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Coral reef condition Kepala Jeri Island, Batam, Riau Islands, Indonesia

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Abstract. *Aunurrahman, Anggoro S, Saputra SW, Muskananfola MR. 2024. Coral reef condition Kepala Jeri Island, Batam, Riau Islands, Indonesia. Biodiversitas 25: 2820-2827.* Understanding the actual condition of vulnerable coral reef ecosystems such as Kepala Jeri Island (Indonesia) is critical to enabling appropriate management planning. This research aimed to identify current coverage, observe the condition of the coral ecosystem, and identify the species composition of coral reefs in Kepala Jeri Waters. Data collection includes the spatial distribution, actual condition, and species composition of the coral ecosystem on Kepala Jeri Island, Riau Islands, Indonesia. Using an algorithm-based classification, we analyzed the spatial distribution of coral reefs from Landsat 8 OLI imagery. The study used Landsat OLI 8 images from the US Geological Survey (USGS) and observed the data using a line intercept transect. We obtained the actual coral conditions and species composition through field observation. The results revealed a total distribution of 239.67 ha of coral reef ecosystem in the surrounding area of Kepala Jeri Island. Unfortunately, the coral reef on Kepala Jeri Island was in poor condition, with an approximate living coral coverage of only 5-29.33%. Compared to other locations, we found the sand cover to be the highest, ranging from 28.33 to 51.67%. We also found that the seagrass bed had invaded the coral ecosystem, suggesting a reduced or absent population of halos grazers. Only the western and northern sides of Kepala Jeri Island exhibit adequate coral diversity despite discovering 26 coral species. Even though 26 coral species were found on Kepala Jeri Island, only the western and northern sides have adequate coral diversity. The findings suggest that the coral reef ecosystem on Kepala Jeri Island is under severe degradation, while the risk of further degradation remains. Therefore, human intervention is absolutely important to improve the coral reef ecosystem on Kepala Jeri Island, ensuring its sustainability.

Keywords: Coral distribution, degradation, intervention, invasion, seagrass

Abbreviations: USGS: United States Geological Survey, OLI: Operational Land Imager, SI: Similarity Index

INTRODUCTION

Coral reefs are an essential ecosystem in coastal areas. Only tropical and temperate regions can host coral reef ecosystems (Kusumoto et al. 2020). Geographically, most coral reefs are located between latitudes 30°N and 30°S (Hochberg and Gierach 2021). According to the World Population Review (2024), several countries with the largest coral coverage include Indonesia (17.95%), Australia (17.22%), the Philippines (8.81%), and France (5.02%). The presence of macroinvertebrates is closely related to the health of the surrounding coral reefs. If coral reefs are healthy, macroinvertebrates will exist in that environment (Marsuki et al. 2013). The most recent bleaching event in Indonesia happened in 2015 and 2016. However, not all of Indonesia was severely impacted. In this case, only a few places had a mostly stable coral cover, and some even saw a small increase (Razak et al. 2024).

Unfortunately, the change in environmental conditions has forcefully put nature under pressure. Coral reefs worldwide face massive environmental pressures (Hughes et al. 2017). Several causes, such as climate change, overfishing, habitat destruction, and pollution, are the main drivers of coral reef decline (Eddy et al. 2021). According to Price et al. (2019), coral tends to move to higher latitudes due to global warming issues, with declining coverage in tropical areas and increasing coverage in temperate areas. According to Souter et al. (2021), global coverage of hard coral declined from 33.3% to 28.8% between 2009 and 2018, representing 13.5% of total hard coral coverage. Severe coral reef damage is found in many locations, such as the Great Barrier Reefs (De'Ath et al. 2012), the Philippines (Licuanan et al. 2019), Mexico (Rioja-Nieto and Álvarez-Filip 2019), Australia (Pisapia and Pratchett 2014), and Indonesia (Williams et al. 2019). Unfortunately, the decline of coral reefs is not only affecting the coverage but also the diversity (Clements and Hay 2019).

Coral belongs to the group invertebrates, consisting of four groups: scleractinian corals, octocorals, sponges, and ascidians (O'Brien et al. 2020). Coral inhabits coastal areas within the depth range of <1 to 85 m, with a dominant distribution at depths <10 m (MacDonald et al. 2016; Glasl et al. 2017). Coral reefs are always in symbiosis with zooxanthellae (Stambler 2017). Typically, coral requires a good environment to survive and grow accordingly (Gust et al. 2014). Coral growth requires appropriate environmental conditions, including salinity, temperature, turbidity, total suspended solid concentration, and the absence of oil film (Girard and Fisher 2018).

Coral reefs provide various environmental services, and coral species composition is crucial in safeguarding the shoreline, seagrass beds, and mangrove forests (Schoonees et al. 2019). The existence of coral reefs enables waves to break before reaching the coastline, significantly reducing their force. Coral reefs also promote marine fish diversity (Komyakova et al. 2018). According to Limmon et al. 2020, there are approximately 4,350 coralfish species in Indonesia and the Philippines alone.

The environmental services provided by the coral ecosystem are a key aspect that supports the livelihood of most communities on small islands. Small island communities strongly depend on coastal resources, especially coral fish (Watson et al. 2016). Therefore, the degradation of the coral ecosystem would disrupt the community's survivability. Some disasters are believed to be more likely to destroy coral reefs that are far apart or have different current patterns (Gilmour et al. 2013). The coral reef's size and form, the water current's speed, and the local hydrodynamics can all change how long coral larvae stay in one place (Doropoulos and Babcock 2018). Given the ecological significance of coral reefs, we should not overlook their declining coverage. Coral reefs are important because they serve as a biodiversity pool as well as support for fish stocks. The decline of coral reef extent has caused a decline in fish catches of up to approximately 60% since 1950, despite increased fishing efforts and a loss of coral reef-associated biodiversity of up to approximately 63% (Eddy et al. 2021). The current cover greatly influences the condition of coral reefs in the surrounding area; this is very important to pay attention to determine the species composition of coral reefs (Lubis et al. 2018a). According to scientific studies, several ocean currents patterns along the coasts of several Indonesian islands have changed a lot in the last few decades. Scientists have observed a significant increase in current cover, particularly during specific periods of the year. Therefore, many scientists link this phenomenon to global climate change (Eddy et al. 2021). This affects how plankton and other marine creatures move and their abundance. Coral reefs are also worsening, with fewer coral communities appearing everywhere. The main reasons for the deterioration of coral reef ecosystems in Indonesia are believed to be coral bleaching, sedimentation, and human actions (Dutton et al. 2000). The decline in coral reef cover and diversity is a global problem beyond Kepala Jeri Island. Since 1980, various factors such as rising sea surface temperatures, ocean acidification, pollution, and human activities like overfishing and physical damage have led to the loss of around 50% of the world's coral reefs, and the rate of destruction continues to increase (Eddy et al. 2021).

Kepala Jeri Island is an island in Batam City on the western side of Batam Island. Geographically, Kepala Jeri Island is located approximately 6.5 nm from Batam Island. Even though Kepala Jeri Island is not close to Batam Island, the impact of industrial activities in Batam still reaches the island. Regular monitoring of the ecological conditions of coral reefs, such as species composition and percentage of live coral cover, is essential to identify changing trends and threats that may occur in the coral reef ecosystem on Kepala Jeri Island. Furthermore, the measurement and analysis of ocean current patterns surrounding coral reefs can offer insights into the hydrodynamics impacting crucial processes like nutrient supply, larval recruitment, and growth. This knowledge can serve as a foundation for efficient management and ensuring the sustainability of coral reefs in the area. There needs to be more information about the current condition of coral reefs in developing management strategies for the coral ecosystem (Comte and Pendleton 2018). Given the importance of Kepala Jeri Island and the alarming state of the oil spill, it is critical to understand its actual condition, particularly its coral ecosystem. This research aimed to identify current coverage, observe the condition of the coral ecosystem, and identify the species composition of coral reefs in Kepala Jeri Waters, Riau Islands, Indonesia.

MATERIALS AND METHODS

We researched Kepala Jeri Island, Batam City; therefore, we collected relevant information for coral spatial analysis and field observation data. The United States Geological Survey (USGS) provided Landsat OLI 8 images used in the study and so, acquired on 12 February 2022. We conducted field observation on the opposite side in April 2023. The study utilized a line intercept transect as an observational technique to verify the accuracy of the coral reef distribution map generated through spatial analysis. We established four survey stations on Kepala Jeri Island to collect relevant data on the condition of the coral reefs, and the transect spanned a length of 50 meters. We distributed the sampling stations around Kepala Jeri Island, including stations A (western), B (northern), C (southern), and D (eastern), to represent the condition from all four sides of the island. The parameters observed for the coral coverage survey included coral life form coverage and species composition.

We analyzed spatial data to determine the distribution and coverage of coral reefs on Kepala Jeri Island. We carried out the data analysis using a digital number reanalysis algorithm. We used the (B3+B4)/(B3+B2) algorithm to detect the coral ecosystem. B2, B3, and B4 of the Landsat 8 OLI imagery represent the visible lights, including blue (B2), green (B3), and red (B4). We then classified using the newly developed digital number to identify coral coverage. We quantify each pixel into a digital number (DN) using the image's spectral information to facilitate image classification. The coverage classes resulting from the analysis include coral reefs, seagrass beds, sand, and water columns, as shown in Table 1.

We conducted a descriptive analysis of coral coverage and species composition. Furthermore, coral composition was analyzed for the similarity index. The analysis aimed to comprehend the ecological relationship between stations better. The similarity index was analyzed using Jaccard's formula as follows:

$$SI = \frac{a}{a+b+c} \times 100\%$$

Where:
SI : similarity index (%)
a : number of coral species found in both locations
b : number of coral species found only in the first location
c : number of coral species found only in the second location

RESULTS AND DISCUSSION

Coral coverage and distribution

The coral reef ecosystem on Kepala Jeri Island covers an area of 239.67 ha; it surrounds the island at various distances from the coastline and varies in thickness. Coral reefs on Kepala Jeri Island are available at a depth of 1-10 m. Thus, the coral reef ecosystem on Kepala Jeri Island has diverse characteristics related to its area, distance from the coastline, and depth.

Table 1. The classification for shallow water

Coverage	Digital Number (DN) range
Water column	<0.83
Coral reef	0.83-0.895
Seagrass bed	0.895-0.925
Sand	>0.925

Coral coverage is highest on the island's western side, while the southern side has the lowest (Figure 1). The approximate coverage of coral reefs on the northern, western, eastern, and southern sides of Kepala Jeri Island is 95.27 ha, 108.95 ha, 29.77 ha, and 5.68 ha, respectively. Sand and seagrass also cover the shallow-water ecosystem and coral reefs (Figure 1).

Coral reef condition

Despite significant coverage, Kepala Jeri Island's coral reef ecosystem must be in better condition. The living coral coverage is quite low, with an approximate proportion of only 5 to 29.33%. The sand dominates the coral ecosystem, covering 28.33-51.67% (Figure 2) (Putra et al. 2018).

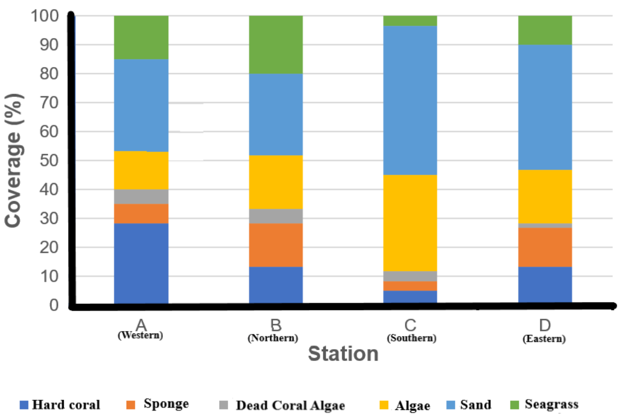

Figure 1. Comparison of coral reef coverage in Kepala Jeri Island

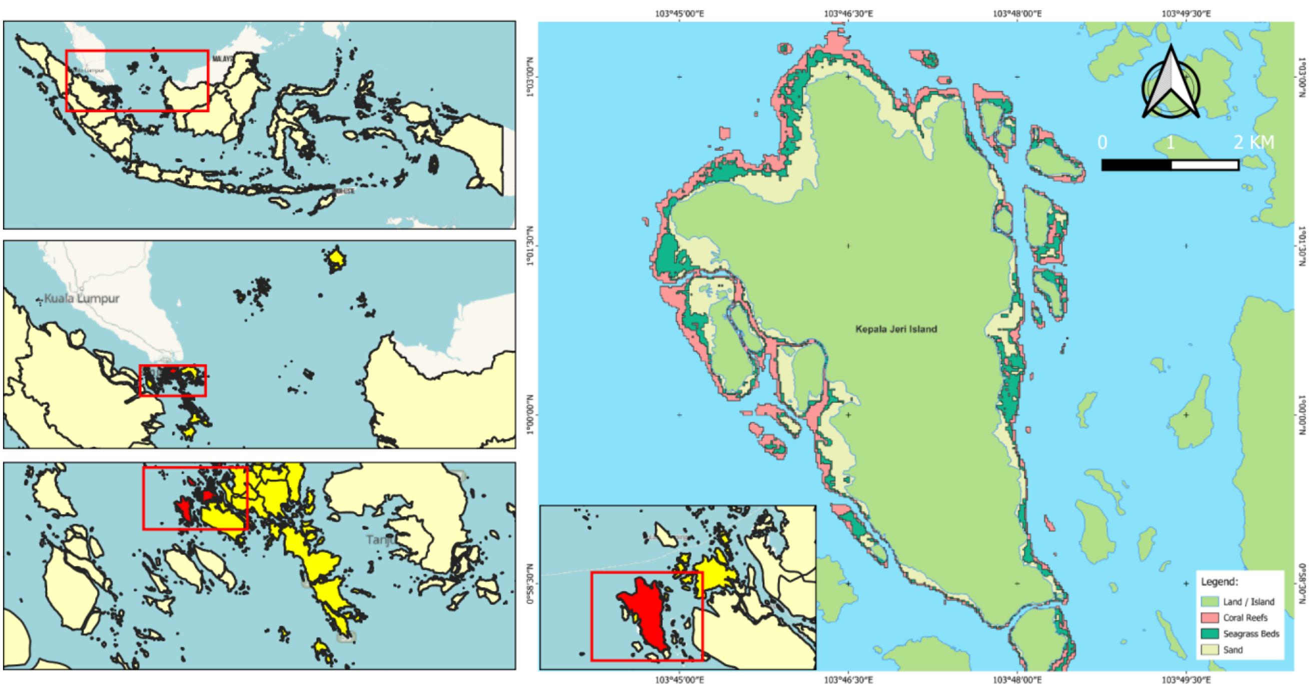

Figure 2. Spatial distribution coral reef ecosystem in Kepala Jeri Island, Belakang Padang, Batam City, Riau Islands, Indonesia

The general coral reef on Kepala Jeri Island is under severe disturbance, the coral reefs have low coverage and keep losing their suitable habitat. The field observation result confirms the invasion of seagrass into the coral reef ecosystem (Figure 3).

Species composition

Field observation revealed that Kepala Jeri Island is home to 26 distinct coral species. However, we anticipate a substantial species distribution, and the species makeup exhibits significant variation. Table 2 shows the detailed coral species availability at each sampling station.

Almost half of the coral species available on Kepala Jeri Island grow on the island's western side (Table 2). The species availability in other stations could have been higher, especially on the southern and eastern sides of the island. The coral coverage at each station could potentially influence the species' availability. We performed a correlation study to determine the connection between the extent of coral coverage and the abundance of coral species. Investigations revealed an important relationship between the extent of coral cover and the number of species on Kepala Jeri Island. This analysis produced a correlation coefficient of 0.998, indicating a strong relationship between coral cover and species abundance. Therefore, the greater the coral cover available, the greater the possibility of coral species being present, and vice versa.

Differences in the availability of coral species raise questions regarding the similarity of species composition between stations. Therefore, we conducted a more in-depth analysis using the Jaccard method to determine the similarity index. Table 3 shows that the similarity matrix on coral species differed less between sampling stations. Based on the analysis, the highest species similarity was only 14.29% between stations A (western) and C (southern). We found no species similarity between stations C (northern) and D (eastern). The low species similarity between observation stations on Kepala Jeri Island indicates that coral species have different habitat suitability.

Table 2. Species composition of the coral reef in Kepala Jeri Island, Batam City, Indonesia

Species	Station			
	A	B	C	D
Acanthochaetetes wellsi		1		
Acropora digitifera	1		1	
Acropora sp.	2			
Amphimedon sp.		1		
Astreopora myriophthalma		1		
Cymbastella sp.	1			1
Euplacella sp.		2		
Favia stelligera	2	1	1	
Goniastrea actinata	1			
Haliclona koremella	1			
Heliopora coerulea		1		
Lendenfeldia complex		1		
Lobophyllia cf corymbosa	1			
Luffariella metachromia			1	
Macrodactyla doreensis		1		
Mycale lampra	1			
Pachyseris rugosa	1			
Padobacia sp.				1
Pavona cactus		1		
Pavona decussata		1		
Platygyra sp.	1			2
Pocillopora danae	1			
Porites cylindrica		1		1
Porites nigrescens				1
Sarcophyton sp.	1			
Turbinaria peltata	1			
Total	13	11	3	5

Note: A: Western, B: Northern, C: Southern, D: Eastern

Table 3. Similarity matrix of coral species composition between observation stations in Kepala Jeri Island, Batam City, Indonesia

Station	A (Western)	B (Northern)	C (Southern)
B (Northern)	4.35%		
C (Southern)	14.29%	7.69%	
D (Eastern)	12.50%	6.67%	0.00%

Figure 3. Coral reef actual condition in Kepala Jeri Island, Batam City, Indonesia (scale: 1:5 with a ruler): A. *Goniastrea actinata*; B. *Favia stelligera*; C. *Euplacella* sp.

Discussion

This study investigates the condition of coral reefs, species composition, and current patterns in Kepala Jeri Island, Batam, Riau Islands, Indonesia. The results show that coral reefs are an important component in the coastal areas of Kepala Jeri Island, especially on this small island (Kench et al. 2014; East et al. 2018). Coral growth that exceeds the sea surface causes reef bleaching and decay, eventually forming sandy land after a long time (Stoddart and Steers 1977). As a result (Lesser 2004), coral ecosystems coexist on most small islands, including Kepala Jeri Island.

The findings reveal that coral is a living organism that naturally grows and extends as long as suitable habitat is available (Takao et al. 2015). On Kepala Jeri Island, the coral growth contributes to land development and provides important ecosystem services. Coral reefs allow waves to break before they reach the land, reducing erosion risk (Kim et al. 2020; Escudero et al. 2021). Moreover, the calm waves that resulted from this process change the likelihood of sedimentation in the nearshore areas (Pomeroy et al. 2021).

However, the results indicate that Coral Reef Island, including Kepala Jeri Island, is considered one of the most vulnerable ecosystems (East et al. 2018). Coral reefs typically grow in an oceanic environment with good water quality (Wenger et al. 2016; MacNeil et al. 2019). The study found that several key parameters for coral reef degradation, such as temperature, salinity, turbidity, and the concentration of total suspended solids, can lead to a disturbance in coral growth (Ennis et al. 2016; Tanzil et al. 2019; Asmawi et al. 2020). Environmental factors such as temperature, salinity, and water quality can contribute to the poor condition of the coral reef ecosystem on Kepala Jeri Island. Global climate change has caused sea surface temperatures to rise, which can lead to coral bleaching. Furthermore, unstable salinity levels and decreased water quality due to pollution can also suppress the growth and resilience of coral reefs. However, we must also consider human factors such as overfishing, physical damage resulting from human activities, and sedimentation from development activities in coastal areas as the primary causes of this problem. These parameters are typically under control on small islands like Kepala Jeri Island on small islands like Kepala Jeri Island, and these parameters are typically under control because anthropogenic activities that could change environmental conditions are unavailable or very limited (Vercelloni et al. 2019).

The vulnerability of coral ecosystems on small islands is increasing (van Hooidonk et al. 2016; Riniwati et al. 2019), including small islands in Batam City, particularly Kepala Jeri Island. According to the study findings, live coral coverage was only 5-29.33%. This result is lower than the previous study, which covered 37.87±2.59% (Bachtiar et al. 2023). It is very important to monitor the condition of coral reefs in the Riau Islands; this can reduce the vulnerability level, including in the entire Riau Islands region (Lubis et al. 2018b).

The research aims to examine the coral ecosystem's health and determine what kinds of coral reefs are in the water around Kepala Jeri Island. Western islands have the most coral cover, while southern islands have the least, according to the study. Additionally, people think the oil spill from Singapore's Tuas Harbor affects the health of the coral reefs on Kepala Jeri Island. Hartuti et al. (2023) reported waste oil activity is often seen in the water surrounding Batam during the northwest monsoon season, which spans from November to April. The oil spill at Tuas Harbor can potentially spread to all surrounding waters, including Batam and Kepala Jeri Island. Unfortunately, this will make the area's coral reef environment worse.

Regarding geography, Kepala Jeri Island is next to Tuas Harbor to the south, and oil spills can occur on this island during a northwest typhoon. Furthermore, Xu and Chua (2016) stated the northern monsoon quickly cleaned up oil spills from Tuas Harbor, which could have polluted the water around Kepala Jeri Island. Unfortunately, the industrial activities on Batam Island, the main island in Batam City, and the location of most industrial activities can impact the surrounding islands negatively (Fahrullah et al. 2018). Therefore, there is a possibility that the pollution will eventually reach Kepala Jeri Island. Apart from industrial activities, various ships use Batam's waters as cruise lines; the neighboring country, Singapore, experiences high ship traffic in the Singapore Strait (Kang et al. 2021); this changes the risk of an oil spill event.

According to the research findings, about half of the coral species on Kepala Jeri Island grow on the island's western side. Unfortunately, species availability at other stations was lower, especially on the southern and eastern sides of the island. A correlation analysis found a significant positive relationship (r=0.998) between coral coverage and species abundance, indicating that the greater the coral coverage, the more coral species are likely to exist (Pan et al. 2023). However, the coral reef ecosystem on Kepala Jeri Island could be in better condition, with living coral coverage as low as 5 to 29.33% (Lee et al. 2019; Yeemin et al. 2024).

This study revealed that oil spills from the Tuas Port in Singapore may contribute to the degradation of coral reefs on Kepala Jeri Island. Oil films can promote sedimentation by binding suspended and dissolved sediments, increasing their depositions (Pan et al. 2023). There is also much seagrass in the coral reef ecosystem, which suggests that seagrass is moving into the coral habitat. The reason is that the disturbances have made the sand halos that normally separate the two ecosystems disappear (Steiner and Willette 2015; Ruiz-Abierno and Armenteros 2017; Winters et al. 2020; Sutrisno et al. 2021). This rapid change in the coastal environment has promoted seagrass expansion into the coral reef areas, further contributing to the degradation of the coral reef ecosystem on Kepala Jeri Island.

Declining populations of grazing species or accelerated seagrass growth often cause seagrass invasions into coral ecosystems. Coral-associated seagrass grazers are common in coral reefs to keep seagrass from growing too much in the coral ecosystem. This creates halos and spaces between the seagrass and coral ecosystems (Bilodeau et al. 2022). However, ecological disturbances, such as increased turbidity and sedimentation rates, may reduce or even eliminate these grazers. According to Ong et al. (2024), the clustered coral ecosystem has a reduced or absent population of sand halos.

The present study found the highest coral cover in the present study, the highest coral cover on the island's western side, while the southern side had the lowest. The estimated coral reef coverage on the northern, western, eastern, and southern sides of Kepala Jeri Island is 95.27 ha, 108.95 ha, 29.77 ha, and 5.68 ha, respectively. Given the current state of the coral reef ecosystem on Kepala Jeri Island, further coral degradation is possible; an increased sedimentation rate most likely causes this degradation. Additionally, one of the ecological roles of seagrass is sediment trapping (Barcelona et al. 2023). Seagrass is a natural ecosystem between the coral reef and shore areas, both with and without mangrove ecosystems (Akhand et al. 2021). Seagrass sediment trapping should reduce the sediment supply to the coral ecosystem. Regrettably, seagrass also dominates the coral ecosystem on Kepala Jeri Island. Therefore, there is a potential that sediment trapping will also occur in coral ecosystems, causing further disturbance to coral reefs.

Our research findings demonstrate the need for interventions to improve control of seagrass development, particularly in coral reef ecosystems. Without intervention, the Kepala Jeri Island coral reef will likely no longer exist. The extension of seagrass, combined with the absence of halo grass, would result in coral reef burial (Harborne et al. 2006). Seagrass beds eventually cover the coral ecosystem (James et al. 2023).

The coral ecosystem on Kepala Jeri Island spans an area of approximately 239.67 ha, with the island's western side exhibiting the largest coral coverage. In contrast, the southern side displays the smallest. The coral reef ecosystem is typically in poor condition, where living coral coverage only accounts for 5-29.33%. Moreover, the sand coverage has surpassed coral reef coverage in Kepala Jeri Island, accounting for 28.33-51.67%, while seagrass has started invading the coral ecosystem. On Kepala Jeri Island, there are 26 coral species. The species disperse across the entire island, with the western region boasting the highest number of species. Jaccard's similarity analysis showed a weak relationship between stations, with a similarity index between 0.00% and 14.29%. The correlation analysis revealed a strong relationship between the number of coral species and the extent of the coral ecosystem. Our research findings regarding the condition of the coral reef ecosystem on Kapal Jeri Island, which has quite low live coral cover (only around 5-29.33%), align with the trend of decreasing coral reef conditions reported in various previous studies in Indonesia and other tropical regions. Furthermore, the diversity of coral species on Kepala Jeri Island is relatively low, with only 26 species identified, which suggests similarities with the coral reef degradation observed in similar locations. Furthermore, the low level of coral species similarity across research stations on Kepala Jeri Island suggests a non-uniform distribution of species, potentially due to local and regional factors influencing the coral reef ecosystem in the region.

Human activities such as coastal development, tourism, and pollution can potentially contribute to the degradation of the coral reef ecosystem on Kepala Jeri Island through physical damage, sedimentation, chemical pollution, and overfishing. Understanding and addressing these impacts is critical to effective regional coral reef conservation and management efforts. Next, we cannot overlook the impact of climate change and ocean acidification on coral reefs. Rising sea temperatures, ocean acidification, and extreme weather events pose significant threats to the health and condition of coral reefs in the surrounding area of Kepala Jeri Island. These factors can cause coral bleaching, reduced calcification, and increased disease susceptibility, all of which contribute to the decline of reef ecosystems.

Finally, it's essential to address arguments suggesting that the observed degradation of the coral reef ecosystem on Kepala Jeri Island could be part of a natural reef cycle. While natural processes certainly play a role in reef dynamics, human intervention has significantly accelerated the degradation of coral reefs worldwide. By addressing unsustainable human activities and implementing effective conservation measures, we can work towards mitigating the impact of human intervention on coral reef ecosystems. By considering these factors and engaging in meaningful discussions, we can better understand the complex interactions between human activities and natural processes and work towards sustainable management and conservation practices for coral reef ecosystems.

Reducing coral reef cover and diversity can significantly impact local marine ecosystems and communities. Coral reefs are a habitat for various species of fish, invertebrates, and other marine organisms, so degradation of this ecosystem can threaten biodiversity, reduce fisheries productivity, and disrupt the ecological balance of coastal areas. We can implement several specific interventions to improve the coral reef ecosystem on Kepala Jeri Island, such as rehabilitating coral reefs by transplanting healthy coral fragments and controlling destructive human activities like overfishing and waste disposal. Integrated management of coastal and marine areas involving all stakeholders is also important for the region's sustainability of coral reef ecosystems.

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REFERENCES

Akhand A, Watanabe K, Chanda A, Tokoro T, Chakraborty K, Moki H, Tanaya T, Ghosh J, Kuwae T. 2021. Lateral carbon fluxes and CO_2

evasion from a subtropical mangrove-seagrass-coral continuum. Sci Total Environ 752: 142190. DOI: 10.1016/j.scitotenv.2020.142190.

Asmawi S, Rifa'i MA, Mahyudin I, Ruslan M. 2020. Protection of turbidity on reefs along the southeast coast of the Kalimantan during the 2015 El Niño. J Wetl Environ Manag 8 (2): 45-62. DOI: 10.20527/jwem.v8i1.216.

Bachtiar I, Hadi TA, Karnan K, Bachtiar NT. 2023. Other faunas, coral rubbles, and soft coral covers are important predictors of coral reef fish diversity, abundance, and biomass. Fish Aquat Sci 26 (4): 268-281. DOI: 10.47853/FAS.2023.e23.

Barcelona A, Colomer J, Serra T. 2023. Spatial sedimentation and plant captured sediment within seagrass patches. Mar Environ Res 188: 105997. DOI: 10.1016/j.marenvres.2023.105997.

Bilodeau SM, Schwartz AW, Xu B, Paúl Pauca V, Silman MR. 2022. A low-cost, long-term underwater camera trap network coupled with deep residual learning image analysis. PLoS One 17 (2): e0263377. DOI: 10.1371/journal.pone.0263377.

Clements CS, Hay ME. 2019. Biodiversity enhances coral growth, tissue survivorship and suppression of macroalgae. Nat Ecol Evol 3: 178-182. DOI: 10.1038/s41559-018-0752-7.

Comte A, Pendleton LH. 2018. Management strategies for coral reefs and people under global environmental change: 25 years of scientific research. J Environ Manag 209: 462-474. DOI: 10.1016/j.jenvman.2017.12.051.

De'Ath G, Fabricius KE, Sweatman H, Puotinen M. 2012. The 27-year decline of coral cover on the Great Barrier Reef and its causes. Proc Natl Acad Sci 109 (44): 17995-17999. DOI: 10.1073/pnas.1208909109.

Doropoulos C, Babcock RC. 2018. Harnessing connectivity to facilitate coral restoration. Front Ecol Environ 16 (10): 558-559. DOI: 10.1002/fee.1975.

Dutton IM, Bengen DG, Tulungen JJ. 2000. The challenges of coral reef management in Indonesia. In Oceanographic Processes of Coral Reefs (pp. 335-350). CRC Press. DOI: 10.1201/9781420041675-24.

Eddy TD, Lam VW, Reygondeau G, Cisneros-Montemayor AM, Greer K, Palomares ML, Bruno JF, Ota Y, Cheung WW. 2021. Global decline in capacity of coral reefs to provide ecosystem services. One Earth 4 (9): 1278-1285. DOI: 10.1016/j.oneear.2021.08.016.

Ennis RS, Brandt ME, Wilson Grimes KR, Smith T. B. 2016. Coral reef health response to chronic and acute changes in water quality in St. Thomas, United States Virgin Islands. Mar Pollut Bull 111 (1-2): 418-427. DOI: 10.1016/j.marpolbul.2016.07.033.

Escudero M, Reguero BG, Mendoza E, Secaira F, Silva R. 2021. Coral reef geometry and hydrodynamics in beach erosion control in North Quintana Roo, Mexico. Front Mar Sci 8: 684732. DOI: 10.3389/fmars.2021.684732.

Fahrullah H, Zulkarnaini Z, Syahril S. 2018. Distribution model of dispersed BOD5 waste (nonpoint source pollution-bod) in coastal watersof Buluh Island Batam City Riau Archipelago. Jurnal Ilmu Lingkungan 12 (2): 140-151. DOI: 10.31258/jil.12.2.p.140-151. [Indonesian]

Gilmour JP, Smith LD, Heyward AJ, Baird AH, Pratchett MS. 2013. Recovery of an isolated coral reef system following severe disturbance. Science 340 (6128): 69-71. DOI: 10.1126/science.1232310.

Girard F, Fisher CR. 2018. Long-term impact of the Deepwater Horizon oil spill on deep-sea corals detected after seven years of monitoring. Biol Conserv 225: 117-127. DOI: 10.1016/j.biocon.2018.06.028.

Glasl B, Bongaerts P, Elisabeth NH, Hoegh-Guldberg O, Herndl GJ, Frade PR. 2017. Microbiome variation in corals with distinct depth distribution ranges across a shallow-mesophotic gradient (15-85 m). Coral Reefs 36: 447-452. DOI: 10.1007/s00338-016-1517-x.

Gust KA, Najar FZ, Habib T, Lotufo GR, Piggot AM, Fouke BW, Laird JG, Wilbanks MS, Rawat A, Indest KJ, Roe BA. 2014. Coral-zooxanthellae meta-transcriptomics reveals integrated response to pollutant stress. BMC Genomics 15: 591. DOI: 10.1186/1471-2164-15-591

Harborne AR, Mumby PJ, Micheli F, Perry CT, Dahlgren CP, Holmes KE, Brumbaugh DR. 2006. The functional value of Caribbean coral reef, seagrass and mangrove habitats to ecosystem processes. Adv Mar Biol 50: 57-189. DOI: 10.1016/S0065-2881(05)50002-6.

Hartuti M, Parwati E, Prayogo T, Sulma S, Ibrahim A, Afgatiani PM, Wijaya AD, Kusuma FB, Herdanis C. 2023. Oil spill distribution analysis using multi sensor satellite data in Batam-Bintan and Karawang Waters. AIP Conf Proc 2941 (1): 030036. DOI: 10.1063/5.0181687.

Hochberg EJ, Gierach MM. 2021. Missing the reef for the corals: Unexpected trends between coral reef condition and the environment at the ecosystem scale. Front Mar Sci 8: 1-10. DOI: 10.3389/fmars.2021.727038.

Hughes TP, Barnes ML, Bellwood DR, Cinner JE, Cumming GS, Jackson JB, Kleypas J, Van De Leemput IA, Lough JM, Morrison TH, Palumbi SR. 2017. Coral reefs in the Anthropocene. Nature 546: 82-90.

James RK, Keyzer LM, Van de Velde SJ, Herman PM, Van Katwijk MM, Bouma TJ. 2023. Climate change mitigation by coral reefs and seagrass beds at risk: How global change compromises coastal ecosystem services. Sci Total Environ 857: 159576. DOI: 10.1016/j.scitotenv.2022.159576.

Kang HS, Loon SC, Wong JH, Harun MA, Abdulhamid MF, Nusyirwan IF, Kadir AS, Koto J, Ee JY. 2021. Prediction of ship collision risk on Singapore Strait using AIS data. J Transportation Syst Eng 8 (2): 21-28. DOI: 10.11113/jtse.v8.173.

Kench PS, Owen SD, Ford MR. 2014. Evidence for coral island formation during rising sea level in the central Pacific Ocean. Geophys Res Lett 41 (3): 820-827. DOI: 10.1002/2013GL059000.

Kim T, Baek S, Kwon Y, Lee J, Cha SM, Kwon S. 2020. Improved coastal erosion prevention using a hybrid method with an artificial coral reef: Large-scale 3D hydraulic experiment. Water 12 (10): 2801. DOI: 10.3390/w12102801.

Komyakova V, Jones GP, Munday PL. 2018. Strong effects of coral species on the diversity and structure of reef fish communities: A multi-scale analysis. PLoS One 13 (8): e0202206. DOI: 10.1371/journal.pone.0202206.

Kusumoto B, Costello MJ, Kubota Y, Shiono T, Wei CL, Yasuhara M, Chao A. 2020. Global distribution of coral diversity: Biodiversity knowledge gradients related to spatial resolution. Ecol Res 35 (2): 315-326. DOI: 10.1111/1440-1703.12096.

Lee C-L, Wen CK, Huang Y-H, Chung C-Y, Lin H-J. 2019. Ontogenetic habitat usage of juvenile carnivorous fish among seagrass-coral mosaic habitats. Diversity 11 (2): 25. DOI: 10.3390/d11020025.

Lesser MP. 2004. Experimental biology of coral reef ecosystems. J Exp Mar Bio Ecol 300 (1-2): 217-252. DOI: 10.1016/j.jembe.2003.12.027.

Licuanan WY, Robles R, Reyes M. 2019. Status and recent trends in coral reefs of the Philippines. Mar Pollut Bull 142: 544-550. DOI: 10.1016/j.marpolbul.2019.04.013.

Limmon G, Delrieu-Trottin E, Patikawa J, Rijoly F, Dahruddin H, Busson F, Steinke D, Hubert N. 2020. Assessing species diversity of Coral Triangle artisanal fisheries: A DNA barcode reference library for the shore fishes retailed at Ambon harbor (Indonesia). Ecol Evol 10 (7): 3356-3366. DOI: 10.1002/ece3.6128.

Lubis MZ, Anurogo W, Hanafi A, Kausarian H, Taki HM, Antoni S. 2018a. Distribution of benthic habitat using Landsat-7 Imagery in shallow waters of Sekupang, Batam Island, Indonesia. Biodiversitas 19 (3): 1117-1122. DOI: 10.13057/biodiv/d190346.

Lubis MZ, Pujiyati SRI, Pamungkas DS, Tauhid M, Anurogo W, Kausarian H. 2018b. Coral reefs recruitment in stone substrate on Gosong Pramuka, Seribu Islands, Indonesia. Biodiversitas 19 (4): 1451-1458. DOI: 10.13057/biodiv/d190435.

MacDonald C, Bridge TC, Jones GP. 2016. Depth, bay position and habitat structure as determinants of coral reef fish distributions: Are deep reefs a potential refuge? Mar Ecol Prog Ser 561: 217-231. DOI: 10.3354/meps11953.

MacNeil MA, Mellin C, Matthews S, Wolff NH, McClanahan TR, Devlin M, Drovandi C, Mengersen K, Graham NA. 2019. Water quality mediates resilience on the Great Barrier Reef. Nat Ecol Evol 3 (4): 620-627. DOI: 10.1038/s41559-019-0832-3.

Marsuki ID, Sadarun B, Palupi RD. 2013. Coral reef condition and clam abundance in Indo island waters. Jurnal Mina Laut Indonesia 1 (01): 61-72. [Indonesian]

O'Brien PA, Tan S, Yang C, Frade PR, Andreakis N, Smith HA, Miller DJ, Webster NS, Zhang G, Bourne DG. 2020. Diverse coral reef invertebrates exhibit patterns of phylosymbiosis. ISME J 14 (9): 2211-2222. DOI: 10.1038/s41396-020-0671-x.

Ong TW, McManus LC, Vasconcelos VV, Yang L, Su C. 2024. Seeing halos: Spatial and consumer-resource constraints to landscape of fear patterns. bioRxiv: 2024-04. DOI: 10.1101/2024.04.15.587800.

Pan H, Tang K, Zhuo J, Lu Y, Chen J, Lv Z. 2023. Underwater acoustic technology-based monitoring of oil spill: A review. J Mar Sci Eng 11 (4): 870. DOI: 10.3390/jmse11040870.

Pisapia C, Pratchett MS. 2014. Spatial variation in background mortality among dominant coral taxa on Australia's Great Barrier Reef. PLoS One. 9: e100969. DOI: 10.1371/journal.pone.0100969.

Pomeroy AW, Storlazzi CD, Rosenberger KJ, Lowe RJ, Hansen JE, Buckley ML. 2021. The contribution of currents, sea-swell waves, and infragravity waves to suspended-sediment transport across a coral reef-lagoon system. J Geophys Res Oceans 126 (3): e2020JC017010. DOI: 10.1029/2020JC017010.

Price NN, Muko S, Legendre L, Steneck R, van Oppen MJ, Albright R, Ang Jr P, Carpenter RC, Chui AP, Fan TY, Gates RD. 2019. Global biogeography of coral recruitment: Tropical decline and subtropical increase. Mar Ecol Prog Ser 621: 1-17. DOI: 10.3354/meps12980.

Putra RD, Suryanti A, Kurniawan D, Pratomo A, Irawan H, Raja TS, Kurniawan R, Pratama G. 2018. Responses of herbivorous fishes on coral reef cover in outer island Indonesia (Study Case: Natuna Island). In E3S Web Conf 47: 04009. EDP Sciences. DOI: 10.1051/e3sconf/20184704009.

Razak TB, Lamont TA, Hukom FD, Alisa CA, Asri AR, Ferse SC. 2024. A review of the legal framework for coral reef restoration in Indonesia. Ocean Coast Manag 248: 106944. DOI: 10.1016/j.ocecoaman.2023.106944.

Riniwati H, Harahab N, Abidin Z. 2019. A vulnerability analysis of coral reefs in coastal ecotourism areas for conservation management. Diversity 11 (7): 107. DOI: 10.3390/d11070107.

Rioja-Nieto R, Álvarez-Filip L. 2019. Coral reef systems of the Mexican Caribbean: Status, recent trends and conservation. Mar Pollut Bull 140: 616-625. DOI: 10.1016/j.marpolbul.2018.07.005.

Ruiz-Abierno A, Armenteros M. 2017. Coral reef habitats strongly influence the diversity of macro-and meiobenthos in the Caribbean. Mar Biodivers 47: 101-111. DOI: 10.1007/s12526-016-0553-7.

Schoonees T, Gijón Mancheño A, Scheres B, Bouma TJ, Silva R, Schlurmann T, Schüttrumpf H. 2019. Hard structures for coastal protection, towards greener designs. Estuar Coast 42: 1709-1729. DOI: 10.1007/s12237-019-00551-z.

Souter D, Planes S, Wicquart J, Logan M, Obura D, Staub F. 2021. Status of coral reefs of the world: 2020 report. DOI: 10.59387/WOTJ9184.

Stambler N. 2017. The zooxanthellae-hard-coral symbiosis. In: Grube M, Seckbach J, Muggia L (eds.). Algal and Cyanobacteria Symbioses. World Scientific, London. DOI: 10.1142/9781786340580_0014.

Steiner SC, Willette DA. 2015. Dimming sand halos in Dominica: New expansion of the invasive seagrass *Halophila stipulacea*. Reef Encoun 30: 43-45.

Stoddart DR, Steers JA. 1977. The nature and origin of coral reef islands. In: Jones OA, Endean R (eds.). Biology and Geology of Coral Reefs Volume IV: Geology 2. Academic Press, New York.

Sutrisno D, Sugara A, Darmawan M. 2021. The assessment of coral reefs mapping methodology: An integrated method approach. IOP Conf Ser Earth Environ Sci 750 (1): 012030.

Takao S, Yamano H, Sugihara K, Kumagai NH, Fujii M, Yamanaka Y. 2015. An improved estimation of the poleward expansion of coral habitats based on the inter-annual variation of sea surface temperatures. Coral Reefs 34: 1125-1137. DOI: 10.1007/s00338-015-1347-2.

Tanzil JT, Goodkin NF, Sin TM, Chen ML, Fabbro GN, Boyle EA, Lee AC, Toh KB. 2019. Multi-colony coral skeletal Ba/Ca from Singapore"s turbid urban reefs: Relationship with contemporaneous in-situ seawater parameters. Geochim Cosmochim Acta 250: 191-208. DOI: 10.1016/j.gca.2019.01.034.

Van Hooidonk R, Maynard J, Tamelander J, Gove J, Ahmadia G, Raymundo L, Williams G, Heron SF, Planes S. 2016. Local-scale projections of coral reef futures and implications of the Paris Agreement. Sci Rep 6 (1): 1-8. DOI: 10.1038/srep39666.

Vercelloni J, Kayal M, Chancerelle Y, Planes S. 2019. Exposure, vulnerability, and resiliency of French Polynesian coral reefs to environmental disturbances. Sci Rep 9 (1): 1027. DOI: 10.1038/s41598-018-38228-5.

Watson MS, Claar DC, Baum JK. 2016. Subsistence in isolation: Fishing dependence and perceptions of change on Kiritimati, the world's largest atoll. Ocean Coast Manag 123: 1-8. DOI: 10.1016/j.ocecoaman.2016.01.012.

Wenger AS, Williamson DH, da Silva ET, Ceccarelli DM, Browne NK, Petus C, Devlin MJ. 2016. Effects of reduced water quality on coral reefs in and out of no-take marine reserves. Conserv Biol 30 (1): 142-153. DOI: 10.1111/cobi.12576.

Williams GJ, Graham NA, Jouffray JB, Norström AV, Nyström M, Gove JM, Heenan A, Wedding LM. 2019. Coral reef ecology in the Anthropocene. Funct Ecol 33 (6): 1014-1022. DOI: 10.1111/1365-2435.13290.

Winters G, Beer S, Willette DA, Viana IG, Chiquillo KL, Beca-Carretero P, Villamayor B, Azcárate-García T, Shem-Tov R, Mwabvu B, Migliore L, Rotini A, Oscar MA, Belmaker J, Gamliel I, Alexandre A, Engelen AH, Procaccini G, Rilov G. 2020. The tropical seagrass Halophila stipulacea: Reviewing what we know from its native and invasive habitats, alongside identifying knowledge gaps. Front Mar Sci 7: 300. DOI: 10.3389/fmars.2020.00300.

World Population Review. 2024. Countries with coral reefs 2024 [WWW Document].

Xu M, Chua VP. 2016. A numerical study on flow and pollutant transport in Singapore coastal waters. Mar Pollut Bull 111 (1-2): 160-177. DOI: 10.1016/j.marpolbul.2016.07.014.

Yeemin T, Sutthacheep M, Pengsakun S, Klinthong W, Chamchoy C, Suebpala W. 2024. Quantifying blue carbon stocks in interconnected seagrass, coral reef, and sandy coastline ecosystems in the Western Gulf of Thailand. Front Mar Sci 11: 1297286. DOI: 10.3389/fmars.2024.1297286.