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Changes in Functional and Species Diversity of Seagrass - Associated Fish Due to Anthropogenic Disturbance: A Case Study in Tanjung Merah, North Sulawesi, Indonesia

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ABSTRACT

Seagrass meadows are crucial for supporting fish diversity and abundance, thereby enhancing fisheries resources. However, these ecosystems are increasingly threatened by anthropogenic activities that directly impact fish populations. This study aimed to investigate the patterns of fish species utilizing seagrass habitats at Tanjung Merah, North Sulawesi, by comparing data collected during the pre-disturbance period (2004-2005) and the post-disturbance period (2014-2022). The objective was to assess the effects of anthropogenic pressures on both the seagrass meadows and their associated fish communities. This study employed the swept area method with beach seine and analyzed seagrass coverage changes through satellite data. Our findings revealed a significant decrease in species richness and fish abundance in Tanjung Merah ($P<0.01$) following the onset of anthropogenic pressures. A decline in beta diversity was also observed, with fish assemblages prior to disturbance exhibiting greater heterogeneity compared to those after disturbance, indicating that anthropogenic activities had a considerable impact on species composition. Additionally, the findings indicate a shift in the functional trait composition of fish associated with seagrass meadows. Species possessing traits related to greater adaptability and resilience – such as an omnivorous diet, high swimming ability, wide habitat range (visitor type), and high salinity tolerance became more prominent. Conversely, species with traits indicative of lower adaptability or greater specialization declined in response to increased anthropogenic pressure. Moreover, satellite data showed a progressive seagrass decline over time, with coverage estimated at 47.30, 43.02, 31.66, and 35.19 hectares across the study periods. The fish diversity index were assessed at moderate level, while the dominance fish species varied temporally, presumably influenced by environmental fluctuations. These findings suggest a strong correlation between seagrass loss and the reduction of seagrass-associated fish populations in Tanjung Merah, primarily attributable to anthropogenic disturbances. This study highlights the urgent need for the conservation effort to the vulnerable seagrass ecosystems and associated fish populations in Tanjung Merah.

INTRODUCTION

Indonesia's marine ecosystems are rich in biodiversity and offer essential contributions to support the livelihoods and well-being of communities. However, nowadays seagrass ecosystems in Indonesia are threatened by anthropogenic activities such as coastal development, reclamation, deforestation, seaweed farming, as well as habitat modification, urbanization, and climate change **(Magurran *et al*., 2015; Socolar *et al*., 2016; Unsworth *et al*., 2018; McKenzie *et al*., 2021)**. Reclamation provides economic benefits but also significantly impacts ecosystem services **(Tian *et al*., 2021)**. It affects the coastal morphology, hydro-oceanography, declined seawater quality, and deterioration of marine ecosystems **(Priyandes & Majid, 2009)**. Moreover, coastal construction such as ports, wharves, and bridges has increased the cumulative ecological impact of reclamation, which is also influenced by a combination of population growth, industrialization, and economic development **(Lu *et al*., 2023)**.

Seagrass is a flowering marine plant with a root and rhizome system. It can exist in either monospecific or mixed-species (multispecific) forms, forming meadows that are distributed along coastlines in temperate and tropical regions **(Short *et al*., 2007)**. Seagrass beds host a diverse array of organisms, including those living on the seabed (benthos), in the water amidst seagrass leaves (nekton and plankton), and those adhering to the leaves both permanently (epibiota) and temporarily **(Zurba, 2018)**. Ecologically, seagrass plays several crucial roles. It serves as a feeding ground for economically important fish species **(Carroll & Peterson, 2013; Blandon & Zu Ermgassen, 2014)** and functions as a nursery ground for juvenile fish **(Jones, 2014; Irawan *et al*., 2018)**. Additionally, seagrass supports high species richness and abundance **(Ambo-Rappe *et al*., 2013; Hidayati & Suparmoko, 2018)**. Seagrass is experiencing a global decline of over 7% annually, with approximately 29% destroyed due to human activities **(Brodie & De Ramon N'yeurt, 2018)**. The decline in both the size and coverage of seagrass habitats has profound effects on the surrounding ecosystem, leading to the loss of important fish nursery areas, reduced production of organic matter, increased coastal erosion, and changes in nutrient regulation and carbon storage **(Boudouresque *et al*., 2016; Unsworth *et al*., 2019)**. This decline also directly affects the fish that depend on seagrass habitats, resulting in reductions in species diversity, abundance, and community homogenization **(Iacarella *et al*., 2018)**.

Tanjung Merah is one of the aquatic zones located in Bitung city, North Sulawesi, Indonesia. This region is notable for its extensive seagrass coverage along the coastline and its direct adjacency to a coral reef ecosystem. Seagrass in Tanjung Merah is vital for local fisheries since it provides essential spawning and nursery habitat for marine fishes **(Syahailatua, 2015)**. It encompasses a unique and intricate array of marine fauna, which has attracted the attention of both domestic and international marine scientists since the 1990s **(Manik, 2007)**. In recent years, this area has become a local tourist destination. Since 2014, as a part of the special economic zone initiative in Bitung, reclamation activities have been conducted near Tanjung Merah's shoreline, accompanied by the establishment of facilities for small boat docking. However, reclamation activities contribute to the degradation and loss of seagrass habitats, increase turbidity, and, if these human activities continue without effective management, they could have lasting effects on ecosystem productivity **(Jiang *et al*., 2020; Tis'In *et al*., 2023)**. Although seagrass habitat play a crucial role in coastal ecosystems, their importance in Indonesia remains relatively overlooked by society, government, and policymakers when compared to other ecosystems like mangroves and coral reefs **(Potouroglou *et al*., 2017; Sondak & Kaligis, 2022)**.

The monitoring of seagrass and associated fish is pivotal for effectively managing and sustaining coastal environments **(Rustam, 2019)**. Activities that can influence the functionality of seagrass beds and the fish biota surrounding them must be identified as crucial risks, providing foundational information and evidence for local authorities to undertake further mitigation efforts in the area **(Sondak & Kaligis, 2022)**. This study focuses on the changes in habitat functions and fishes in Tanjung Merah, North Sulawesi, as a result of anthropogenic disturbances. The research aimed to assess the status of seagrass in the Tanjung Merah area and to determine the patterns of fish communities considering the role of seagrass as a spawning, nursery, and feeding ground. Additionally, it investigated the key species that might play an important role for seagrass associated-fish communities. Furthermore, to assess the impact of anthropogenic pressures - particularly reclamation activities - on the functional roles of seagrass habitat and seagrass associated fish communities in Tanjung Merah, we formulated the following hypotheses: First, there will be a significant decline in seagrass coverage after reclamation activities in Tanjung Merah; second, species composition and abundance of associated fish are expected to change with the decline in seagrass coverage, whereas temporary residents and visiting fish species in seagrass beds are expected to be less impacted compared to permanent residents.

MATERIALS AND METHODS

1. Study area

The study was conducted in the waters of Tanjung Merah, North Sulawesi, Indonesia (1.40233 N, 125.11964 E) (Fig. 1). The geographical proximity of Tanjung Merah to the Lembeh Strait renders it subject to the influence of water masses originating from the Molucca Sea and Tomini Bay. The area is engaged in various human activities; such as marine transportation, fishing, sports, and tourism, which could affect marine ecosystems and marine life **(Syahailatua, 2015)**. Seagrass ecosystems in this area are extensively distributed along the coastline and are directly adjacent to coral reefs. The prevailing seagrass species in this area are *Enhalus acoroides* and *Thalassia hemprichii*. The research was conducted to obtain short-time series dataset to investigate the seagrass profile in periods as before and after reclamations through investigating the seagrass conditions and seagrass-associated fishes.

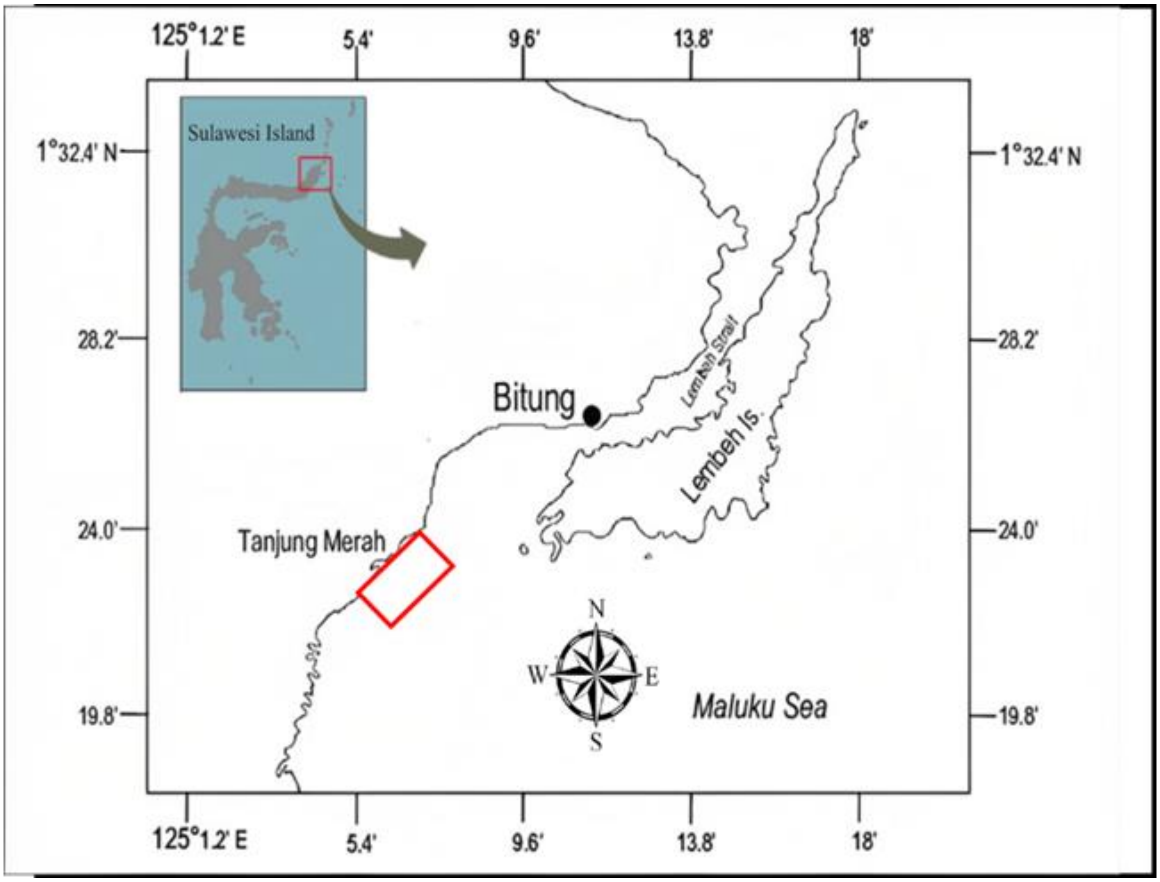

Fig. 1. Samping location in Tanjung Merah, North Sulawesi, Indonesia

2. Field collection

Fish specimens were collected within the seagrass meadow area using a beach seine measuring 20m in the primary length and 3m in wingspan, in conjunction with a bucket. The beach seine operation followed the swept area method, with a 100m length applied to obtain 6.000m^2 swept area **(Manik, 2007)**. The fish sampling was executed perpendicularly to the coastline during tidal movements at an approximate depth of 1-1.5m, and was conducted eight times with three replicates per sampling event. The procured fish samples were carefully preserved in plastic bags, appropriately labelled, and preserved in an icebox. Subsequent procedures involved precise measurements of length and weight using digital scales, accompanied by photographic documentation. Fish identification was accomplished using references sourced from established literature **(Kuiter & Tonozuka, 2001; Kimura & Matsuura, 2003; Peristiwady, 2006; Allen & Erdmann, 2012; White *et al*., 2013)**.

3. Fish data analysis

The parameters observed for the fish data encompass community structure, species richness and abundance, beta-diversity and functional trait composition. The structure of fish community analysis included three indices to provide information on the composition and distribution of fish species to evaluate ecological balance. The Shannon-Wiener diversity index (H') was used to indicate the balance of diversity by assessing the a distribution of the number of individuals per species, determining whether diversity is low or high **(Odum, 1971)**. The Simpson's dominance index (C) was utilized to ascertain the dominance of fish species within an ecological community and to identify the most frequently encountered species **(Odum, 2005)**. Moreover, the similarity in the distribution of individuals across species was determined by comparing the diversity index with its maximum value through the calculation of the evenness index (E), following references from **Odum (1971)**. Species richness and abundance of seagrass-associated fish were calculated for each period using a t-test and the Wilcoxon test to determine significant differences between the before and after periods **(McDonald, 2014)**. The change in species composition over the study period was examined using the formula %F = (number of species present at each sampling time / total number of species present during the study period) x 100, where F= frequency of species occurrence **(Campo *et al*., 2006)**. Beta-diversity was assessed by using the Bray-Curtis dissimilarity method to measure the level of difference between species compositions before and after anthropogenic disturbance **(Anderson *et al*., 2011)**. The Bray-Curtis index quantifies dissimilarity by considering the abundance of shared species, placing greater emphasis on species abundance rather than merely their presence or absence **(Bray & Curtis, 1957)**. This analysis utilized R version 4.1.3 to conduct statistical analysis and visualizations. The following packages were employed: "reshape2, dplyr and tidyr" packages were used for data transformation and preparation **(Wickham, 2007; Wickham *et al*., 2023, 2024)** and "vegan" for ecological diversity assessment **(Oksanen *et al*., 2024).** Additionally "ggplot2" was used to visualize the result **(Wickham, 2016)**.

Functional trait data were collected based on several considerations, including the ability of a species to adapt to environmental changes **(Villeger *et al*., 2010; Sunday *et al*., 2015; Iacarella *et al.*, 2018; Costa *et al*., 2023)**. The key traits used in this context included trophic status, swimming ability, resilience (fecundity), residency, salinity tolerance, and whether the species exhibited generalist or specialist characteristics. Databases such as FishBase and WoRMS were utilized to obtain information regarding these traits **(Froese & Pauly, 2025; WoRMS Editorial Board, 2025)**.

4. Seagrass data analysis

The seagrass datasets employed in this study over different periods, namely before and after reclamations, were sourced from the Landsat-7 and Landsat-8 imagery, respectively (Fig. 2). The research falls under the USGS (United States Geological

Survey) Landsat Surface Reflectance category and has undergone both geometric and atmospheric corrections, which are freely accessible online. The sensors used in the imagery are within the visible and infrared bands, boasting a spatial resolution of 15m. Data analysis were systematically executed in three distinct stages: the preliminary phase of image processing was facilitated using the QGIS 3.8 platform, encompassing procedures such as image selection, composite generation, image cropping, and corrective adjustments. Once procured, the image data underwent visual interpretation, aiming to discern and categorise seagrass coverage visible in the images. To transform multi-spectral image data into delineated spatial element classes, an unsupervised classification approach was adopted **(Prahasta, 2008)**. Within this unsupervised classification framework, representative sample areas were delineated using data derived from targeted point object collection or *in-situ* field sampling, thus determining class characteristics. Variations in benthic coverage were meticulously evaluated by juxtaposing classified image data across periods of study. This assessment leveraged thematic change analysis which was followed by formula: [benthic cover at time i] + "-" + [benthic cover at time j] **(Eastman, 2009)**, and the results were stored in an Excel workbook format, then processed and analyzed to obtain changes in seagrass cover over the study period.

RESULTS

1. Status of seagrass beds at Tanjung Merah

Based on the analysis of the seagrass area from satellite data collected across a 100 ha expanse centered on the sampling point, a clear reduction in the seagrass area is evident. The area decreased from 47.3 ha (2005) to 43.02 ha (2014). Furthermore, a significant decline was also observed in 2017 (31.66 ha), followed by a slight increase to 35.19 ha (2022) (Table 1). Consequently, there was an approximate reduction of 12.11 ha in seagrass area within Tanjung Merah and its surrounding when comparing the most recent data from 2022 to the initial dataset in 2005 (Fig. 2).

Table 1. The total area of seagrass within 100 ha from sampling location

Area	Year			
	2005	2014	2017	2022
Seagrass (ha)	47.3	43.02	31.66	35.19
Non-seagrass (ha)	53.75	55.15	66.51	62.98

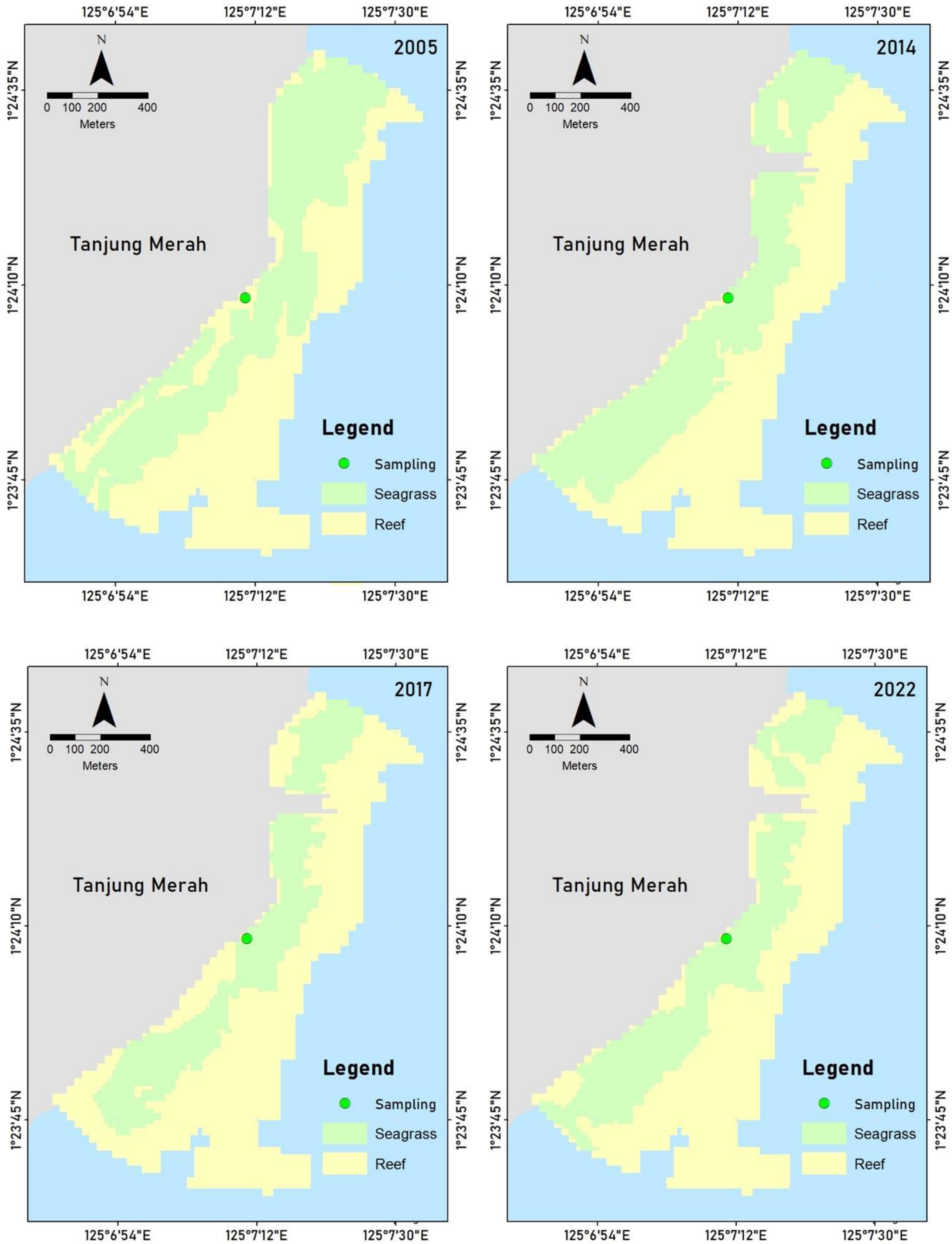

Fig. 2. Map showing the seagrass bed area spanning 100 ha centered around the sampling point in the water of Tanjung Merah for each surveyed year

2. Composition and trends in seagrass fish assemblages

Based on the outcomes from two distinct time points before and after reclamation within the same Tanjung Merah location (Fig. 3), a total of 25.664 individuals comprising

122 species (47 families), and 2.656 individuals from 94 species (42 families) were documented, respectively. The families most frequently encountered in the 'before' period were Labridae, Apogonidae, Pomacentridae, Monacanthidae, Siganidae, Atherinidae, Lethrinidae, Mullidae, and Tetraodontidae, whereas in the 'after' period was Labridae was the most dominant family, while the remaining families comprised fewer than five species in each period. Seagrass-associated fish in Tanjung Merah with the highest total abundances (>1.000 individuals) during the 'before' period included *Ostorhinchus margaritophorus*, *Halichoeres papilionaceus*, *H. melanurus*, *Siganus canaliculatus*, *Plotosus lineatus*, *O. hartzfeldii*, and *Nematalosa japonica*. However, the abundance in the 'after' period decreased, with only four species showing the highest total abundance: *Atherinomorus endrachtensis*, *A. vaigiensis*, *O. margaritophorus*, and *H. papilionaceus* (> 200 individuals).

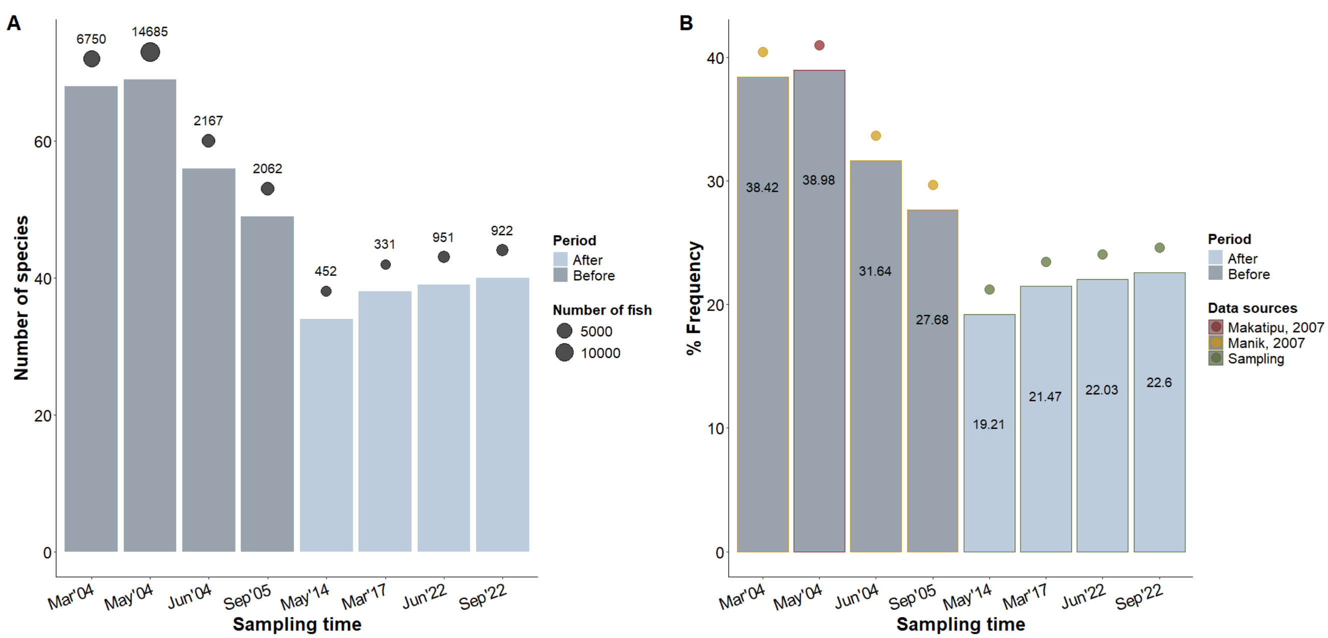

Fig. 3. Number of species, total number of fish individual and species occurrence frequency

During the 'before' period, the highest number of species and the highest abundance were observed in May 2004, while the lowest numbers was reported in September 2004. In the 'after' period, the highest and lowest numbers of species occurred in September 2022 and May 2014, respectively. However, the highest and lowest abundances were recorded in June 2022 and March 2017, respectively (Fig. 3). The seagrass-associated fish species in Tanjung Merah between the two periods suggest that anthropogenic stress has had a significant negative impact especially on species richness and abundance ($P< 0.05$, Table 2). A significant difference in abundance suggests that the overall number of individuals (across all species) changed between the time periods, with a substantial decline in the number of fish observed over the time periods. These differences indicate that the community composition has changed over time, either by species being added or lost or by changes the number of individuals within those species.

Table 2. Comparison of ecological parameters before and after anthropogenic pressure: Statistical differences uusing the Wilcoxon test and t-test

Ecological index	Period	Range	Mean	stdev	*P*-value
Species richness	Before	51-70	61,75	8,8	
	After	34-40	38	2,7	**0.01**
Abundance	Before	2062-14685	6423	5923,4	
	After	331-951	578	318,7	**0.001**
Diversity index	Before	2-2,68	2,33	0,32	
	After	1,87-2,72	2,36	0,38	0,93
Eveness index	Before	0,49-0,68	0,56	0,08	
	After	0,5-0,7	0,62	0,09	0,41
Dominance index	Before	0,1-0,32	0,18	0,09	
	After	0,12-0,25	0,18	0,05	0,86

The trend of seagrass fish diversity and their species composition in Tanjung Merah according to the frequency of fish occurrence (%F) during the sampling phases, showed a significant drop in May 2014. However, the frequency of fish occurrence after these sampling periods slightly increased, although the change was not substantial. This trend aligns with the abundance of individuals; a decline in fish numbers was observed in the first sampling of ‘after’ period (May 2014 and March 2017), followed by a slight increase thereafter. This condition might be related to the impact of reclamation activities in 2014. The seagrass-associated fish that were recorded in all four sampling events before reclamation but were not found at all afterward included *Corythoichthys intestinalis, Pelates quadrilineatus, Pentapodus trivittatus,* and *Pomacentrus tripunctatus*. Conversely, the fish as *A. endrachtensis* was absent in the earlier dataset but was consistently observed after reclamation.

3. Community structure of seagrass-associated fish

The community structure of fish in Tanjung Merah, based on alpha diversity index, showed no significant differences between the two periods, although the overall community structure was higher than in the ‘after’ period ($P > 0.05$, Table 2). The species diversity index (H') ranged from 1.95 to 2.59 before reclamation, while after reclamation, it ranged from 1.87 to 2.72. The highest diversity index was recorded in June 2004, whereas the lowest occured in September 2005. In the 'after' period, diversity peaked in March 2017 and dropped to its lowest in June 2022. Overall, these results indicate a relatively healthy seagrass-associated fish community. The evenness values ranged from

0.48 and 0.66 in the 'before' period and from 0.5 to 0.7 in the ‘after’ period, while dominance values ranged from 0.1 to 0.33 before reclamation and from 0.1 to 0.25 afterward. Generally, the evenness values for both periods fall within the moderate-high category, while the dominance patterns, on average, indicate low dominance (Table 2, Fig. 4). An exception was noted during the June 2004 sampling, which recorded a dominance index of 0.33, classified as moderate dominance due to the significant presence of one species.

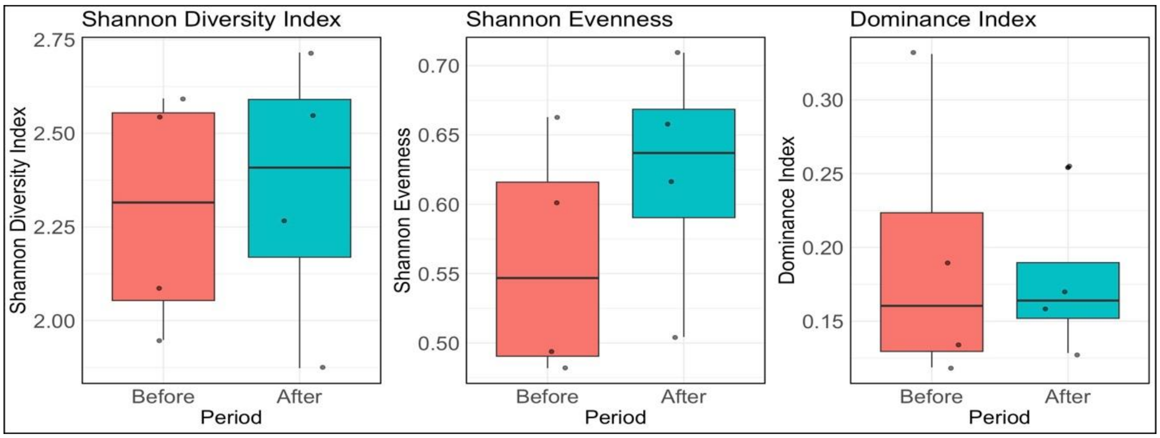

Fig. 4. Boxplot comparison of Shanon diversity index, eveness and dominance of seagrass fish before and after anthropogenic pressure

4. Beta diversity

A value of 0.92 suggests that the two periods have a very high level of dissimilarity in terms of species composition and abundance. This means that the disturbance drastically altered the species composition. The separation suggests a clear distinction species composition, with ‘before’ period clustered toward the left side of the plot, while the ‘after’ period were more spread toward the right. The ‘before’ group (red circles) appears to have more variability and was more dispersed compared to the ‘after’ group (black triangles), which was more compact (Fig. 5). This could indicate that the species composition prior to disturbance was more heterogeneous, while the post-disturbance phase exhibited greater homogeneity. The reduction in beta diversity after disturbance might indicate that the anthropogenic stressor caused a loss of species diversity, leading to a more uniform community structure. The higher beta diversity in the ‘before’ period could indicate a more complex ecosystem with a more diverse range of species and ecological interactions.

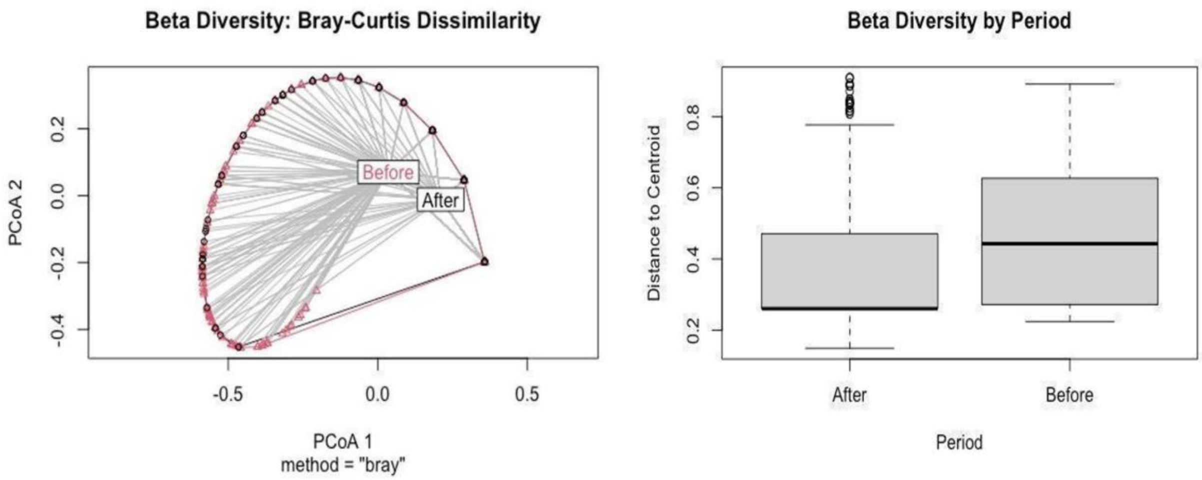

Fig. 5. Comparison of beta diversity between seagrass-associated fish before and after using Bray-Curtis dissimilarity

5. Changes in seagrass fish composition and functional trait

A shift in fish species composition and functional traits associated with seagrass beds was observed before and after exposure to anthropogenic stressors. Prior to these stressors, *Ostorhinchus margaritophorus*, *Halichoeres papilionaceus*, and *Halichoeres melanurus* were the three most abundant species. However, following the impact, the dominant species composition changed to *Atherinomorus endrachtensis, Atherinomorus vaigiensis*, and *Ostorhinchus margaritophorus* emerging as the most abundant. A shift in species composition was also noted among the top 10 most abundant species.

The composition of functional trait groups for seagrass-associated fish (Fig. 6) was determined based on traits such as trophic status, swimming ability, resilience (fecundity), residency status, and salinity tolerance to assess the resilience and vulnerability of these species to ecological shifts induced by anthropogenic pressures. Reductions in seagrass area and cover, along with increased sedimentation, threaten certain species more susceptible to these changes. The functional traits were categorized into three groups: species from 'before', 'after' and those present in both periods. Notably, there was a significant shift in trophic groups due to anthropogenic pressures: omnivorous species increased from 18.7 to 30.4%, while carnivores and herbivores declined from 64 to 56.5% and 17.3 to 13%, respectively (Fig. 6). Additionally, fish species with high swimming ability rise in composition in the 'after' period, from 11 to 20%, while those with low swimming ability decreased from 34.2 to 20%. The composition of species, specific to the before period, is similar to that occurring throughout both periods (Fig. 6).

Significant differences were also observed in fish residency composition. Permanent resident were most prevalent among species present in both periods. In contrast, while temporary residents were most prominent among species found exclusively in the before period, with similar proportions in the after and both periods (34.78 and 34.3%, respectively). Visitor species showed a notable increase in the 'after' period, reaching 50% compared to 28.7% in the 'before' period and 28.9% across both. Differences in salinity tolerance were noted, with an increase in species tolerant of low salinity (brackish water) in the 'after' period, compared to those adapted to high salinity, which dominated in the 'before' period and across both (Fig. 6). Generalist fish species were most prevalent among those present in both timeframes, while species with specific traits were more frequently found in those occurring exclusively before the onset of anthropogenic pressure.

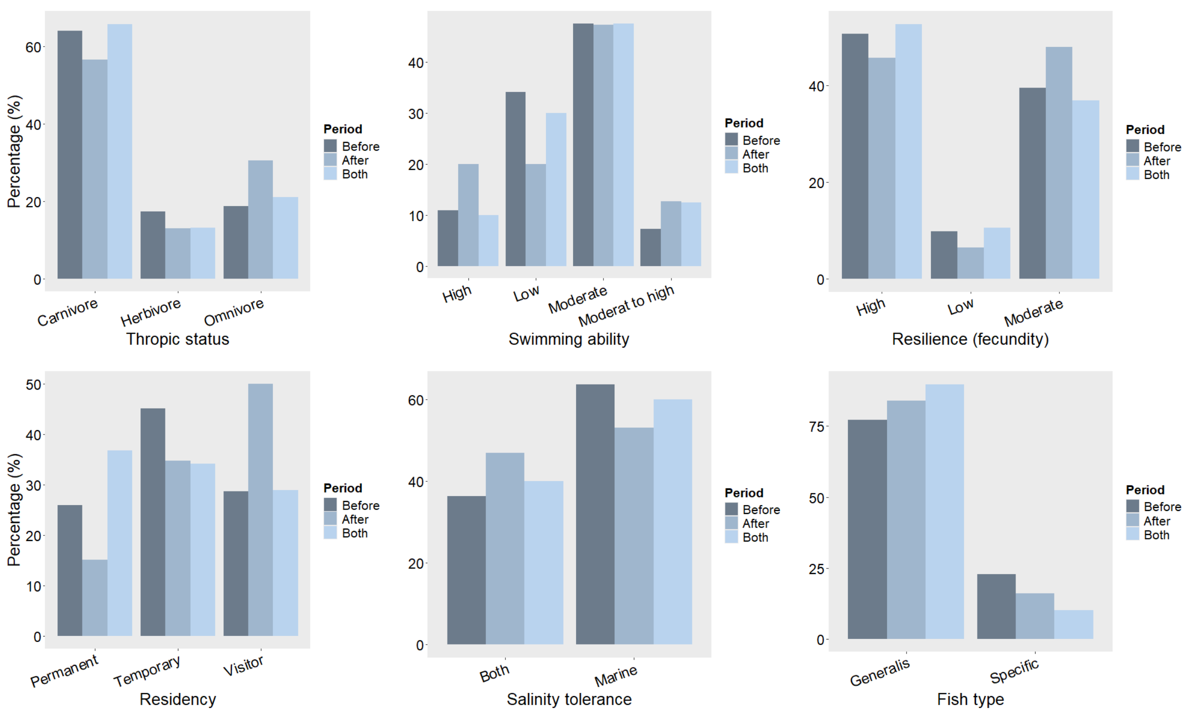

Fig. 6. Changes in the composition of seagrass -associated fish in Tanjung Merah based on functional traits

DISCUSSION

Based on the analysis of the seagrass area, the most substantial reduction in seagrass coverage was observed in the area where a small dock had been constructed, serving as a harbor for small vessels (gray-colored area) in the northern direction from the sampling point (Fig. 2). In addition to reclamation activities in this region, actions such as boat propeller operation, mooring, and anchoring could contribute to detrimental effects on the surrounding seagrass beds **(Luff *et al*., 2019; Sondak & Kaligis, 2022)**. Ship anchors have the potential to inflict physical damage on seagrass beds, while their associated turbidity can reduce light penetration within the water column, leading to reduced light availability and hindering seagrass growth in the vicinity **(Browne *et al*., 2017)**.

A previous study reported by **Susetiono (2004)** identified a total of eight seagrass species were identified in Tanjung Merah, including *Enhalus acoroides, Thalassia hemprichii, Cymodocea rotundata, C. serrulata, Syringodium isoetifolium, Halophila ovalis, Halodule pinifolia,* and *H. uninervis,* contributing to an overall seagrass coverage of up to 90% in 2004. However, in 2017, the number of seagrass species declined to only four species: *Enhalus acroides, Thalassia hemprichii, Cymodocea rotundata*, and *Halophila ovalis*, with an average seagrass coverage reduced to 49.4% **(Monika, 2018)**. In 2022, the seagrass species count remained at four species, with an average coverage of 42.7% **(Rizqi, 2022)**. These data confirm the absence of certain seagrass species and the significant reduction in seagrass coverage or density during this time span.

Fish abundance is expected to be higher in seagrass meadows with greater density and coverage. The diversity of fish species is more pronounced in multi-species seagrass ecosystems with dense vegetation, compared to monospecific counterparts with lower density **(Ambo-Rappe *et al*., 2013)**. This phenomenon helps explain the decline in the seagrass-associated fish species and abundance in Tanjung Merah, where seagrass species and coverage are diminishing. Additionally, the reduction in seagrass beds area contributes to the loss of habitat connectivity and the reduced habitat availability for fish that depend on seagrass ecosystems in this region.

During the 'before' period in Tanjung Merah, the captured fish species showed notable diversity, with dominant species including *Ostorhinchus margaritophorus, Siganus canaliculatus, Plotosus lineatus, O. hartzfeldii, Nematalosa japonica, Halichoeres papilionaceus* and *H. melanurus.* Notably, two species of *Halichoeres* were also reported as dominant in Kema, North Minahasa **(Du *et al*., 2018)** and in East Bolaang Mongondow Regency **(Yalindua *et al*., 2023)** of North Sulawesi. However, the dominant species changed to *Atherinomorus endrachtensis, A. vaigiensis, O. margaritophorus,* and *H. papilionaceus* after reclamation activities; *Atherinomorus endrachtensis*, a planktivorous species, was found only in seagrass canopies with less complex habitats **(Serrano *et al.*, 2023)**. Similarly, *A. vaigiensis,* which forages and seeks shelter from predators by migrating into mangrove habitats **(Martin *et al.*, 2015)**, was also recorded only in the 'after' period. This suggests that these species were able to survive under the changed seagrass conditions (Fig. 2), possibly due to reduced predation pressure. Previous studies conducted in 2004, 2005, and 2007 reported that seagrass-associated fish in Tanjung Merah region were high abundant in both species richness and individuals numbers **(Makatipu, 2007; Manik, 2007; Syahailatua, 2015)**. However, a recent study, showed a significant difference in species diversity and abundance between the 'before' and 'after' periods (Fig. 3), and notable decline in fish occurrence in May 2014 following reclamation activities. This led to changes in species composition, where *Corythoichthys intestinalis, Pelates quadrilineatus, Pentapodus trivittatus,* and

Pomacentrus tripunctatus are absent during ‘after’ period. *Pelates quadrilineatus* has been reported as a dominant species in seagrass meadows **(Phinrub *et al*., 2018; Tongnuni *et al.,* 2024)**, and it was also dominant in the study area prior to reclamation activities. In contrast, *P. trivittatus* was identified as a permanent resident of seagrass habitats **(Phinrub *et al.,* 2014)**. The persistent decline in species diversity and abundance of seagrass-associated fish in the Tanjung Merah area significant ecological changes in this region. This trend particularly altering the conditions within the seagrass habitat that crucial for resident fish species.

Based on previous studies, the variation in dominant fish species composition within seagrass beds in Tanjung Merah region is primarily influenced by differences in sampling months. For instance, month characterized by calm winds, such as March 2017 yielded distinct result compared to sampling times during windy (e.g., September 2005 and 2007) due to tidal surges, wherein fish that cannot withstand these conditions tend to migrate to safer habitats **(Manik, 2007)**. However, trend analysis indicates that this factor does not significantly drive species composition changes. The most notable outcome is the decreasing abundance of dominant fish species upon comparing data between 'before' and 'after' periods.

Aside from the decline in species richness and abundance, anthropogenic pressures also reduce beta-diversity **(Iacarella *et al*., 2018; McKinley *et al*., 2022)**. This is evident from the observed differences in beta-diversity and the decrease in seagrass-associated fish species during the ‘after’ period compared to the ‘before’ period (Fig. 5). The primary factors driving these changes are the loss of species richness and shifts in the composition of seagrass-associated fish communities, which are responses to environmental changes **(Hooper *et al*., 2005)**. The reduction in seagrass coverage and spatial area significantly impacts food availability and shelter for fish species dependent on these ecosystem. A growing body of literature has documented the decline in beta-diversity in both marine and freshwater fish communities, as a result of anthropogenic pressures **(Gutiérrez-Cánovas *et al*., 2013; Iacarella *et al*., 2018; Ellingsen *et al*., 2020; De Santis *et al*., 2023)**.

Our results indicate that anthropogenic alter both the composition and richness of fish species, as well as their functional traits. Notably, species with traits such as omnivorous feeding habits, high swimming ability, high residency (visitor) type, and greater tolerance to salinity fluctuations (species able to thrive in both marine and brackish environments). The proportion of these species increased during the 'after’ period suggesting that these generalist species have persisted due to their adaptability and resilience to environmental changes. In contrast, specialist species types declined, as they are generally more susceptible to anthropogenic pressures and more prone to extinction because they are specifically adapted to specific habitat types **(McKinney & Lockwood, 1999; Travers & Potter, 2002; Iacarella *et al*., 2018)**. This decline was particularly evident in species with narrow dietary preferences, low swimming ability, restricted habitat choices, and low salinity tolerance after reclamation (Fig. 6).

The species consistently present in 'before' periods, such as *Siganus canaliculatus, Lethrinus harak, Ostorhinchus margaritophorus,* and *Halichoeres papillonaceus* **(Nakamura & Tsuchiya, 2008)**, are primarily classified as permanent residents that rely on seagrass beds throughout their life stages. These species are typically abundant due to their strong association with this habitat. However, despite their generalist nature and ability to adapt to a range of environmental conditions, a significant decline in their abundance was observed following the reclamation activities. This decline can be attributed to the degradation of their primary habitat, the seagrass beds, which are essential for their foraging, shelter, and breeding. Although these species are typically classified as generalists, they are still vulnerable to anthropogenic impacts when their core habitat is altered or degraded **(McKinney & Lockwood, 1999)**. The loss of seagrass habitat, due to both direct physical damage from reclamation and indirect environmental changes such as altered water quality and sedimentation, may have disrupted the ecological processes that sustain these species, leading to a noticeable reduction in their abundance. This situation underscores the importance of habitat integrity for the survival of marine species, even those with broad ecological tolerances.

This study observed a decline in seagrass due to anthropogenic pressures, resulting in a significant impact on a decrease in beta-diversity (Fig. 5) and the homogenization of fish species, which increasingly belong to generalized categories. Seagrass plays a vital role in providing a habitat for reproduction, shelter, and foraging, thus influencing the trophic structure, it serves as a refuge for epibenthic organisms, which constitute a food source for fish that rely on the seagrass detritus cycle **(Iacarella *et al*., 2018)**. The presence of herbivorous fish that consume seagrass and subsequent carnivorous fish that prey on seagrass-associated fish **(Manangkalangi *et al*., 2022)** demonstrates a continuous food chain within the seagrass ecosystem. The decline and degradation of seagrass, largely attribured to anthropogenic disturbances such as development and reclamation activities, contribute to a reduction in diversity and abundance of fish. This phenomenon is further compounded by the decrease in more specialized species e.g., *P. trivittatus*, as permanent residents possessing traits less adaptable to the diminishing ecological habitat resulting from anthropogenic disturbances.

This substantial decline both diversity and abundance in both species diversity and abundance and also the reductions of seagrass coverage serves as an indicator of ongoing ecological shifts within the seagrass ecosystem in Tanjung Merah. This finding highlights the urgent need for conservation efforts to protect the vulnerable seagrass ecosystems and associated fish populations, emphasizing the necessity of immediate conservation measures.

CONCLUSION

The study in Tanjung Merah, North Sulawesi, reveals significant impacts of anthropogenic activities on seagrass ecosystems and associated fish populations. Seagrass coverage declined from 47.3 ha (2004) to 35.19 ha (2022) over the study period. This decline led to a decrease in species richness, fish abundance (P<0.01) and beta diversity. This decline also resulted in a shift in fish community composition, displaying a pattern of homogenization. The species encountered manifest a more generalized form with traits such as omnivorous diets and high swimming ability, while specialized types dwindle due to their inability to adapt to environmental habitat shifts. This study further provides evidence that the diminishing assemblages of seagrass-associated fish in Tanjung Merah are attributed to the reduction in seagrass area, coverage, and species diversity, largely to anthropogenic pressures such as development and reclamation activities. The loss of seagrass habitat disrupts ecological processes, reducing primary production, and threatens the survival of endangered species and the livelihoods of communities dependent on these resources. The findings underscore the urgent need for conservation efforts to protect vulnerable seagrass ecosystems and associated fish populations.

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