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Article

Temporal Assessment of Seagrass Degradation on Singkep and Lingga Islands, Riau Islands Province, Indonesia (2016-2020)

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Abstract: Seagrass plays a crucial role in coastal ecosystems, necessitating its preservation to maintain ecosystem health. This study addresses the degradation of seagrass meadows in the coastal regions of the Riau Islands, Indonesia, utilizing remote sensing techniques and spatial data analysis. Satellite imagery offers a cost-effective means of monitoring seagrass health in shallow coastal waters. In October 2020, the research team conducted the study at six stations—four on Lingga Island and two on Singkep Island. Utilized Sentinel-2 satellite imagery from 2019 and applied the Depth Invariant Index (DII) along with Support Vector Machine (SVM) classification. In-situ observations, conducted simultaneously, validated the satellite data and facilitated seagrass accuracy assessment, including species identification using the Seagrass-Watch (Transect Quadrant) methodology. The results reveal significant seagrass degradation in the Riau Islands. The DII method detected extensive seagrass losses, covering approximately 175 km^2 of seagrass meadows across Lingga and Singkep Islands. Species identification confirmed the presence of *Halophila ovalis*, *Halophila minor*, *Thalassia hemprichii*, and identified *Enhalus acoroides* as the dominant species. This research gives important insights into the temporal degradation of seagrass environments along the coastal regions of the Riau Islands, highlighting the importance of continued monitoring and preservation efforts.

Keywords: degradations; remote sensing; Riau Islands, seagrass, sentinel-2

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1. Introduction

Seagrasses, submerged angiosperms thriving in marine environments, serve crucial roles in shallow waters worldwide (Pranowo *et al*., 2019). They function as primary producers and provide critical ecosystem services such as spawning and feeding grounds, carbon sequestration, sediment stabilization, and nutrient cycling (Hemminga & Duarte, 2000). Additionally, seagrass meadows support endangered species such as dugongs (*Dugong dugon)* and sea turtles (*Chelonia mydas, Eretmochelys imbricata*) (Mateo *et al*., 1997). Despite their ecological importance, seagrass meadows covering approximately 30,000 km^2 across the Indonesian Archipelago remain relatively understudied (Kuriandewa, 2009). These dynamic ecosystems experience rapid changes, including shifts in biomass, distribution, species composition, growth, and associated flora and fauna (McKenzie, 2003). Effective monitoring of seagrass ecosystems requires a combination of techniques, including both field-based and remote sensing approaches. (Mederos-Barrera *et al*., 2022; Traganos *et al*., 2022). Satellite imagery is useful for efficiently gauging the conditions of water in shallow waters. (Congalton & Green, 2010). The Depth Invariant Index method, correcting for water column interference in satellite images, has been widely employed for seagrass mapping (Manuputty *et al*., 2015). While numerous studies have focused on improving the mapping accuracy of seagrass habitats (Dekker *et al*., 2011; Mumby, Green, *et al*., 1997), relatively few have addressed the temporal and spatial patterns of seagrass degradation, particularly in tropical regions like Indonesia, where anthropogenic pressures and environmental change threaten their persistence (Fortes *et al*., 2018; Waycott *et al*., 2009). This study shifts the focus toward evaluating seagrass degradation in Lingga and Singkep Islands. It employs the DII method with SVM classification, integrating seagrass coverage and species identification field data (Tamondong *et al*., 2013). By addressing the critical issue of seagrass degradation in these coastal ecosystems, this research contributes to our understanding of seagrass health and resilience (McKenzie *et al*., 2022). This study’s objective is to calculate the extent of seagrass degradation in the coastal of Singkep and Lingga Islands by utilizing the Sentinel-2 satellite imagery. Furthermore the outcomes of this study aim to reveal temporal and spatial changes in seagrass coverage and species identification that affected the seagrass region (Chen & Zhao, 2022).

2. Materials and Methods

This study was conducted on Lingga and Singkep Islands, located in the Riau Islands Province of Indonesia (Figure 1). The methodology integrated Sentinel-2 satellite imagery with field-based seagrass observations. The Sentinel-2 data from 2016 to 2020 underwent processing, with in-situ observation took six stations with stations A, B, and C on Singkep Island and stations E and F on Lingga Island. These locations were chosen to represent the seagrass areas in the research sites (Gunawan *et al*., n.d.). The selection of six sampling locations was based on their ecological significance, seagrass presence and representation of diverse coastal conditions between Singkep and Lingga Islands. The selection of sampling locations was also considered based on accessibility for in-situ validation.

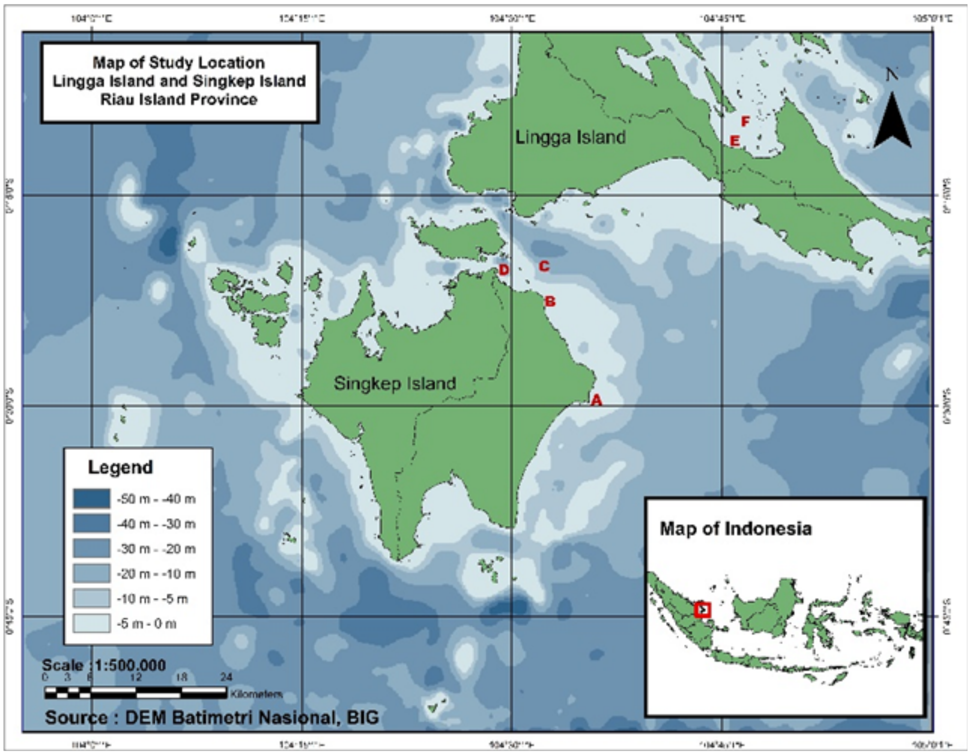

Figure 1. Map of the study location, on Singkep Island and Lingga Island

The methods used in this study are categorized into satellite image processing and in-situ observation (Roca *et al*., 2025). Satellite image processing was conducted using QGIS, an open-source GIS software (Carpenter *et al*., 2022). It was employed for atmospheric correction, Depth Invariant Index (DII) calculation, classification, and spatial analysis (Simpson *et al*., 2024). The classification applied in this study achieved an overall accuracy (OA) of 68.5% (Thomasberger *et al*., 2023). For in-situ observation, several tools were used: a Global Positioning System (GPS) for coordinate measurements, quadrant transects following the Seagrass-Watch protocol, roll meter, species identification checklist, stationary tools, underwater cameras, and snorkels.

2.1. Image Processing Data

Sentinel-2 imagery used in this study due to its high spatial resolution, frequent revisit time, and multispectral capabilities, making it well-suited for monitoring shallow coastal environments like seagrass meadows (Nur *et al*., 2021). Compared to other satellite images, Sentinel-2 provides free and accessible data with up to 10 m resolution, allowing for detailed seagrass mapping and temporal analysis image processing data is performed within several steps, such as geometric correction, radiometric conversion and atmospheric correction, image segmentation, and image enhancement (Elma *et al.*, 2024). Geometric correction is the process of adjusting the position of a satellite image according to the position of the earth's surface. The Sentinel-2 geometric corrections were performed using the rational polynomial coefficient (RPC) model. Atmospheric correction was applied to remove scattering and absorption effects, thereby retrieving accurate surface reflectance values. Radiometric adjustments were made to normalize pixel brightness values and reduce inconsistencies caused by sensor characteristics and illumination differences. Image enhancement used to improve the gray level from an image. The DII was calculated based on the equation formulated, which adjusts reflectance ratios between spectral bands to account for depth-related attenuation (Lyzenga, 1978).

$$\text{Depth-invariant index}_{ij} = \ln(L_i) - \left[\left(\frac{Ki}{Kj}\right)\ln(L_{ij})\right] \tag{1}$$

$$\frac{K_i}{K_j} = a + \sqrt{(a^2+1)}\ dan\ a = \frac{\sigma_{ii} - \sigma_{jj}}{2\sigma_{ij}} \tag{2}$$

where, Li and Lj = reflectance value of the band-I and band-j. Ki/Kj = ratio coefficient attenuation of the band-i and j. σii = Variance of the band i, σjj = Variance of the band j and σij ij = Covariance of the band.

2.2. In-Situ Observation (Ground Truth)

Monitoring is observation of an ecosystem, usually to cope with changes. This activity is carried out to manage and protect resources in the system (L. McKenzie *et al*., 2003). Monitoring of seagrass meadows is repeated over and over in benthic ecosystems in a particular area, which observes the status and condition of the seagrass meadows, whether its stable, increasing, or decreasing (Arselan *et al*., 2025). Seagrass monitoring could be done using various methods such as Seagrass-Watch. Data were collected on three transects with a length of 100 m each, and the distance between one transect and the other was 50 m. In addition to calculating the area of cover with the transect quadrant, species identification for each transect station was also carried out (Mumby, Green, *et al*., 1997).

2.3. Seagrass Loss Quantification

The assessment of seagrass degradation was conducted using pixel-based calculations within ArcGIS software. Specifically, the Pixel Calculate Statistics (Data Management) tool was employed to generate a table containing pixel counts for each seagrass class in various slices of an input categorical raster. Degradation assessment was based upon covers and health changing classes of seagrasses, the pixel counts analyzed for each class within the raster for quantification of seagrass meadow changes over time. This method enables identifying areas being degraded by either natural or anthropogenic processes or other factors. The output from this analysis provides valuable information for understanding the status and trends of seagrass ecosystems in the study area. Combining these pixel-based calculations with the other methods mentioned earlier, we aimed to create a comprehensive assessment of seagrass meadows, integrating both remote sensing data and in-situ observations.

3. Results

3.1. Coverage

Sentinel image processing results to show for the west monsoon season (Figure 2) in February 2019. The image in February was chosen to represent 2019, because it is the data with the cleanest cloud cover among other months, so the satellite can take images without any cloud cover. The classification using the Depth Invariant Index (DII) and Support Vector Machine (SVM) algorithm successfully distinguished seagrass from other benthic classes, including coral, sand, sediment, clouds, and mangroves

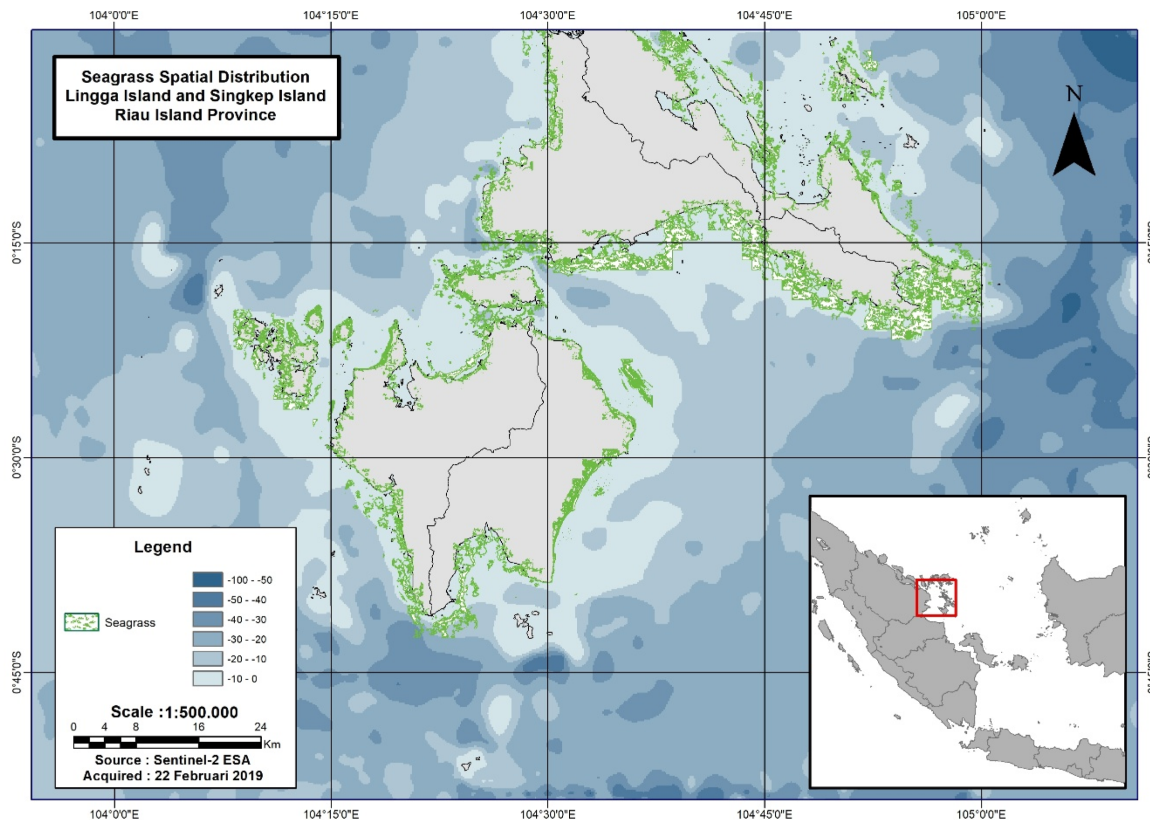

Figure 2. Seagrass ecosystem map at February 2019

Based on the seagrass distribution map above, with a DII method and SVM classification image in February 2019 (Figure 2) which represents the west monsoon season, has a seagrass spatial distribution area of 173 km^2. With the distribution of seagrass on the Singkep Island spread in the northeast and southwest. Meanwhile, the distribution of seagrass in Lingga Island lies in the northeast and south of the island. Spatial analysis revealed that seagrass coverage on Singkep Island was approximately 68 km^2, on Lingga Island 81 km^2, and surrounding small islands 24 km^2, with Lingga Island having the largest seagrass extent.

Table 1. Spatial area distribution of seagrass beds in Singkep and Lingga Island

	Singkep Island	Lingga Island	Surrounding Islands	Total Area
Spatial Area (km^2)	68	81	24	173

In-situ observations with the distribution of seagrass beds in Singkep Island represented by stations A, B, C, and D. with a maximum coverage area of 88.4% found at station C, which is in Kote village and it has very good seagrass conditions, while the minimum coverage area with 45.7% found at station A with quite good seagrass conditions, station A is located near the airport. Dabo Singkep. The distribution of seagrass beds on the Lingga Island, represented by stations E and F, has a very good and thick coverage, with a maximum coverage area of 98.4% (Table 2).

Table 2. Seagrass coverage presentation

Station Name	Location (Islands)	Coordinates (Degree-Minutes-Second)	Coverage (%)	Condition (*CoreMap LIPI*)
A	Dabo (Singkep)	0°29'28.50"S - 104°35'39.25"E	45,7	Quite Good
B	Kote (Singkep)	0°24'17.30"S - 104°32'58.54"E	88	Very Good
C	Kote (Singkep)	0°23'4.42"S - 104°33'3.07"E	88,4	Very Good
D	Kote (Singkep)	0°21'58.62"S - 104°32'4.21"E	52,5	Quite Good
E	Daek (Lingga)	0°11'57.48"S - 104°48'18.41"E	98,4	Very Good
F	Daek (Lingga)	0°11'23.13"S - 104°48'9.94"E	95,4	Very Good
Average			78,0	

The species *Enhalus acoroides* are spreading in both locations, as *Enhalus acoroides* is a widely distributed and common seagrass species, along with *Thalassia hemprichii*. However, the population appears to be stable. Seagrass in the Lingga and Singkep Islands mostly grows in muddy areas, medium to coarse sand, debris, and dead coral. It thrives in the tidal zone at depths ranging from 1 to 10 meters. Additionally, seagrass in these islands continues to serve as a feeding and nursery ground for marine biota. The Lingga and Singkep Islands are also feeding zones for Green Turtles (*Chelonia mydas*), Hawksbill Turtles (*Eretmochelys imbricata*), and Dugongs (*Dugong dugon*), all of which rely on seagrass as their primary food source.(CoreMap-LIPI, 2014).

The classification of seagrass in Lingga and Singkep Island uses the DII method and has an OA (Overall Accuracy) value of 68.5%. While considered acceptable for benthic habitat mapping, this OA value also indicates the presence of potential misclassifications, especially in areas where seagrass spectral signatures overlap with sand or algal substrates. Such misclassifications are particularly likely in deeper or turbid environments, where reflectance values between seagrass and other benthic features become indistinguishable. The OA value with a value between 65-70% can be considered good enough for the results of the accuracy test of benthic habitat mapping using remote sensing (Mumby, Edwards, *et al*., 1997).

3.2. Degradation

The analysis of seagrass degradation in the Riau Islands, spanning both the West Monsoon Season and East Monsoon Season over the five-year period from 2016 to 2020, reveals noteworthy trends in the state of these coastal ecosystems. These seasonal patterns highlight a gradual but consistent decline in seagrass coverage, indicating increasing environmental stress and potential long-term impacts on marine biodiversity and ecosystem services.

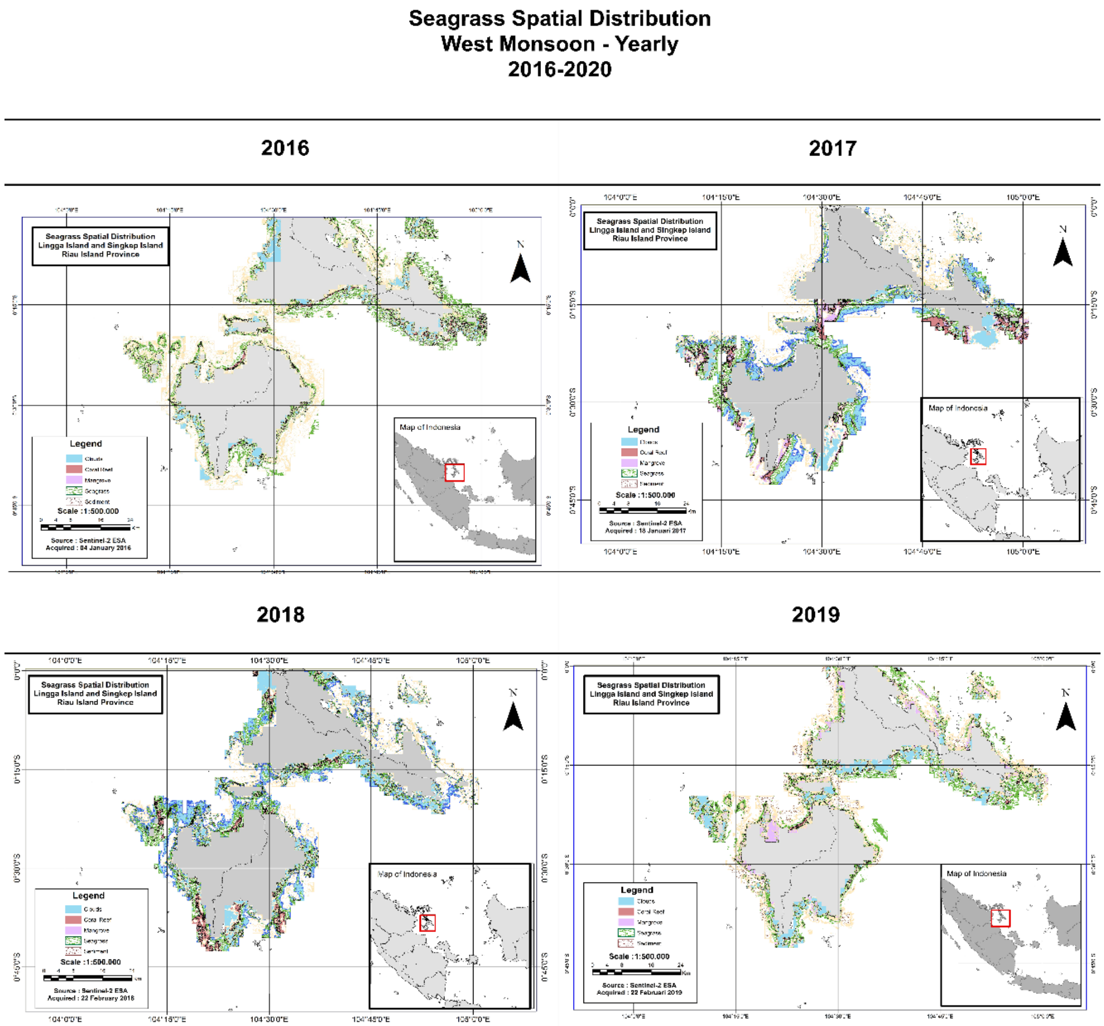

Figure 3. Seagrass degradation each year during west monsoon seasons

During the west monsoon season (Figure 3), the average seagrass coverage remained relatively stable at around 353 km² over the five-year period. However, a closer examination of the data unveils a concerning aspect. The coverage started at 376 km² in 2016 but steadily declined to 327 km² in 2020. This five-year period witnessed a significant loss of 49 km² of seagrass coverage in the WMS (West Monsoon Seasons). This gradual but consistent decrease like in Table 3 and Figure 4, the decrease in seagrass meadows in the region raises concerns about the health and sustainability of coastal ecosystems, which heavily rely on seagrass for various ecological functions.

Table 3. Seagrass yearly coverage in west monsoon seasons

	West Monsoon (km²)					
	2016	2017	2018	2019	2020	Average
Seagrass	376	366	351	347	327	353,4
Sediment	558	508	517	470	455	501,6
Clouds	111	114	143	158	106	126,4

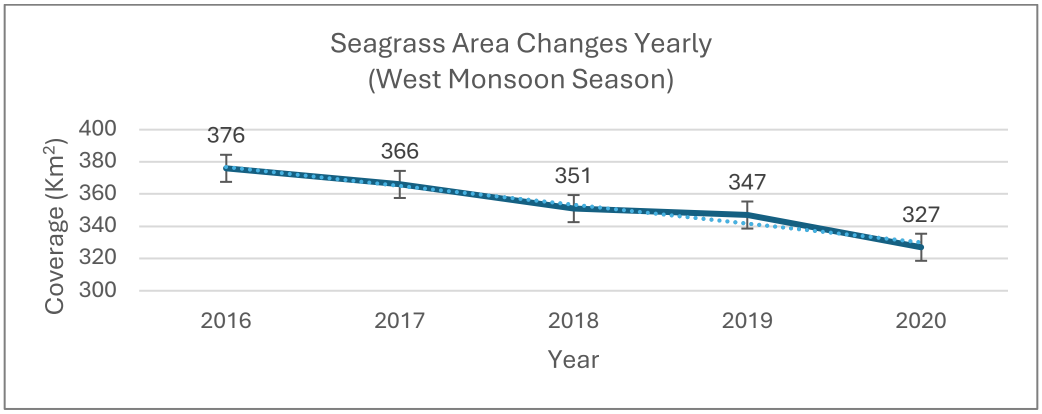

Figure 4. Seagrass temporal coverage during west monsoon seasons

In a similar pattern, the average seagrass coverage during the EMS (East Monsoon Season) (Figure 5) closely resembled that of the WMS, maintaining a level of approximately 353 km². However, a closer examination of the data shows a consistent decline in seagrass coverage over the same five-year period. Starting at 370 km² in 2016, it steadily decreased to 310 km² in 2020. The EMS experienced a more substantial loss of 60 km² of seagrass coverage during this time. This decline further underscores the challenges faced by seagrass ecosystems in the Riau Islands.

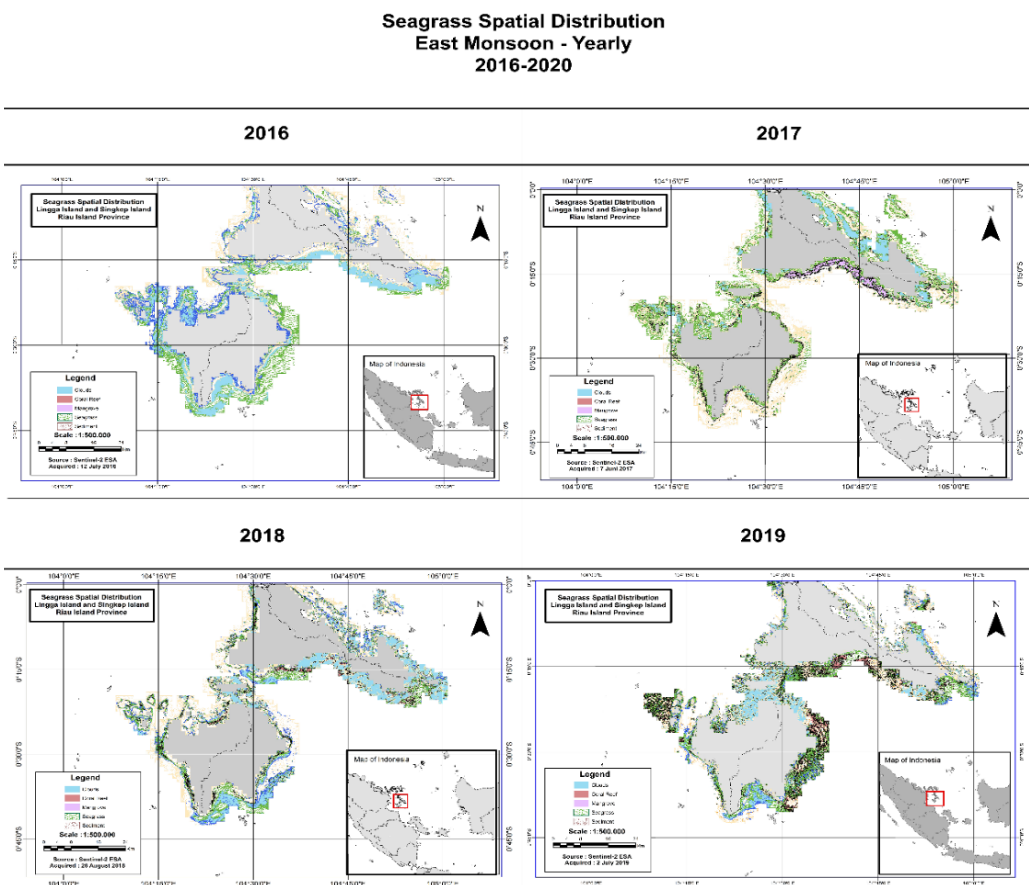

Figure 5. Seagrass degradation each year during east monsoon seasons

Table 4. Seagrass yearly coverage in east monsoon seasons

	East Monsoon (km²)					
	2016	2017	2018	2019	2020	Average
Seagrass	370	351	330	329	310	338
Sediment	472	427	518	478	456	470,2
Clouds	126	148	194	120	83	134,2

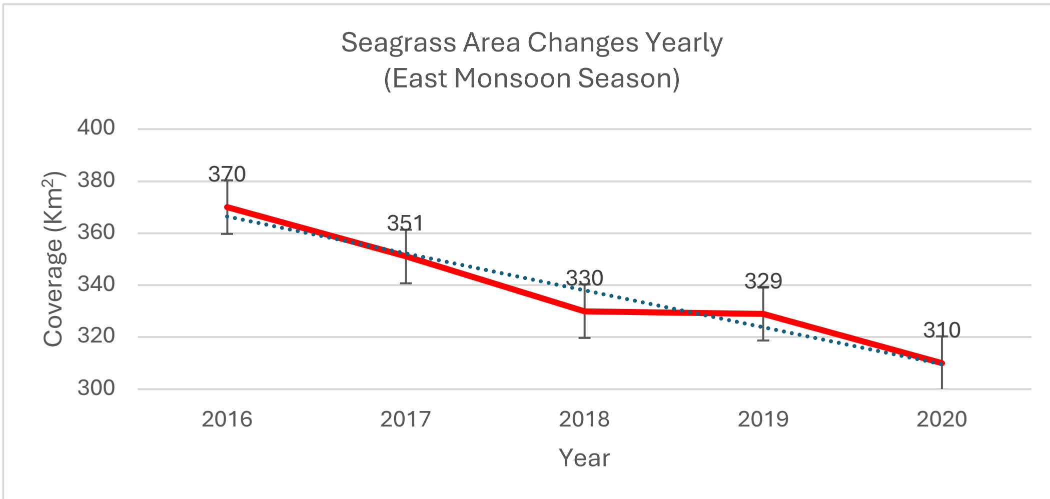

Figure 6. Seagrass temporal coverage during east monsoon seasons

The data from both monsoon seasons (Figure 4 and Figure 6), collectively highlight a critical issue, a seagrass degradation. Despite the initial appearance of stability in average coverage, a closer look reveals a consistent trend of decline over the five years. The reasons for this degradation require further investigation, possibly encompassing factors like water quality, sedimentation, climate change, and human activities. Comprehensive conservation efforts and continuous monitoring are essential to reverse this trend and ensure the preservation of these invaluable coastal ecosystems.

4. Discussion

The study discussion presents the findings from this research on the degradation of seagrass meadows in the Riau Islands while find about these findings in context with previous studies and working hypotheses. During both the WMS and EMS over the five-year period, seagrass coverage showed a concerning loss trend. These results match global findings suggesting that seagrass ecosystems are increasingly vulnerable to changes in environmental and human impacts, such as sedimentation, pollution, and coastal development (James *et al*., 2023). The dominance of *Enhalus acoroides* and the presence of multiple seagrass species reflect the ecological richness of the area, yet the ongoing loss in seagrass cover signifies significant challenges in sustaining biodiversity and associated ecosystem services (Wan, 2023). The accuracy level of 68.5% exposes some methodological limitations. Cloud cover presented a significant challenge in acquiring consistent satellite imagery, particularly during monsoon periods. his reduced the number of usable cloud-free images and led to temporal gaps in the dataset, potentially skewing the interpretation of seagrass degradation trends. Certain areas might appear to have experienced a loss of seagrass cover simply because earlier data were captured under clearer conditions, while later imagery was limited or obscured. As a result, some regions may not be fully represented in the analysis. To address this limitation, future studies could incorporate additional data sources such as drone imagery, cloud-penetrating radar, or cloud masking algorithms to improve temporal consistency and spatial coverage.

While destructive fishing methods were not widely reported, seagrass degradation in the study area was primarily driven by ocean pollution, particularly from tin mining activities in Lingga Island (Priyansah *et al*., 2025). Sediment runoff from mining operations increases water turbidity, reducing light penetration crucial for seagrass photosynthesis. Additionally, heavy metal contamination from tin mining may alter water quality and disrupt the delicate balance of the marine ecosystem, further stressing seagrass habitats and affecting their ability to support biodiversity (Zhang *et al.*, 2025). The implications of seagrass degradation extend beyond biodiversity, affecting carbon sequestration, sediment stability, and the livelihood of coastal communities (Ambomasse *et al*., 2024). Addressing these issues requires collaborative conservation efforts, targeted policy interventions, and continued monitoring (Jones *et al*., 2025). Integrating seagrass conservation into spatial marine planning frameworks is also vital. Community-based conservation programs, such as participatory monitoring and rehabilitation, could enhance awareness and stewardship among local stakeholders.

Future research should explore the drivers of degradation, including water quality and climate change impacts, while employing advanced remote sensing techniques to enhance spatial and temporal analysis. These steps will provide deeper insights into the resilience of seagrass ecosystems and inform more effective management strategies for coastal conservation.

5. Conclusions

This study successfully achieved its objectives by evaluating the status and temporal degradation of seagrass ecosystems in Lingga and Singkep Islands, Riau Province. The findings indicate that seagrass beds in these areas exhibit significant ecological importance, with a robust coverage reaching up to 78% and the presence of four distinct species—*Thalassia hemprichii, Enhalus acoroides, Halophila minor,* and *Halophila ovalis*. However, over the five-year period from 2016 to 2020, consistent degradation was observed, with a total loss of 49 km² during the West Monsoon Season and 60 km² during the East Monsoon Season, revealing critical threats to these ecosystems. The results demonstrate the effectiveness of remote sensing methods, particularly the DII and SVM classification, for mapping and assessing seagrass degradation. Given this, however, achievement of improvements at methodological levels such as its accuracy level (68.5%) and difficulties with cloud cover calls for further refinement and additional complementary techniques.

Thus, conservation efforts should be grabbed at an earliest for the seagrass ecosystems, which would be important for biodiversity, carbon sequestration, and the income of communities. Future research should focus on identifying the drivers of degradation and improving monitoring approaches to ensure the sustainable management of these critical coastal habitats.

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