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Spatial Dynamics and Ecological Health of Lantebung Mangrove Ecosystem, in Bira Village, Makassar, Indonesia

Dinamika Spasial dan Kesehatan Ekologis Ekosistem Mangrove Lantebung, di Desa Bira, Makassar, Indonesia

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ABSTRACT

The mangrove ecosystem is crucial for coastal protection, carbon sequestration, and biodiversity conservation. Therefore, this research aimed to investigate the spatial dynamics and health of the Lantebung Mangrove Ecosystem in Bira Village, Makassar from 2017 to 2023, using the Mangrove Health Index (MHI) derived from satellite imagery to assess changes in mangrove area, evaluate health using Normalized Burn Ratio (NBR), Green Chlorophyll Index (GCI), Structure Insensitive Pigment Index (SIPI), and Atmospherically Resistant Vegetation Index (ARVI) indices, and identify influencing factors, including urbanization, pollution, and conservation efforts. The analysis used Landsat 8 imagery to calculate MHI values and classify health levels. The results showed an increase in mangrove area from 14.45 ha in 2017 to 18.19 ha in 2023, attributed to effective conservation programs. However, MHI values fluctuated, peaking at 370.32 in 2020 and declining to 148.60 in 2023, indicating persistent environmental pressures. This research underscored the need for integrated management practices to enhance mangrove health and resilience against urbanization, pollution, and climate change. The results underscored the importance of remote sensing for monitoring and guiding conservation strategies in the mangrove ecosystem.

INTISARI

Ekosistem mangrove memiliki peran penting dalam perlindungan pesisir, penyimpanan karbon, dan konservasi keanekaragaman hayati. Studi ini meneliti dinamika spasial dan kesehatan Ekosistem Mangrove Lantebung di Desa Bira, Makassar dari tahun 2017 hingga 2023 dengan menggunakan Indeks Kesehatan Mangrove (Mangrove Health Index - MHI) yang diperoleh dari citra satelit untuk menganalisis perubahan luas mangrove, mengevaluasi kesehatannya menggunakan Normalized Burn Ratio (NBR), Green Chlorophyll Index (GCI), Structure Insensitive Pigment Index (SIPI), dan Atmospherically Resistant Vegetation Index (ARVI), serta mengidentifikasi faktor-faktor yang memengaruhi, seperti urbanisasi, polusi, dan upaya konservasi. Metode yang digunakan melibatkan analisis citra Landsat 8 untuk menghitung nilai MHI dan mengklasifikasikan tingkat kesehatannya. Hasil penelitian menunjukkan peningkatan luas mangrove dari 14,45 ha pada tahun 2017 menjadi 18,19 ha pada tahun 2023, yang dikaitkan dengan keberhasilan program konservasi. Namun, nilai MHI mengalami fluktuasi, mencapai puncak 370,32 pada tahun 2020, tetapi menurun menjadi 148,60 pada tahun 2023, yang menunjukkan adanya tekanan lingkungan yang terus berlanjut. Temuan ini menekankan perlunya praktik pengelolaan terpadu untuk meningkatkan kesehatan dan ketahanan ekosistem mangrove terhadap urbanisasi, polusi, dan perubahan iklim. Studi ini juga menegaskan pentingnya pemanfaatan penginderaan jauh dalam pemantauan dan perumusan strategi konservasi ekosistem mangrove.

Introduction

The mangrove ecosystem is a multifunctional system that offers a variety of resources and essential ecosystem services, contributing significantly to the livelihoods of local communities and the national economy. This ecosystem acts as a buffer against the physical impacts of the ocean, such as waves and tides, while also playing a critical role in the blue carbon cycle by sequestering atmospheric carbon dioxide (Hashim et al. 2022). The ecosystem is also essential in sustaining fishery resources and maintaining the biodiversity of coastal areas. Despite its importance, this ecosystem faces significant threats from reduced area and declining water quality in mangrove waters, which significantly impact the communities that rely on these resources. In Indonesia, the expansion of shrimp farms has been identified as a major threat to the mangrove ecosystem (Richards & Friess 2016).

The Lantebung mangrove ecosystem in Bira Village, Makassar, is one of the remaining mangrove ecosystems in the urban coastal zone of Makassar City and plays an important role in supporting local community activities. This ecosystem provides various ecosystem services for surrounding communities, including coastal protection, fisheries resources, and opportunities for community-based ecotourism development. However, mangroves in urban coastal areas are increasingly threatened by anthropogenic pressures, such as coastal development, waste accumulation, and land-use change, which have been observed to affect the ecological condition of the Lantebung mangrove ecosystem. These pressures may potentially affect mangrove health and reduce the ecosystem services that support local communities, highlighting the importance of continuous monitoring and evaluation of the mangrove ecosystem in this area.

Monitoring of the mangrove ecosystem is needed to provide data and information to support its sustainable management. Remote sensing can be considered a valuable tool for monitoring. It provides an efficient, cost-effective method for assessing large areas over time, offering detailed information on biophysical parameters, including species distribution, structure, and biomass. This technology not only facilitates the mapping and monitoring of

mangrove ecosystems but also enables the detection of changes and the establishment of early warning systems for conservation purposes (Pham et al. 2019).

Recent advancements in remote sensing have significantly enhanced the capacity to monitor and assess the health of the mangrove ecosystem. The Mangrove Health Index (MHI) has been developed as a comprehensive tool to quantify the health of mangrove forests, accounting for factors such as size, distribution, and diversity. By combining remote sensing data and spatial analysis, the MHI provides a systematic approach to monitor changes in mangrove health, guiding conservation efforts and management interventions (Hai et al. 2022). The MHI is instrumental in identifying areas of concern and prioritizing restoration initiatives. By integrating remote sensing with ground-based observations, the MHI enables accurate, timely assessments of mangrove conditions, facilitating the implementation of effective management strategies. This approach not only helps track the success of conservation efforts but also ensures the long-term sustainability of the mangrove ecosystem (Purwanto & Eviliyanto 2021).

Despite significant progress in remote sensing and the development of indices such as MHI, several gaps remain in the current understanding of spatial dynamics and the health of the mangrove ecosystem. Previous research has focused on specific aspects of mangrove health, but there is a need for more comprehensive assessments that integrate ecological, socio-economic, and technological factors (Barbier 2006). Therefore, this research identified and analyzed spatial changes in the Lantebung mangrove ecosystem in Bira Village, Makassar; assessed the mangrove ecosystem's health using the MHI; and explained the factors influencing its spatial dynamics and health. This research included a comprehensive approach, combining remote sensing technology with ground-based observations to understand the factors influencing mangrove health and dynamics. The scope of this research includes evaluating the health of mangrove using the MHI, which is expected to provide in-depth insights into the spatial dynamics and health of the Lantebung mangrove ecosystem. This aims to support more effective management policies and strategies to preserve the mangrove ecosystem.

Methods

Research Location

This research was conducted in the Lantebung Mangrove Ecosystem in Bira Village, Makassar City, Indonesia, as shown in Figure 1. The study site was selected because it represents one of the remaining mangrove ecosystems within the urban coastal zone of Makassar City. The area is located near residential areas and is influenced by various anthropogenic activities, including coastal development and tourism. In addition, the Lantebung mangrove area has been developed as a community-based mangrove ecotourism site, making it an important location to evaluate the spatial dynamics and ecological health of mangrove ecosystems in urban coastal environments.

Tools and Materials

Various tools and materials were used for this research. The analysis used ArcGIS Software for spatial analysis and mapping of mangrove area changes, while the Google Earth Engine (GEE) Platform supported satellite image processing and

vegetation index analysis. The primary data used were Landsat 8 Level 2 satellite images from 2017, 2020, and 2023, which served as the basis for identifying changes in mangrove areas and for conducting the MHI analysis.

Image Collection and Processing

To map the spatial distribution of the Lantebung mangrove ecosystem, the analysis followed several steps using Landsat 8 satellite images from 2017, 2020, and 2023, which had been radiometrically corrected. The images were downloaded from the official United States Geological Survey (USGS) Earth Explorer website and analyzed through the GEE platform (<https://code.earthengine.google.com/>). GEE was a cloud-based platform commonly used for mangrove mapping due to the efficiency in processing large-scale satellite data (Goldberg et al. 2020; Sunkur et al. 2024). GEE detected and monitored changes in mangrove areas, enabling evaluation of mangrove health and dynamics over time (Habibullah et al. 2023). Subsequently, the satellite images were clipped to fit the Area of Interest (AOI), namely the Lantebung

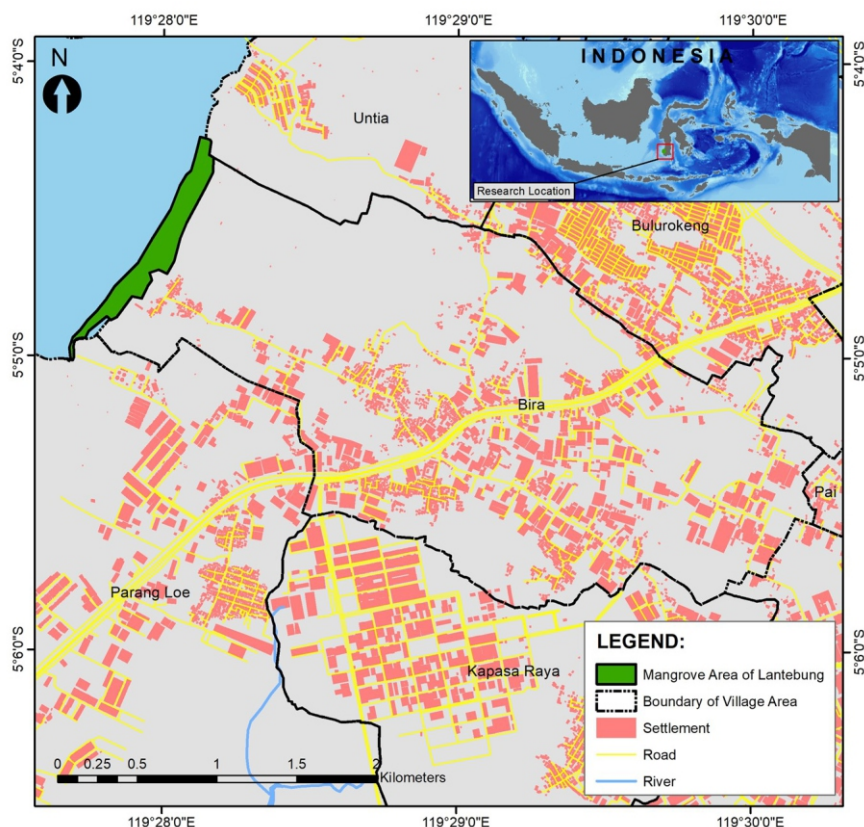


Figure 1. Location of Lantebung Mangrove Ecosystem in Bira Village, Makassar (base map derived from Indonesian Geospatial Information Agency and Landsat imagery; map compiled by the authors)

Mangrove Ecosystem, using ArcGIS software and the GEE platform. The researcher conducted image interpretation and on-screen digitization of Landsat images to identify and map changes in the Lantebung mangrove ecosystem from 2017 to 2023.

Mangrove Health Mapping

Mangrove health mapping was conducted through a series of analytical steps using Landsat 8 Level 2 imagery that had been radiometrically corrected to ensure data accuracy. The process began with transforming satellite imagery using several vegetation indices that represent different physiological and structural conditions of mangrove vegetation. These indices were then integrated to calculate the Mangrove Health Index (MHI), which was used to assess the ecological condition of mangrove stands.

The results of the MHI classification were validated by comparing image analysis with field observations from direct surveys. In addition, statistical analyses were conducted using a confusion matrix, overall accuracy, and kappa coefficient to evaluate the reliability of the classification results. Spatial interpretation was also performed to ensure consistency between the calculated index values and the actual conditions of the mangrove ecosystem.

The MHI was determined based on four vegetation indices representing different aspects of mangrove vegetation condition. The Normalized Burn Ratio (NBR) was used to identify areas experiencing vegetation degradation. This index is calculated using the difference between the Near-Infrared (NIR) and Short-Wave Infrared (SWIR) bands divided by their sum (Hislop et al. 2018).

$$NBR = (NIR - SWIR) / (NIR + SWIR) \dots\dots\dots \text{Equation 1}$$

The Green Chlorophyll Index (GCI) was applied to estimate chlorophyll content in mangrove leaves, which reflects vegetation productivity. The index was calculated as the ratio of the NIR band to the Green band minus one (Schlemmer et al. 2013).

$$GCI = \left(\frac{NIR}{Green} \right) - 1 \dots\dots\dots \text{Equation 2}$$

The Structure Insensitive Pigment Index (SIPI) was used to describe vegetation stress by estimating

the ratio of carotenoids to chlorophyll. This index is calculated from the difference between the NIR and Blue bands divided by the difference between the NIR and Red bands (Gitelson et al. 2007).

$$SIPI = (NIR - Blue) / (NIR - Red) \dots\dots\dots \text{Equation 3}$$

The Atmospherically Resistant Vegetation Index (ARVI) was used to assess mangrove vegetation quality by minimizing the effects of atmospheric disturbances on spectral signals. This index uses the combination of NIR, Red, and Blue bands to reduce atmospheric influence on vegetation reflectance (Budak et al. 2023).

$$ARVI = (NIR - 2 * Red + Blue) / (NIR + 2 * Red + Blue) \dots\dots\dots \text{Equation 4}$$

The Mangrove Health Index (MHI) integrates the four vegetation indices to evaluate mangrove ecosystem quality based on stand structure characteristics such as size, distribution, and coverage (Sugiana et al. 2022). The MHI aimed to determine the health of the mangrove ecosystem by considering various parameters.

$$MHI = 102.12 * NBR - 4.64 * GCI + 178.15 * SIPI + 159.53 * ARVI - 252.29 \dots\dots\dots \text{Equation 5}$$

The calculated MHI values were subsequently used to determine the health status of mangrove ecosystems and to analyze the spatial distribution of mangrove health conditions within the study area.

Data Analysis

This research used a multifaceted approach to understand changes in and the health of mangrove areas from 2017 to 2023. First, this research identified changes in the mangrove area by interpreting Landsat images from 2017, 2020, and 2023. On-screen digitization then mapped the alterations in mangrove coverage over these years. Second, MHI assessed mangrove health by categorizing it into three classes: poor ($MHI < 33.30\%$), moderate ($33.40 < MHI < 66.70\%$), and good ($MHI > 66.80\%$). The MHI values were derived from a combination of vegetation indices, including NBR, GCI, SIPI, and ARVI. Finally, this research evaluated the factors affecting the spatial

dynamics and health of the mangrove ecosystem. This comprised examining various influences, including human activities such as urbanization and pollution, climate change, and conservation efforts. The results were compared with similar previous investigations to provide a comprehensive understanding of the dynamics and health of the mangrove ecosystem.

Result and Discussion

Land Cover Changes of Mangrove Ecosystem

Analysis of Landsat 8 imagery from 2017, 2020, and 2023 revealed significant changes in the mangrove area within the Lantebung Mangrove Ecosystem. On-screen digitization results showed that the mangrove area increased from 14.45 ha in 2017 to 16.16 ha in 2020, and further to 18.19 ha in 2023, as presented in Figure 2. Over six years, the mangrove area expanded by 3.74 ha, with an average annual growth rate of approximately 0.62 ha.

The observed increase in mangrove area is consistent with global trends where targeted rehabilitation and protection programs have led to the

recovery of mangrove forests. Similar research using Landsat imagery had documented the utility of remote sensing in monitoring mangrove cover, canopy height, and biomass changes over time, confirming the effectiveness of the methods for large-scale environmental assessments (Hamilton & Casey 2016). Although the increase in area was promising, it did not necessarily translate into improved mangrove health. This was evident from the decline in the MHI values in certain areas in 2023, suggesting that despite spatial growth, the ecological health of these areas might have been compromised (Fu et al. 2022).

The increase in mangrove area in the Lantebung mangrove ecosystem may be associated with rehabilitation and protection efforts, including community-based mangrove planting activities and local conservation initiatives. These activities can contribute to improving habitat conditions for coastal fauna, protecting against coastal erosion, and enhancing carbon sequestration capacity. These benefits were critical for the sustainability of coastal environments and the well-being of local communities that depend on the ecosystem for livelihoods

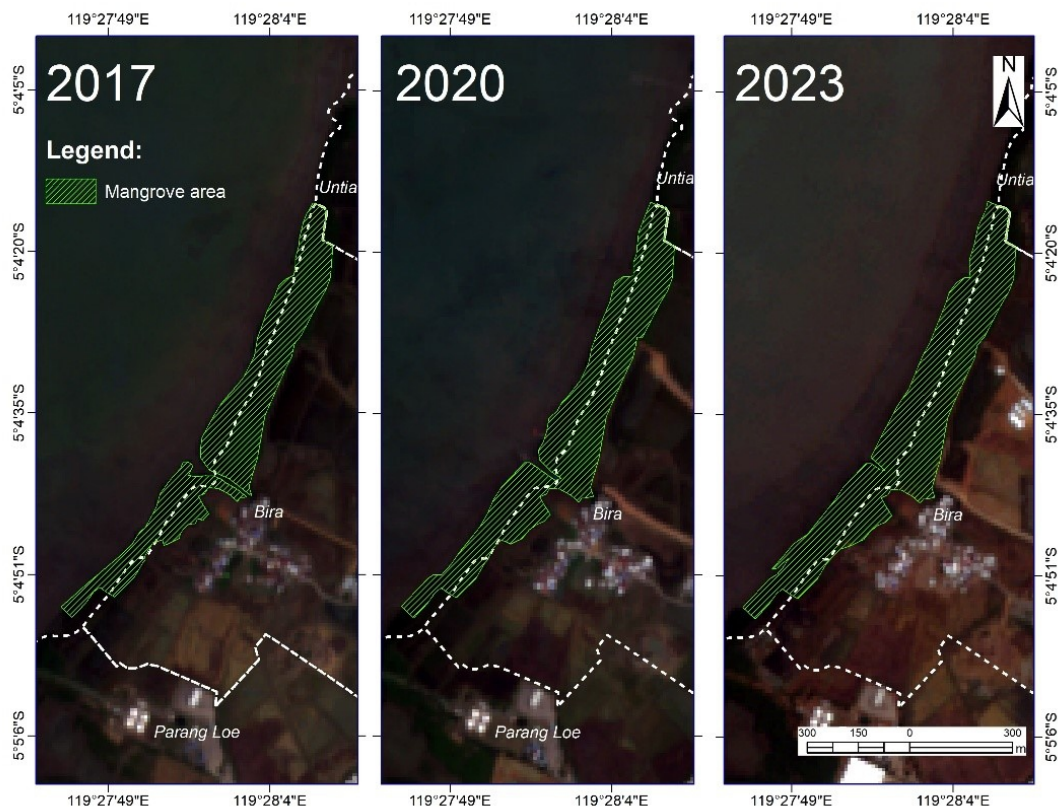


Figure 2. Visualization of true color images of the mangrove area in 2017, 2020, and 2023, and the results of on-screen digitization delineation at Lantebung Mangrove Ecosystem (delineation interpreted by the authors based on Landsat imagery)

(Anwar et al. 2021). However, the decline in MHI values may be associated with pressures such as land-use change related to the expansion of coastal settlements, waste pollution originating from domestic activities, and climate-related disturbances in coastal environments. These pressures necessitate an integrated, sustainable management approach that combines ecological, socio-economic, and policy-governance dimensions. This approach should include an ecological component through ecosystem-based rehabilitation that adapts mangrove species to local environmental conditions, restores natural hydrological systems, and establishes protected areas. A socio-economic component promotes coastal community empowerment, the development of environmentally friendly mangrove-based enterprises, and enhanced education and environmental awareness. The policy and governance component ensures effective regulation, stakeholder collaboration, and the long-term sustainability of the mangrove ecosystem. Continuous monitoring using advanced remote sensing technologies, coupled with community-based management practices, can address the multifaceted challenges faced by mangrove forests, thereby ensuring resilience and ecological function (Dawod & Sharafuddin 2021).

Mangrove Health Status

The MHI evaluated the health of the mangrove ecosystem by combining four vegetation indices, namely NBR, GCI, SIPI, and ARVI, as shown in Figure 3. In 2017, the highest NBR value was 0.449, showing fairly good vegetation condition, while the highest GCI value was 1.931, reflecting moderate chlorophyll content. The highest SIPI value was 2.041, showing moderate pigment condition, and the highest ARVI value was 0.478, reflecting fairly good vegetation quality.

By 2020, the NBR value increased to 0.66, suggesting improved vegetation health. The GCI value increased significantly to 9.35, indicating enhanced plant productivity. The highest SIPI value rose to 3.53, reflecting improved pigment condition, and the ARVI value increased to 0.89, showing higher vegetation quality. However, in 2023, the NBR value decreased to 0.58, which suggests a decline in vegetation condition. The GCI value decreased to 5.85, showing a reduction

in plant productivity. The highest SIPI value was 2.27, which indicates a decrease in vegetation structure, and the ARVI value was 0.75, suggesting lower vegetation quality.

The decline in MHI values in 2023 can be attributed to various interrelated factors, including anthropogenic pressures such as the conversion of coastal land into ponds, settlements, and infrastructure. These factors led to the loss of vegetation and reduced canopy density, coupled with human activities, namely logging, waste disposal, and the accumulation of organic and inorganic waste that disrupted the root system and reduced photosynthetic capacity. Hydrological disturbances and sedimentation due to changes in waterways, embankment construction, alongside unbalanced erosion and sedimentation, reduced soil oxygen supply, and inhibited natural regeneration. Climate change further worsened these pressures through rising temperatures, increased salinity, and altered rainfall patterns, disrupting the freshwater-saltwater balance and suppressing mangrove productivity and chlorophyll content. These conditions were reflected in declines in vegetation index values: NBR decreased due to degradation and loss of biomass; GCI dropped because of a reduction in chlorophyll; SIPI reduced due to disruption of photosynthetic pigments; and ARVI decreased, indicating a reduction in greenness and mangrove vegetation cover.

The observed fluctuations in MHI values are consistent with the results in the literature that emphasize the utility of various vegetation indices for assessing mangrove health. Research has shown that NDVI is commonly used for monitoring mangrove canopy closure, although it may saturate in high-biomass areas. Consequently, NDVI is less effective for detailed mangrove identification (Pastor-Guzman et al. 2018). Indices such as GCI and SIPI offer more sensitive measures of chlorophyll content and vegetation stress, respectively, providing a comprehensive understanding of mangrove health (Oliveira Santos et al. 2024). The integration of NBR, GCI, SIPI, and ARVI provides a robust framework for evaluating the health of the mangrove ecosystem, in line with the methodologies advocated in recent research (Lovelock et al. 2017).

The results underscore the importance of using a

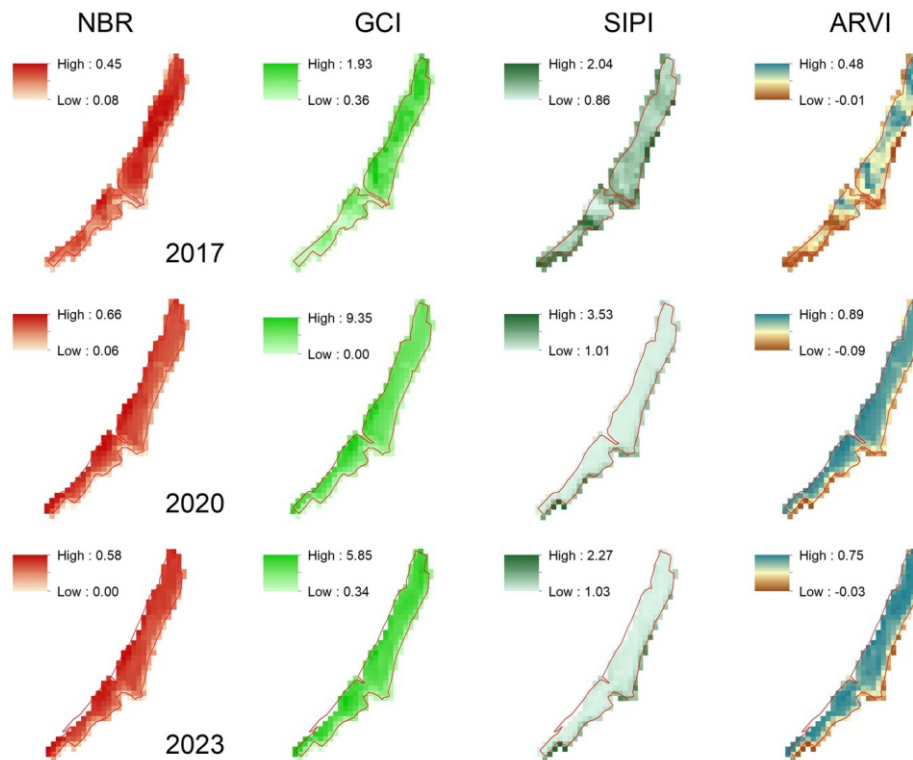


Figure 3. Vegetation indices used for calculating the Mangrove Health Index (MHI) at the Lantebung Mangrove Ecosystem (derived from Landsat imagery and processed by the authors)

combination of vegetation indices to comprehensively assess mangrove health. The increase in NBR, GCI, SIPI, and ARVI values up to 2020 reflects the positive impact of rehabilitation and protection programs at the Lantebung mangrove ecosystem. However, the subsequent decline in these indices by 2023 shows potential stressors affecting mangrove health, underscoring the need for continuous, integrated management efforts. These results emphasize the importance of adaptive management strategies that incorporate regular monitoring using advanced remote sensing technologies to ensure the long-term sustainability of mangrove ecosystem (Hamilton & Casey 2016).

Based on the calculation, which incorporates NBR, GCI, SIPI, and ARVI, the MHI values for the mangrove in Bira Village for the years 2017, 2020, and 2023 are presented in Figure 4. The results show significant ecosystem dynamics, where in 2017 the MHI value ranged from -17.43 to 128.21, then increased markedly in 2020 with a range of 7.26 to 370.32. This reflects ecosystem recovery due to the success of mangrove rehabilitation and planting programs initiated after 2017, improvements in coastal environmental quality through reduced logging and land

conversion activities, as well as stabilization of the natural hydrological system that supports root growth and water circulation. The improvements enhanced chlorophyll content and vegetation productivity, as shown by increases in the GCI and SIPI values.

Despite the increase in mangrove area in 2023, the MHI value actually decreased to a range of 3.87 to 148.61, showing that the expansion in vegetation area was not accompanied by an improvement in ecological quality due to continuing anthropogenic pressures such as waste disposal, coastal development, and fishing activities. These pressures alter soil and water conditions, accompanied by hydrological disturbances in the form of changes in water flow and sedimentation that reduce soil oxygen supply and inhibit natural regeneration. In addition, the impacts of climate change in the form of rising temperatures, increased salinity, and changes in rainfall patterns cause physiological stress on vegetation. Physical rehabilitation efforts also had not fully restored ecosystem functions, resulting in mangrove growth that remained spatially extensive rather than ecologically robust.

The trends observed in the MHI values were

consistent with results in the literature that emphasized the importance of combining various vegetation indices for a comprehensive assessment of mangrove health. Research has shown that the MHI, developed using stand structure dimensions such as size, distribution, and coverage, provided a reliable measure of mangrove forest health. The integration of indices such as NDVI from Landsat imagery is crucial in mapping mangrove areas and monitoring health status over time. The significant increase in MHI values from 2017 to 2020 is consistent with successful rehabilitation efforts documented in similar research (Rahmila et al. 2023). However, the subsequent decline in 2023, despite the spatial expansion, underscores potential underlying issues that require further investigation and sustainable management practices.

The observed decline in MHI values in 2023, despite an increase in mangrove forest area, underscored the complexity of assessing mangrove ecosystem health. These results showed that an increase in vegetation area did not always reflect an

improvement in overall ecological conditions. The decline in MHI was possibly caused by various environmental stress factors, such as changes in hydrology, increased salinity, waste accumulation, and suboptimal management practices, which collectively affect the productivity and physiological balance of mangrove vegetation. Previous literature also emphasized that the evaluation of mangrove health could not rely solely on spatial parameters but also needed to consider structural quality, ecosystem function, and the level of adaptation to environmental pressures.

The results showed the dynamics of the Lantebung mangrove ecosystem, where an increase in the area categorized as “good” from 1.08 ha in 2017 to 11.49 ha in 2020 reflected the success of rehabilitation programs, improvements in the hydrological system, and enhanced vegetation quality (Table 1). However, the decrease in the area categorized as “good” to 11.22 ha in 2023 and the increase in the area categorized as “poor” to 3.46 ha showed that the expansion of

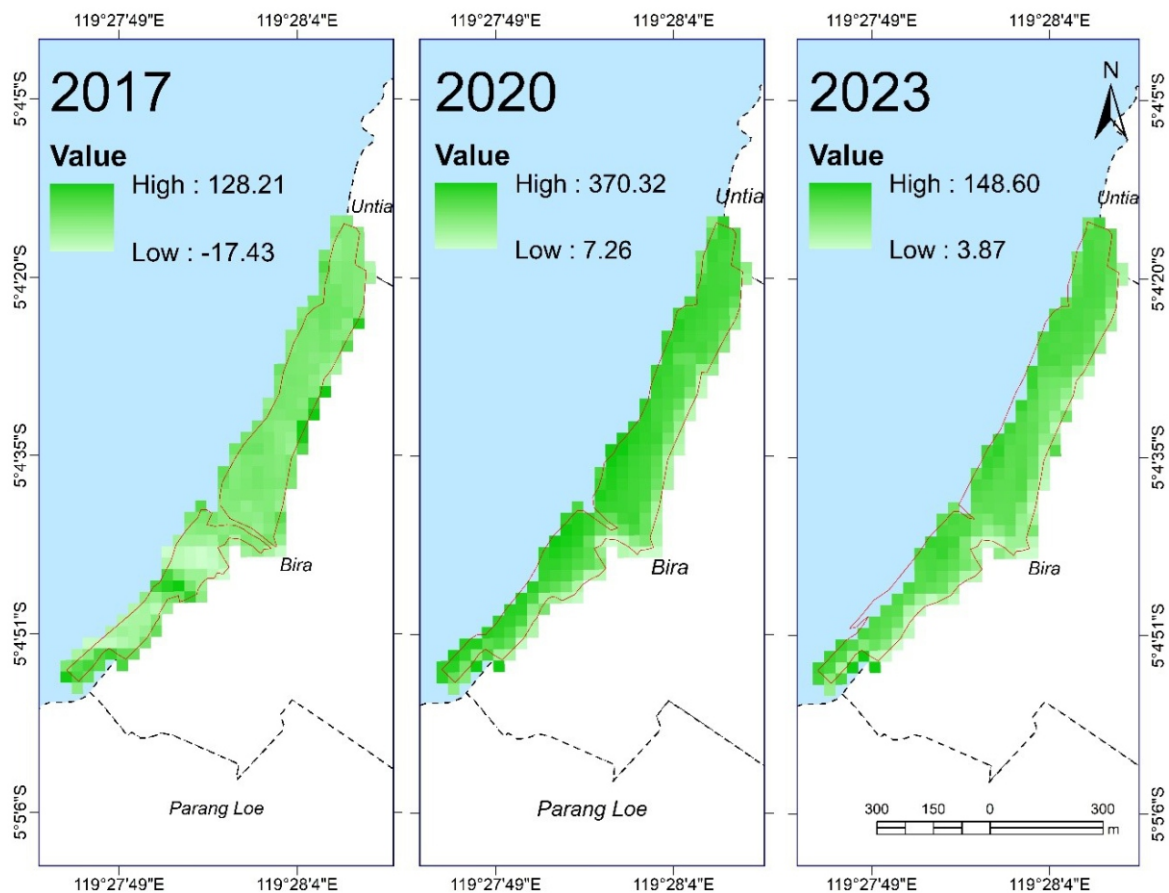


Figure 4. Spatial distribution of Mangrove Health Index (MHI) values at the Lantebung Mangrove Ecosystem (derived from Landsat imagery and processed by the authors)

mangrove area was not always accompanied by an improvement in ecological quality. These differences can be attributed to anthropogenic pressures, hydrological disturbances, the impacts of climate change, and physical rehabilitation efforts that did not fully restore ecosystem functions.

The classification of mangrove health using the MHI provided a comprehensive overview of ecosystem condition (Figure 5), in line with Sugiana et al. (2022), who showed that the MHI was an effective tool for assessing mangrove forest quality based on stand-structure dimensions. The increase in mangrove areas in good health from 2017 to 2020 reflected successful

rehabilitation efforts, consistent with global trends observed in research using vegetation indices for mangrove monitoring (Rahmila et al. 2023). However, by 2023, the subsequent decline in areas with good health, despite an overall increase in mangrove area, suggested ongoing environmental pressures and human activities that impacted the ecosystem.

The results emphasize the critical need for sustained, integrated management strategies to address environmental pressures and human activities that affect mangrove health. The decline in MHI values in some areas in 2023, despite the spatial expansion of mangroves, showed that increasing the area alone is insufficient to ensure ecosystem health. This underscores the importance of comprehensive monitoring and adaptive management practices, not only focused on area expansion but also on improving the overall health and resilience of the mangrove ecosystem (Rahmila et al. 2023). Effective management informed by detailed health assessments using MHI can guide conservation efforts to mitigate

Table 1. Distribution of mangrove classes for each year of analysis at Lantebung Mangrove Ecosystem

MHI Categories	MHI Categories		
	2017	2020	2023
Poor	1.47	1.74	3.46
Moderate	11.91	2.93	3.51
Good	1.08	11.49	11.22
Total	14.45	16.16	18.19

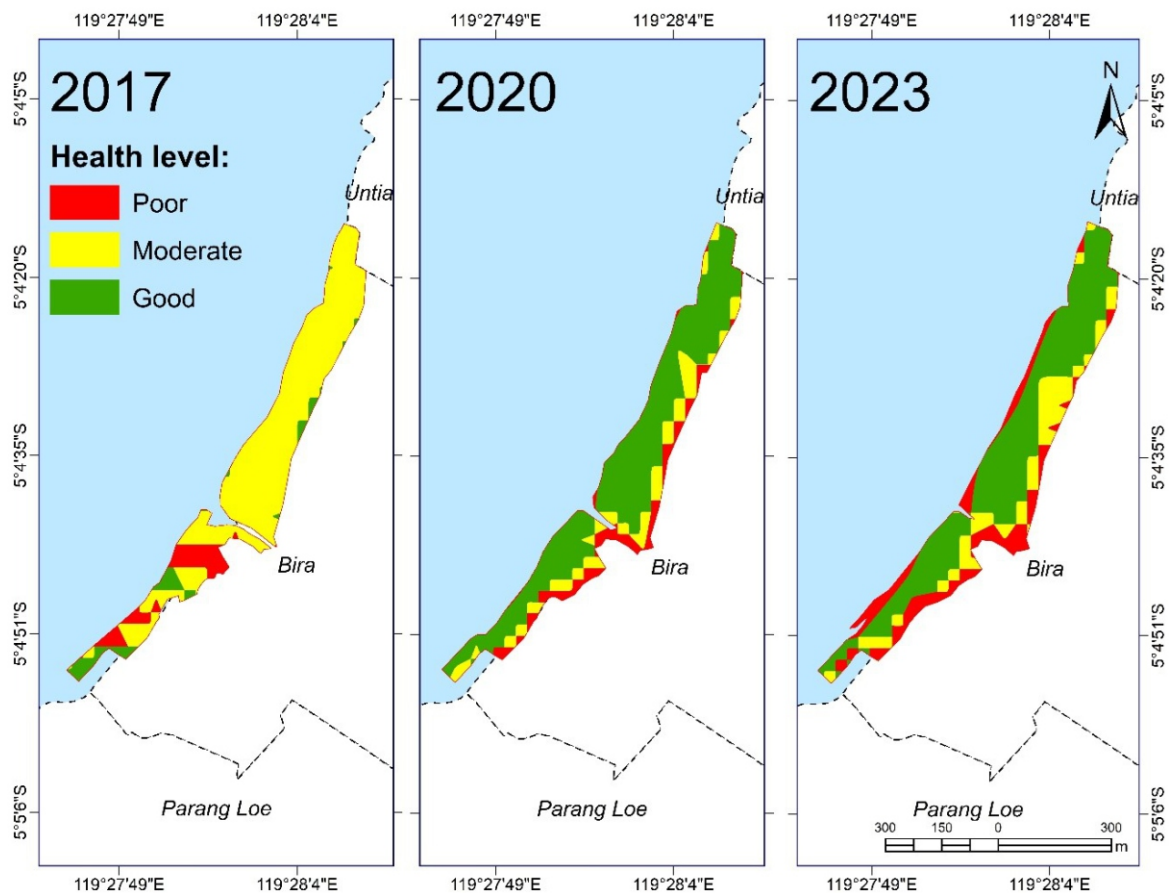


Figure 5. Spatial distribution of mangrove health classification based on the Mangrove Health Index (MHI) at the Lantebung Mangrove Ecosystem (processed by the authors)

environmental pressures and enhance the sustainability of the mangrove ecosystem, thereby preserving ecological functions and benefits for local communities (Sugiana et al. 2022).

Factors Influencing the Spatial Dynamics and Health of Mangrove

Factors influencing the spatial dynamics and health of the mangroves at the Lantebung Mangrove Ecosystem included human activities, particularly urban expansion, waste accumulation along the coastal zone, and pressures related to tourism and settlement development, as well as conservation interventions. Field observations indicated that increasing human activities around the mangrove area, such as land conversion, infrastructure development, and the disposal of domestic waste, contributed to environmental pressures that negatively affected mangrove health. Conversely, conservation initiatives, including community-based mangrove planting, coastal rehabilitation programs, and the establishment of conservation zones, supported the expansion of mangrove cover and helped improve ecosystem conditions. Climate-related factors, such as increasing storm intensity and gradual sea-level rise, also contributed to the dynamics of the mangrove ecosystem.

The impact of urbanization on mangrove health has been well-documented in the literature. Goldberg et al. (2020) mentioned that human activities, including the conversion of mangrove forests to aquaculture and agriculture, led to habitat degradation and fragmentation. Similarly, Conopio et al. (2021) emphasized that land conversion for industrialization and urbanization is a major driver of mangrove loss. These results are consistent with the observed decline in mangrove health in urbanized areas of the Lantebung mangrove ecosystem. On the other hand, conservation efforts had a significant positive impact on mangrove health. Reforestation and protected area management have been effective in enhancing mangrove cover and improving ecosystem health, as reported by (Wong et al. 2021) and Samanta et al. (2021). Natural factors, such as sedimentation and storms, reduced MHI values by directly and indirectly disrupting the ecological balance of the mangrove ecosystem. Excessive sedimentation limits

oxygen diffusion through pneumatophores, altering soil salinity and texture, and inhibiting root growth and natural regeneration. Storms and strong waves cause physical damage, including branch breakage, leaf loss, and root zone erosion. Consequently, these factors reduce canopy density and spectral reflectance in healthy vegetation (particularly in the NIR band), ultimately leading to lower vegetation index values (NBR, GCI, SIPI, and ARVI) and a decline in the physiological and structural health of mangroves, even without a significant reduction in spatial extent.

This research underscores the critical need for focused conservation efforts to mitigate the negative impacts of human activities and environmental changes on the mangrove ecosystem. The influence of urbanization, pollution, and climate change emphasized the complexity of managing mangrove health. Effective conservation strategies must integrate adaptive management practices that address both human-induced and natural stressors. This includes enhancing reforestation programs, implementing stricter pollution controls, and developing climate adaptation measures to bolster the mangrove ecosystem's resilience. Ensuring the sustainability of the Lantebung Mangrove Ecosystem requires a multifaceted approach that combines scientific monitoring, community engagement, and policy support to protect and restore these vital coastal habitats.

Conclusion

This research shows the significant spatial dynamics and health variations of the Lantebung Mangrove Ecosystem from 2017 to 2023. The results showed a significant increase in mangrove area from 14.45 ha in 2017 to 18.19 ha in 2023, indicating the success of conservation and reforestation efforts. However, despite this spatial growth, MHI showed fluctuations, with a peak in 2020 (the highest MHI value of 370.32) followed by a decline in 2023 (the highest MHI value of 148.604). This underscores the ongoing environmental pressures and human activities that impact mangrove health, including urbanization, pollution, and climate change. Although conservation interventions were effective in expanding mangrove cover, sustainable management

practices must be enhanced to address the multifaceted challenges facing the mangrove ecosystem. The integration of remote sensing technology and comprehensive health assessments using indices such as the MHI is essential for guiding effective conservation strategies and ensuring the long-term resilience and sustainability of mangrove forests.

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