactions between land governance regimes, socio-economic pressures, and mangrove ecosystem resilience. This model can visualize how the determination of forest area functions (as an institutional input) interacts with factors driving conversion of functions (such as market demand, economic policies) and ecological conditions (such as land characteristics) to produce outcomes in the form of vulnerability or mangrove conservation. This model can be developed to integrate the concept of socio-ecological resilience (Walker et al., 2006), emphasizing how mangrove resilience depends not only on biophysical conditions, but also on institutional and social adaptation capacity.

**Methodological Implications:** Further research can expand the understanding by using more sophisticated spatial methods, such as high-resolution remote sensing combined with time-series analysis to dynamically monitor changes in mangrove cover in OUA and CPF. Predictive modeling techniques, such as MaxEnt or Random Forest, can be used to identify the spatial and non-spatial factors that have the most influence on the vulnerability of mangrove conversion functions, allowing for more precise identification of high-risk areas (Guisan & Zimmermann, 2000). Participatory approaches, such as participatory mapping, can also be integrated to validate spatial data and understand local people's perceptions of threats to mangroves.

These findings provide a solid basis for Local Governments/Ministry of Environment and Forestry to revise or strengthen zoning regulations and spatial plans in coastal areas. Focusing on strengthening supervision and law enforcement in OUA and CPF that have mangroves is crucial.

Indigenous and local peoples who live and depend on mangrove ecosystems need to be empowered with information about the vulnerability of mangroves in their territories. Active participation in decision-making forums and conservation programs can enhance a sense of ownership and sustainability of management.

**Strengthening Zoning Policy:** It is necessary to review the determination of the function of forest areas, especially in coastal areas that have mangrove ecosystems. Consider reclassifying some ecologically critical OUA and CPF into conservation areas or strict buffer zones.

## CONCLUSION

1. There is a dynamic in the form of an increase in mangrove cover in aggregate in Sorong City for the period 2017-2025. The mangrove cover area was 782.1 hectares in 2017 to 791.27 hectares in 2025. The increase in overall mangrove cover in Sorong City shows that conservation and restoration are accompanied by changes in environmental conditions that are more conducive to mangrove growth. Apart from the ability to recover on its own, the mangrove ecosystem of Sorong City is also restored with human assistance through mangrove rehabilitation activities

2. From the data on deforestation and forestation that occurred per village, a very heterogeneous pattern was revealed. The total deforestation in all villages reached 76.25 hectares, inversely proportional to the total reforestation of 44.38 hectares. Although this reforestation was able to cover most of the mangrove loss, a net deficit of 31.87 hectares still occurred. The implications of these findings on existing theories are significant. These findings reinforce the argument that the effectiveness of mangrove conservation and management efforts is heterogeneous, even within a single administrative area. This requires the Sorong city government to review the effectiveness of mangrove management policies at the sub-district level.

3. Klamana Village is the village that has experienced the largest reduction in mangrove cover. In 2017, Klamana Village had a mangrove area of 158.6 ha, but in 2025 the mangrove area will be reduced to 148.4 ha or a decrease of 10.23 ha (6.8%). The identification of Klamana Village as an area experiencing massive decline requires special attention, an in-depth investigation into its causes and the development of targeted intervention strategies, including a moratorium on mangrove land conversion there. A zoning approach to mangrove management that is more adaptive to local conditions needs to be considered.

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