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Analysis of changes and criticality level of mangrove forest ecosystem as a basis for rehabilitation downstream of Poso Watershed Area, Central Sulawesi, Indonesia

RENDY AHMAD YANI[1,♥], NAHARUDDIN NAHARUDDIN[2], BAU TOKNOK[2], ADAM MALIK[2], AKHBAR AKHBAR[2], SUDIRMAN DAENG MASSIRI[2], SAMSURIZAL M. SULEMAN[3]

[1]Program of Graduate, Universitas Tadulako. Jl. Soekarno Hatta Km. 9, Palu 94148, Central Sulawesi, Indonesia. Tel.: +62-451-429478, Fax.: +62-451-455961, ♥email: rendyahmadyani80@gmail.com

[2]Program of Forestry, Faculty of Forestry, Universitas Tadulako. Jl. Soekarno Hatta Km. 9, Palu 94148, Central Sulawesi, Indonesia

[3]Program of Biology Education, Faculty of Teacher Training and Education, Universitas Tadulako. Jl. Soekarno Hatta Km. 9, Palu 94148, Central Sulawesi, Indonesia

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Abstract. *Yani RA, Naharuddin N, Toknok B, Malik A, Akhbar A, Massiri SD, Suleman SM. 2024. Analysis of changes and criticality level of mangrove forest ecosystem as a basis for rehabilitation downstream of Poso Watershed Area, Central Sulawesi, Indonesia. Biodiversitas 25: 3179-3188.* Effective mangrove forest management requires accurate data and information on changes and criticality levels within the ecosystem. This research aimed to assess changes and determine the criticality levels of mangroves using the Normalized Difference Vegetation Index (NDVI) as a foundation for sustainable conservation and rehabilitation efforts. Multi-temporal satellite data was utilized to analyze mangrove forest cover changes between 2013 and 2023, while NDVI transformations were applied to evaluate forest vegetation density and criticality levels. The results identified five families and 11 mangrove species in the downstream Poso Watershed, Central Sulawesi, Indonesia. These included *Avicennia marina* (Forssk.) Vierh. from the Avicenniaceae family, *Bruguiera gymnorrhiza* (L.) Lam., *Bruguiera cylindrica* (L.) Blume, *Ceriops tagal* (Perr.) C.B.Rob., *Rhizophora apiculata* Blume, *Rhizophora mucronata* Lam., and *Rhizophora stylosa* Griffith from the Rhizophoraceae family, *Sonneratia alba* Sm. from the Sonneratiaceae family, *Xylocarpus granatum* J.Koenig and *Xylocarpus rumphii* (Kostel.) Mabb. from the Meliaceae family, and *Nypa fruticans* Wurmb from the Arecaceae family. The mangrove canopy density downstream of the Poso Watershed was categorized into dense (55,652 ha), moderate (56,863 ha), and rare (67,578 ha). The *R. stylosa* was the dominant species. The criticality assessment classified the mangrove forest as largely damaged, with a TSV_1 value of 190 on a scale of 167-233. Severely damaged or very critical areas covered 35,836 ha (6.58%), damaged or critical areas encompassed 401,462 ha (73.68%), and 107,546 ha (19.74%) were classified as not damaged or not critical. The ecosystem damage was further assessed through vegetation density, with moderate density recorded at 1,259 trees/ha and rare density at 360 trees/ha. Monitoring these changes and criticality levels is essential for successful rehabilitation and demonstrates a strong commitment to sustainable conservation.

Keywords: Canopy density, Landsat, land use, NDVI, *Rhizophora stylosa*

INTRODUCTION

Mangrove forests play a crucial role in coastal communities, serving as habitats for fish, crustaceans, and algae (Bhagarathi and Da Silva 2024). In addition to their ecological functions, these ecosystems act as carbon dioxide (CO_2) absorbers, reducing atmospheric emissions through sequestration (Kusuma et al. 2023; Lu et al. 2023). Mangrove forests possess excellent carbon storage capabilities, significantly mitigating atmospheric emissions (Alongi and Mukhopadhyay 2015; Barni et al. 2016).

Indonesia, which hosts one of the largest mangrove ecosystems globally, has coastal areas covered by mangrove forests that vary in width, ranging from a few meters to several kilometers from the coastline (Cahyaningsih et al. 2022). The country holds approximately 30,000 km² of mangrove forests, encompassing 45 of the world's 75 mangrove species (Purwanti et al. 2023). However, Indonesia has experienced a notable decline in mangrove forest cover, shrinking from 4.2 million hectares in the 1980s to 3.5 million hectares by 1990, with an average loss of 70,000 hectares per year (Rahman et al. 2024). By 2016, this figure had further declined to 2.9 million hectares, with an annual loss of 37,500 hectares. Goldberg et al. (2020) identified aquaculture land conversion, wood extraction, and the expansion of urban and agricultural areas as primary factors contributing to mangrove forest destruction.

The degradation of mangrove ecosystems is closely linked to anthropogenic activities. Rudianto et al. (2020) and Ferreira et al. (2022) attributed mangrove damage to population pressure, rising economic demands, exploitation of wood products, and the conversion of land into ponds. High economic value, particularly on Indonesia’s larger islands, has driven extensive exploitation of these forests. Between 1980 and 2000, it is estimated that 1 to 1.7 million hectares were lost (Dung et al. 2023). Xu et al. (2024) estimated that pond development accounted for 25% of the loss, while the remaining 75% was due to agricultural conversion, over-exploitation, and coastal abrasion.

Climate change poses additional threats to mangrove ecosystems, contributing to rising sea levels, hydrological variations, temperature changes, and elevated CO_2 concentrations in the atmosphere.

Mangrove ecosystems play strategic roles in land use management, particularly in coastal areas. However, improper land use, especially in downstream watershed areas, has led to critical levels of degradation. Moreover, certain community practices, such as converting mangrove land into ponds, industrial zones, and settlements, exacerbate these challenges (Firdaus et al. 2021). The downstream area of the Poso River Watershed, which hosts 544 hectares of mangrove forests, plays a vital role in protecting the community from coastal abrasion and serves as natural wave breakers. Economically, this mangrove forest is also a valuable tourism and recreation resource.

In this context, mangrove ecosystem management has been approached using various models and methods. One common model involves land conversion for settlement development, which has led to ecosystem degradation and reduced economic, ecological, and physical capacities (Akhbar et al. 2022; Merven et al. 2023). Mangrove ecosystems are increasingly threatened due to anthropogenic pressures, population growth, and the persistent risk of land conversion (Benget and Retnaningrum 2020; Ng and Ong 2022). The economic profitability of shrimp ponds, for instance, often justifies the conversion of mangrove forests (Giri et al. 2022).

To ensure the sustainability of mangrove ecosystems and preserve their environmental and biological functions, it is essential to assess their criticality using spatial technologies (Limbong et al. 2023; Hidayah et al. 2024). A key aspect of forest management is the availability of data on the criticality of mangrove ecosystems. Such data are essential for developing sustainable and environmentally friendly management models for the Poso Watershed. This research aimed to evaluate changes and criticality levels of mangroves using the Normalized Difference Vegetation Index (NDVI) as a foundation for sustainable conservation and rehabilitation efforts.

MATERIALS AND METHODS

Research period and location

The research was conducted in two stages. The first stage, from February to November 2023, involved an inventory survey and identification of the mangrove forest. The second stage, from December 2023 to March 2024, focused on analyzing the criticality level of the land using the Normalized Difference Vegetation Index (NDVI) method. Following this, a ground-check analysis was conducted across all downstream areas of the Poso Watershed, which included secondary mangrove forests, ponds, settlements, mixed gardens, and rice fields.

Administratively, the study area is located in Poso Pesisir Sub-district, Poso District, Central Sulawesi, Indonesia. Geographically, it is situated between 120° 40' 41.151"-120° 38' 47.145" E and 1° 24' 57.954"-1° 22' 6.173" S (Figure 1). The topography of the land is flat, with slopes ranging from 0-8% and elevations between 0-10 meters above sea level. According to Schmidt and Ferguson's climate classification, the study area falls under Climate Type A, determined by calculating the number of dry and wet months. The area experiences an average annual rainfall of 3,284.16 mm/year, with temperatures ranging from 19°C to 34°C. Air humidity averaged between 84% and 88%, with the lowest recorded in July and October 2023 at 84.4%, and the highest in February 2023 at 87.6%.

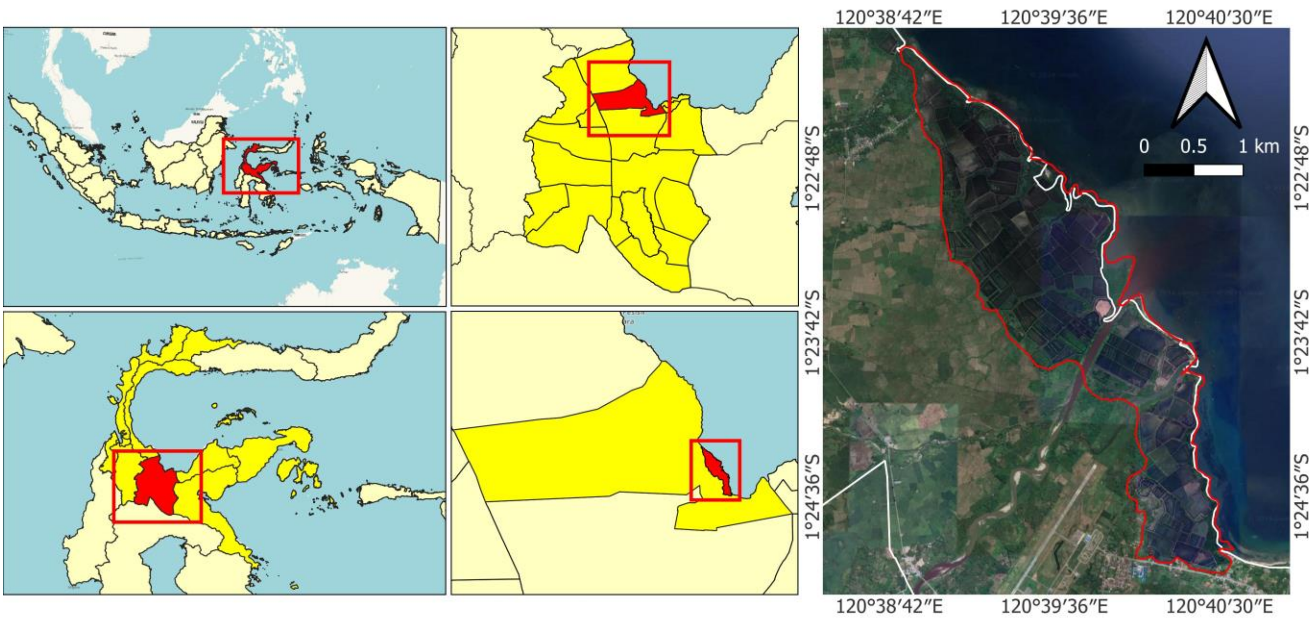


Figure 1. Map of research location in Poso Pesisir Sub-district, Poso District, Central Sulawesi, Indonesia

Data types and sources

The primary data used in this study included Landsat 8 and 9 OLI TIRS images, land cover maps, forest area function maps, soil type maps, land use maps, and field data such as sample plot coordinates and vegetation data. Secondary data were obtained through literature reviews and administrative maps.

Landsat 8 and 9 Onboard Land Imager (OLI) images, with a spatial resolution of 30 meters, were selected as the primary data source to analyze the spatial and temporal dynamics of forest cover in 2013, 2018, and 2023 (Table 1). These images were chosen based on data availability, spectral analysis capabilities, and their ability to capture the distribution characteristics of mangrove forests.

Research stages

Image pre-processing

Pre-processing is a technique used to enhance images by addressing various factors, with the aim of obtaining clearer and more accurate image results that are easier to analyze. When using multi-temporal satellite data, such as Landsat imagery, several issues can arise, including geometric distortions, noise from atmospheric effects, errors due to changes in illumination geometry, and instrument-related inaccuracies (Shahi et al. 2023). The image pre-processing stages typically include data import, format conversion, layer stacking, geometric correction, and image cropping.

Field survey

The survey aimed to gather data and ensure information accuracy by obtaining representative samples from the population. Field survey activities included recording coordinates, observing land cover, and conducting interviews. The location of the field measurement samples was determined based on the results of unsupervised classification and NDVI values. Vegetation potential and mangrove regeneration rates were measured using a sampling intensity of 2%, following the line plot sampling method. Based on the total area of 544.844 hectares, a 10-hectare sample was selected.

The community samples for interviews were targeted in the coastal villages of Bega, Mapane, and Masani in Poso Pesisir District. Respondent samples were chosen using purposive sampling, focusing on village officials and community leaders, with a total of 15 individuals interviewed.

Unsupervised classification

Unsupervised land cover classification was conducted to identify plot locations for field data collection and to validate land cover classes through ground checks. This study applied the k-means clustering algorithm, generating 30 user-defined classes over 5 iterations. The resulting classes were then compared with field survey data and consolidated into three main categories: mangrove forests, water surfaces, and others (which included open land, settlements, mudflats, beaches, and non-mangrove vegetation).

NDVI transformation

NDVI is determined by the absorption of plant chlorophyll at red wavelengths, which is proportional to vegetation density, and by the reflection of Near-Infrared (NIR) radiation (Ginting et al. 2022). Yakushev et al. (2022) explained that NDVI provides data on both high and low vegetation density. The NDVI value is derived from a mathematical equation involving the red band and NIR data from remote sensing. To calculate the density of mangrove forests, the ratio of NIR to the red band is applied using the following formula (Naharuddin 2021):

$$\text{NDVI} = \frac{\text{Near Infra Red} - \text{red}}{\text{Near Infra Red} + \text{red}}$$

The new image produced from the NDVI transformation has a value range between -1 and +1. According to Qiao et al. (2022), the vegetation index for green plants falls between 0.1 and 0.7. The classification of mangrove vegetation density, as outlined by Rhyma et al. (2020), is presented in Table 2.

Ground check

The ground check locations for the land cover classes were based on the results of unsupervised classification analysis. This step was undertaken to establish training areas that represented the appearance of each object in the satellite imagery prior to classification (Zhao et al. 2023). GPS was used for ground checks, and the selection of observation points also considered accessibility. Samples were purposively collected from each representative land cover class. Field data collection employed a combination of the path method and the grid line method, with a transect area of 10 × 10 m². The transect included 10 continuous plots, each 100 meters in length, resulting in a total of 1,000 measurement plots. The plots varied in size according to plant stratification: trees (diameter >10 cm) were sampled on 10 × 10 m² plots, saplings (diameter 2-10 cm) on 5 × 5 m² plots, and seedlings on 2 × 2 m² plots.

Table 1. Remote sensing satellite data

Satellite	Resolution	Path/Row	Acquisition
Landsat 8 OLI TIRS	30 Meter	114 and 61	20 October 2013
Landsat 8 OLI TIRS	30 Meter	114 and 61	08 March 2018
Landsat 9 OLI TIRS	30 Meter	114 and 61	08 October 2023

Source: http://earthexplorer.usgs.gov

Table 2. Mangrove vegetation density class

Class	NDVI value range	Density
1	0-0,32	Rare
2	0,32-0,42	Moderate
3	>0,42-1	Dense

Table 3. Criteria, weights, and scores for assessing the criticality of mangrove ecosystem land using GIS and remote sensing technology

Criteria	Weight value	Description
Land use type (Lut)	45	a. Score 3: Mangrove vegetation (mangrove forest) b. Score 2: Intercropping ponds, Plantations and Mangrove, pond embankments c. Score 1: Intercropping ponds, Plantations and Mangrove, pond embankments
Canopy density (Cd)	35	a. Score 3: Dense canopy density (70-100% or 0.43≤NDVI≤1.00) b. Score 2: Moderate canopy density (50-69% or 0.33≤NDVI≤0.42) c. Score 1: Rare canopy density (<50% or -1.0≤NDVI≤0.32)
Soil resistance to abrasion (Sra)	20	a. Score 3: Soil type is not resistant to erosion (clay texture) b. Score 2: Soil type is resistance to erosion (mixed texture) c. Score 1: Soil type is very resistant to erosion (sand texture)

Image classification

In this study, image classification constituted a fundamental aspect of image vision recognition, aimed at understanding and categorizing entire images under specific labels. Unlike object detection, which involves both the classification and localization of multiple objects within an image, image classification focuses on single-object images. Landsat images from 2013, 2018, and 2023 were classified using the supervised maximum likelihood classifier method. This approach grouped pixels into various classes based on training sample statistics provided by the user, which served as a reference for the classification process.

Data analysis

Analysis of mangrove cover changes

The analysis of changes in mangrove forest land cover was conducted using the GIS method with Arc-GIS software version 10.1, specifically through the overlaying of processed images to identify changes in the observed area. This approach allowed for the assessment of the extent of land cover changes within the mangrove forest ecosystem. At this stage, the identification of mangrove forest cover changes involved directly comparing digital images recorded at different times. The analysis utilized an overlap between land cover classes resulting from guided classifications in 2013, 2018, and 2023. The resulting land cover change information was then presented as a map.

Analysis of mangrove ecosystem land critical level

According to the Guidelines for Inventory and Identification of Critical Mangrove Land, mangrove forests are classified as critical land that cannot support production, protection, or nature conservation functions. This research evaluates mangrove damage resulting from biophysical parameters and remote sensing technology, utilizing primary data obtained from GIS (Geographic Information System) and Landsat satellite imagery. The criteria for assessing critical mangrove land are reported as follows (Rhyma et al. 2020):

Types of land use: Classified into three categories with a weight value of 45. The scoring method is as follows: (i) Score 3: Forest vegetation (mangrove forest); (ii) Score 2: Intercropping ponds, plantations, and mangrove pond embankments; (iii) Score 1: Settlements, industry, non-intercropping ponds, rice fields, vacant land

Canopy density: An important parameter identified based on the range of NDVI (Normalized Difference Vegetation Index) values, with a weight value of 35. The scoring method is: (i) Score 3: Dense canopy (70-100% or $0.43 \leq$ NDVI ≤ 1.00); (ii) Score 2: Moderate canopy (50-69% or $0.33 \leq$ NDVI ≤ 0.42); (iii) Score 1: Sparse canopy (< 50% or $-1.0 \leq$ NDVI ≤ 0.32)

Soil resistance to abrasion or erosion: Obtained from regional maps or other GIS data. Soil is categorized as follows, with a weight value of 20: (i) Score 3: Soil types not resistant to erosion (clay texture); (ii) Score 2: Soil types resistant to erosion (mixed texture); (iii) Score 1: Soil types very resistant to erosion (sand texture)

The criteria for assessment, weights, and scores are summarized in Table 3.

Based on Table 1, the Total Scoring Value (TSV_1) is calculated using the following formula (Naharuddin 2021):

$$TSV_1 = (Lut \times 45) + (Cd \times 35) + (Sra \times 20) \qquad (1)$$

From TSV_1, mangrove ecosystem zoning is determined as follows: (i) Value 100-166: Severely damaged (Very critical), (ii) Value 167-233: Damaged (Critical), (iii) Value 234-300: Not damaged (Not critical)

RESULTS AND DISCUSSION

Normalized Difference Vegetation Index

The NDVI-transformed Landsat 9 OLI imagery categorized four classes: water bodies, non-vegetation, non-mangrove vegetation, and mangrove vegetation. Mangrove and non-mangrove vegetation were distinguished through the visual interpretation of the False Color Composite (FCC) using a 564 band combination. This band combination enhances the appearance of the mangrove ecosystem, with mangrove areas appearing redder to darker, thus facilitating differentiation (Dwiputra and Mustofa 2021). The Near Infrared (NIR) channel in the NDVI transformation was effective in detecting vegetation due to its reflection of NIR more than other wavelengths, attributed to chlorophyll presence (Tran et al. 2022). Consequently, NDVI values for vegetation approach 1, while those for water bodies approach 0. Mangrove vegetation was classified into three density classes: rare, moderate, and dense, as detailed in Table 4.

Table 4. Range of NDVI values in Poso Watershed Downstream, Central Sulawesi, Indonesia

Class	Landsat 9 OLI TIRS year 2023
Water body	-0,1-0.1
Non vegetation	0.1-0.2
Rare mangrove	0.2-0.32
Moderate mangrove	0.32-0.42
Dense mangrove	0.42-0.8

Table 5. Changes in mangrove forest cover density

Year	Mangrove Density (ha)			Non-mangrove (ha)	Total area (ha)
	Rare	Moderate	Dense		
2013	55.543	63.322	167.940	258.039	544.844
2018	57.915	73.249	110.815	302.865	
2023	67.578	56.863	55.652	364.751	

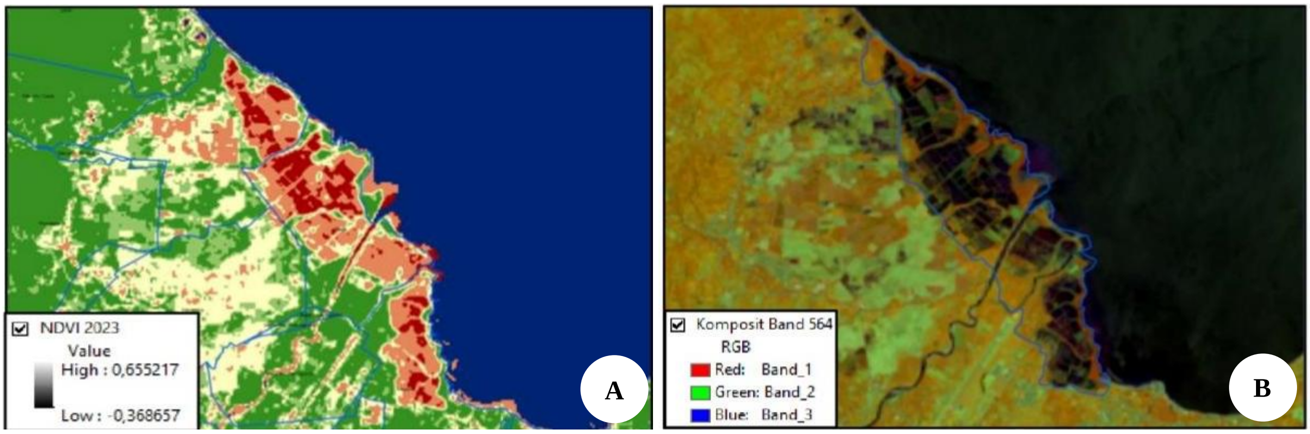


Figure 2. A. NDVI transformation result; B. Landsat 9 OLI composite image 564 (false color)

The NDVI values in Landsat 9 OLI imagery were divided into five classes ranging from -1 to +1, including water bodies and non-vegetation. Mangrove vegetation density was categorized into three classes: rare, moderate, and dense, with density value proportional to the number of individuals per pixel. The classification results allowed for the determination of mangrove vegetation density across different areas (Table 4 and Figure 2). Changes in mangrove vegetation density were analyzed based on the year of satellite image recording. According to Table 8, high-density mangrove vegetation indicated by the highest NDVI value. According to Qiao et al. (2022) the highest NDVI value is determined by the chlorophyll content.. However, the highest NDVI values were typically observed in mature mangroves aged 7 to 10 years (Suyarso and Avianto 2022). However, the highest NDVI values were typically observed in mature mangroves aged 7 to 10 years (Suyarso and Avianto 2022).

Classification of mangrove canopy density

Unsupervised and supervised classification methods were applied to the NDVI transformation. For land cover classification in 2013, 2018, and 2023, three mangrove density classes were identified: rare, moderate, and dense. Areas with rare mangrove vegetation were depicted in yellow, indicating a density index ranging from 0.2 to 0.32. Moderate and dense mangrove densities were represented by light and dark green, corresponding to index values from 0.32 to 0.42 and 0.42 to 0.8, respectively. These color-coded indices reflect increases in vegetation density.

The interpretation of Landsat satellite imagery from 2013, 2018, and 2023 revealed changes in mangrove forest cover density, area, and distribution. In 2013, the dominant mangrove density class covered an area of 167.94 hectares. By 2018 and 2023, this area decreased to 110.815 hectares and 55.652 hectares, respectively, a reduction of 33% (Table 5). This decrease corresponded with a rapid increase in non-mangrove cover, which expanded from 258.039 hectares to 364.751 hectares (70%). In 2015, non-mangrove cover was primarily classified in the very dense category with NDVI values between 0.81 and 1. Masani Village experienced an increase in mangrove density from 2013 to 2023, while Mapane and Bega Villages saw a decrease in density, attributed to land conversion for settlements, fish ponds, and other uses.

High levels of mangrove density in the downstream areas of the Poso Watershed support the aquatic environment and livelihoods of coastal communities. Mangrove vegetation serves as habitat for fish and provides a natural food supply for marine fisheries through the decomposition of organic matter and waste produced by fauna. Denser mangrove vegetation enhances the natural food sources for fisheries, positively impacting the livelihoods of coastal communities dependent on fisheries. Xu and Zhao (2021) emphasized that maintaining the density and area of ecosystems is crucial for providing both tangible and intangible benefits.

The area of rare mangrove vegetation increased by 2,372 hectares from 2013 to 2018 and by 12,035 hectares from 2018 to 2023 (Figure 3). NDVI analysis and direct observations indicate that this increase was primarily due to the presence of young plants and seedlings, which are visible in satellite imagery due to their light absorption and reflection properties. In the moderate density category, the area increased from 63,322 hectares to 73,249 hectares by 2018, an increase of 9,927 hectares. However, from 2018 to 2023, the area decreased by 16,386 hectares. This decline was attributed to a significant reduction in the very dense mangrove category, which decreased from 167,940 hectares in 2013 to 55,652 hectares by 2023, representing a loss of 112,288 hectares over 10 years. Major factors contributing to this degradation include the expansion of ponds and residential areas, as well as the harvesting of mangrove wood for charcoal and firewood.

Changes in mangrove forest cover

Research results indicate that changes in mangrove cover downstream of the Poso Watershed from 2013 to 2023 occurred across all villages due to land clearing and natural damage. Spatial analysis documented these changes in the Poso Watershed Downstream over the decade. Interviews with the Sintuwu Maroso Forest Management Unit (FMU) revealed significant mangrove conversion, with each unit of mangrove land being converted, on average, by 20% for pond creation and residential development.

The decline in mangrove area in the downstream Poso Watershed from 2013 to 2023 was drastic, as illustrated by the graph's trend. Mangrove areas were recorded at 286,805 hectares in 2013, 241,979 hectares in 2018, and 180,093 hectares in 2023 (Table 6 and Figure 4). The changes during the periods from 2018 to 2023 and from 2013 to 2018 were 61,886 hectares and 44,826 hectares, respectively. This reduction in mangrove area is inversely proportional to the significant increase in non-mangrove forest area, which rose from 258,039 hectares in 2013 to 365,751 hectares in 2023, reflecting a substantial conversion over the decade.

The density level of dense mangrove forest was found to decline from 2013 to 2023. This decrease in forest density was attributed to the growing population in the area and the increasing conversion of mangrove forests into pond cultivation areas. Changes in mangrove cover from 2013 to 2023 primarily reflect damage and reduction in mangrove areas, rather than an increase (Figure 5).

The most significant deforestation from 2013 to 2018 occurred in Bega Village, with a loss of 37.5 hectares over five years, while Masani experienced the smallest loss at 1.2 hectares. The rate of mangrove ecosystem damage was assessed through image data analysis by overlaying data from 2013 and 2023. The damage rate was determined based on the difference in cover area between these years (Table 7). The results of this analysis reveal the extent of cover area changes, as detailed in Table 8.

The increasing degradation of the mangrove ecosystem downstream in the Poso Watershed has been attributed to both natural and human factors. The mixed substrate conditions, which are resistant to erosion, impede proper mangrove growth. Additionally, predation by gastropods and crustaceans on propagules hinders tree regeneration (Komiyama et al. 2020), and flooding during the rainy season exacerbates the issue. Human activities, such as exploiting mangroves for various needs without considering sustainability, also contribute significantly to the degradation (Bhagarathi and Da Silva 2024).

Monika and Yadav (2022) identified several human activities contributing to the increasing degradation of mangrove ecosystems in Indonesia, including large-scale encroachment for charcoal production, firewood, building materials, land control for fish farming, settlements, agriculture, mining, and industry. These factors were similarly observed in the downstream Poso Watershed, with the exception of mining and industry. Lubis et al. (2023) noted that forest degradation and deforestation are influenced by factors such as the age of the logged-over forest and proximity to settlement centers, roads, and rivers.

Table 6. Changes in mangrove forest cover

Year	Mangrove (Ha)	Non-mangrove (Ha)	Total area (Ha)
2013	286.805	258.039	544.844
2018	241.979	302.865	
2023	180.093	364.751	

Table 7. Mangrove changes in downstream of Poso Watershed, Central Sulawesi, Indonesia 2013-2023

Village	Mangrove change area (Ha)		
	2013-2018	2018-2023	2013-2023
Bega	-38.531	-37.095	-75.626
Mapane	-6.950	-21.992	-28.942
Masani	-1.575	-8.438	-10.012

Note: -(decrease)

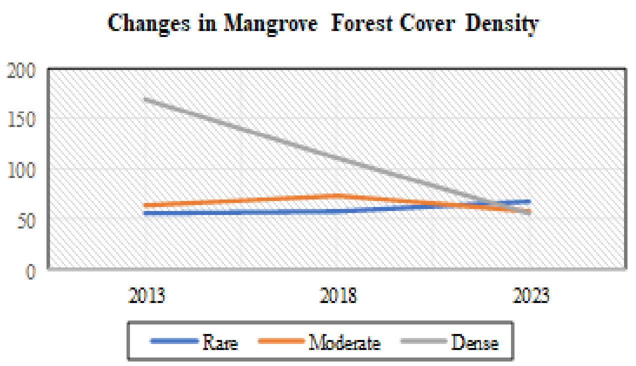
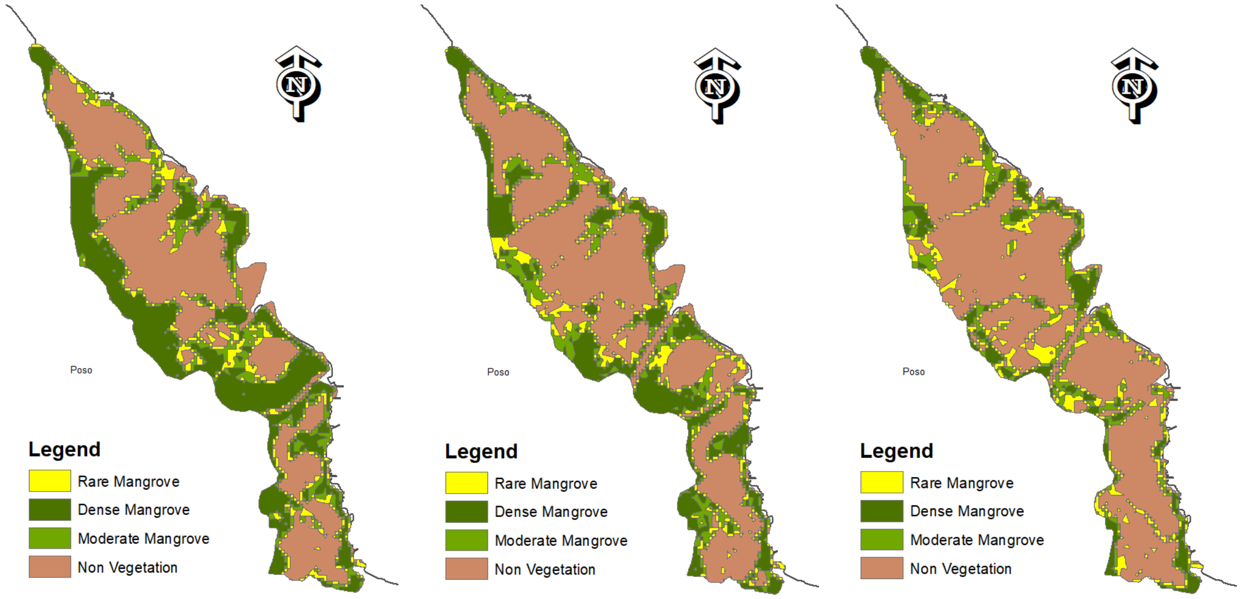


Figure 4. Changes in mangrove forest cover



A **B** **C**

Figure 5. Map of mangrove forest cover density in Poso Watershed Downstream, Indonesia: A. 2013; B. 2018; and C. 2023

Criticality level of mangrove forest ecosystem

Mangrove damage in Bega, Mapane, and Masani Villages, as indicated by the two indicators, was categorized into functional damage. This was due to the conversion of mangrove areas into ponds, as shown by the NDVI results (Figures 6 and 7). Despite this, the overall composition of mangroves was still found to be favorable, with good density, diverse types of mangroves, and a presence of mature trees.

Analysis revealed that the NDVI values of mangrove vegetation were critical. However, the damage observed can serve as a reference for restoring mangrove vegetation, especially considering that sapling density was still classified as good. Effective rehabilitation efforts can aid in the recovery of mangrove ecosystems through natural restoration processes.

Management of the mangrove ecosystem in Bega, Mapane, and Masani Villages in Poso District, Central Sulawesi Province, requires improvement, particularly in areas converted to ponds. The mangrove farmer group in Bega Village has undertaken replanting efforts, which have also provided an additional source of income. While there is significant public awareness of the importance of mangrove ecosystem and coastal environment sustainability, full support from the local government is still lacking. The results obtained from scoring and weighting of parameters related to criticality are summarized in Table 8.

Table 8. The critical level of mangrove forest

Critical level	Total score	Area
Severely damaged/Very critical	100-166	35.836
Damaged/Critical	167-233	401.462
Not damaged/Not critical	234-300	107.546
Total		544.844

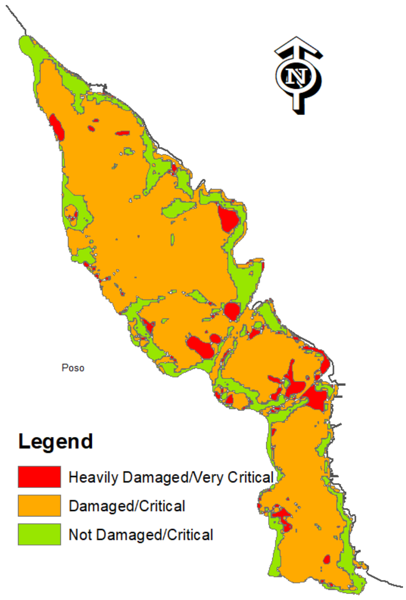


Figure 6. The critical level distribution map of mangrove forest

The criticality level of the mangrove forest was assessed based on three aspects: (i) Type of land use, (ii) Level of canopy density, and (iii) Soil resistance to abrasion.

Type of land use: Various land uses downstream of the Poso Watershed include settlements, non-intercropping ponds, plantations, and vacant land. The expansion of community settlements, driven by population growth, impacts mangrove areas through the development of ports, ponds, rice fields, and other economic activities. The lack of effective policy enforcement on land use contributes to excessive pressure on mangrove forests downstream.

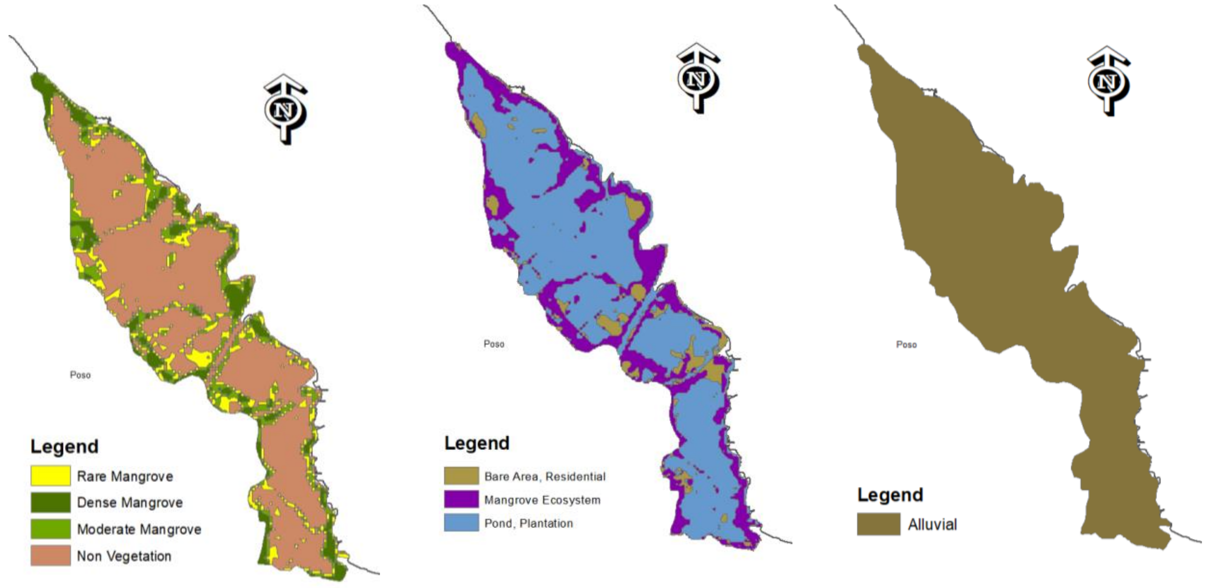


Figure 7. Map of Poso Watershed Area, Central Sulawesi, Indonesia: A. Mangrove forest cover density; B. Land use; C. Soil resistance to erosion

Canopy density level: Canopy density was measured using NDVI analysis. Downstream mangrove areas were categorized as dense on the NDVI scale (0.42-0.8). High-density values indicate optimal photosynthesis and healthy canopy growth, while low-density values suggest poor foliage, thin canopies, or damage from insects, diseases, drought, wind, competition, or soil compaction. Canopy density significantly affects the health and sustainability of the mangrove ecosystem.

Soil resistance to abrasion: Soil resistance to abrasion is influenced by soil type and texture. Predominantly clay soils in the area are not resistant to erosion, and riverbank areas experience severe abrasion due to flooding. The criticality level of the mangrove forest, calculated using the TSV_1 formula, was 190 on a scale of 167-233.

Mangrove canopy density was predominantly classified as dense, with 67,578 hectares, and the highest density level is found in Bega Village, covering 38.39 hectares. Soil resistance to abrasion covered 544,844 hectares (100%) across three villages, with alluvial soil being the dominant type. According to the Decree of the Minister of Agriculture No. 837/Kpts/Um/11/1980, alluvial soil is classified as not resistant to abrasion. The critical level of mangrove forest downstream in the Poso Watershed, was classified as severely damaged, covering 35,836 hectares. Areas classified as damaged and not damaged were 401,462 hectares and 107,546 hectares, respectively.

The criticality level of the mangrove forest downstream of the Poso Watershed was predominantly categorized as damaged. Despite the presence of mangrove forests in severely damaged and undamaged conditions, the area was relatively small. Damage to mangrove forests adversely affected coastal communities, reducing fish stocks and impacting residential areas during strong winds. Rehabilitation efforts were hence essential to mitigate the negative effects of mangrove forest damage.

Community and institutional participation in mangrove forest management is crucial. Mohamed et al. (2023) noted that strict and unilateral management by local governments results in low conservation commitment. Abdullah et al. (2014) and Hasani et al. (2023) found that Community-Based Conservation programs, which focus on participation and involve local institutions, are more effective. Nijamdeen et al. (2022) reported that stakeholder participation in mangrove forest management optimizes roles and prevents coordination issues.

The mangrove forest ecosystem downstream of the Poso Watershed was spread in 544,844 hectares, with 11 mangrove species, including *Avicennia marina* (Forssk.) Vierh., *Bruguiera gymnorrhiza* (L.) Lam., *B. cylindrica* (L.) Blume, *Ceriops tagal* (Perr.) C.B.Rob., *Rhizophora apiculata* Blume, *R. mucronata* Lam., *R. stylosa* Griffith, *Sonneratia alba* Sm., *Xylocarpus granatum* J.Koenig, *X. rumphii* (Kostel.) Mabb., and *Nypa fruticans* Wurmb. Canopy density was categorized into dense, moderate, and rare, covering 55,652 hectares, 56,863 hectares, and 67,578 hectares, respectively. The dominant species in the Lower Poso Watershed was *R. stylosa*. The criticality level assessment, based on land use, canopy density, and soil resistance, showed 35,836 hectares (6.58%) as severely damaged, 401,462 hectares (73.68%) as damaged, and 107,546 hectares (19.74%) as not damaged. The damage level, based on density and vegetation cover, included 1,259 trees per hectare classified as moderate density and 360 trees per hectare classified as sparse density. Analyzing these changes and criticality levels provided valuable quantitative information for sustainable management and conservation planning.

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