Megabenthos Assemblages and Benthic Dynamics for Sustainable Coral Reef Management in Biak, Papua

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Abstract

Coral reef ecosystems are home to a diverse array of biota, including megabenthos, which serve as indicators of the present condition of these ecosystems. This research examines the occurrence and abundance of megabenthos as well as their relationship to coverage of benthic coral and turf algae in coral reef ecosystem. Sampling was conducted at 14 reef sites in Biak, Papua, Indonesia. The coverage of benthic groups and megabenthos was observed by using an underwater photographic transect and a belt transect, respectively. Coverage of coral and turf algae ranges from 5.4 to 53.7 % and from 23.9 to 68 %, respectively. The most abundance megabenthos from all locations and years was sea urchin Diadema spp., followed by Linckia laevigata, and the lowest abundance was sea cucumber. Predatory coral polyps Acanthaster planci have a lower abundance and occurrence than the other predatory coral snail, Drupella. Overall, we found a positive correlation between the abundance of Diadema spp. and Linckia laevigata and turf algae cover, and a negative correlation between the abundance of lobster Panulirus and coral cover. Human influence, such as fishing activity on economically important megabenthos groups (snail Trochidae, giant clams, lobsters, sea cucumbers), might play a role in shaping megabenthos assemblages. This research supports the sustainable management of Biak's marine ecosystems, which provide vital ecological functions and economic resources for coastal communities.

Keywords: *Benthic, Diadema, Echinoderm, Mollusc, Starfish*

Introduction

Coral reefs are tropical marine ecosystems renowned for their complex biological relationships, rich biodiversity, high productivity, and varied habitats (Sobha *et al*., 2023; Pellerin *et al*., 2025). As a result, the diversity and abundance of benthic communities in these tropical reefs are likely influenced by habitat type (de Bakker *et al*., 2017; Tebbett *et al*., 2023; Aji *et al*., 2024). The benthic composition of the coral reef ecosystem may determine what kind of reef organisms occupy the areas for nursery, predation, and reproduction. Benthos, benthic organisms that live on the bottom waters of marine ecosystems, are commonly found (Stratmann *et al*., 2020; Sun *et al*., 2025). Their size ranges from tiny to large and is often classified into meiobenthos, macrobenthos, and megabenthos. Benthos that can be easily spotted by the human naked eye in situ are megabenthos with have a size of more than 1 cm (Stratmann *et al*., 2020). The abundance and distribution of megabenthos in the reef ecosystems depend on the cover of live coral, the primary habitat-forming organisms on coral reefs (Rodríguez *et al*., 2022). Due to their limited mobility, megabenthos are easily susceptible to environmental and habitat changes

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(Command *et al*., 2023; Sun *et al*., 2025). As increasing sea water temperature and higher human activity may have a severe impact on the coral reef ecosystem by declining coral coverage (de Bakker *et al*., 2017; Hughes *et al*., 2018; Aji *et al*., 2024), which subsequently influences the megabenthos community (Dharmawan *et al*., 2019; Rizqi *et al*., 2019).

Megabenthos comprised a diverse array of biota, including molluscs, crustaceans, and echinoderms (Arbi *et al*., 2017). The presence of megabenthos is important for the ecosystems, whose role varies from controlling the small organism population (predation), nutrient cycling, to ecosystem engineering by providing habitats for other organisms (Moerland *et al*., 2016; van der Ouderaa *et al*., 2021; Command *et al*., 2023). However, due to degraded habitat and human activities, the abundance and distribution of megabenthos in coral reef ecosystems can be impacted (Manik *et al*., 2024). Some species of megabenthos may have economic value as food sources; thus, they are exploited for trade, such as giant clams, snails, lobsters, and sea cucumbers, which leads to a decrease in their abundance (Bennett *et al*., 2025; Lionata *et al*., 2025). Among echinoderm species, sea cucumber is the most vulnerable to overfishing due to its ease of capture and high market demand (Setyastuti *et al*., 2018, 2024; Ramírez-González *et al*., 2020). Other species may be exploited for souvenirs or handicraft materials, which confer economic value (Bennett *et al*., 2025), such as starfish, mollusc Trochidae, and Tridacna. Furthermore, the outbreak of coral polyp predators, snail *Drupella* spp. (Moerland *et al*., 2016) and crown-of-thorns starfish (COTS) (Tkachenko and Hoang, 2022) may reduce coral cover in ecosystems. It has been reported that the feeding behaviour of COTS on live coral impacts reef systems and leads to the degradation of coral reefs in the Indian Ocean and the Indo-Pacific region (Foo *et al*., 2024). The substrate availability previously occupied by coral may now be replaced by other opportunistic benthic groups, such as turf algae and macroalgae (Crisp *et al*., 2022), which increases the likelihood of influencing the population of an algae-eating sea urchin (Ditzel *et al.,* 2022). Thus, understanding the abundance and habitat of megabenthos in coral reef ecosystems is necessary for better management and conservation.

Biak, Papua, which is located in the eastern part of Indonesia, is an example of a region with high marine biodiversity and a relatively healthy coastal ecosystem. This region covers a total area of around 2.600 km^2 with a coordinate location between 134^o 47' – 136^o East Longitude and 0^o 55' – 1^o 27 South Latitude (BPS, 2024). The majority of people living in Biak depend on the ocean's natural resources. Through the Coral Reef Rehabilitation and Management Program (Coremap), the Indonesian government has conducted monitoring of coral reef and megabenthos conditions across Indonesian waters, including Biak, Papua Province (Dharmawan *et al*., 2017, 2019; Hadi *et al*., 2020). The megabenthos groups that are monitored on the Coremap program are blue sea star, crown-of-thorns starfish, sea cucumber, snail *Trochidae*, giant clam, coral-eating snail *Drupella*, sea urchin, and lobster (Arbi *et al*., 2017; Dharmawan *et al*., 2019).

The purpose of this study is to examine the occurrence and abundance of megabenthos in the coral reef ecosystems of Biak waters. Further in-depth analysis is needed to determine whether coral and turf algae-dominated reefs have positive or negative effects on the distribution of megabenthos. The information supports the sustainability of Indonesia's marine ecosystems, which provide ecological and economic value for coastal communities.

Materials and Methods

This study was carried out in Biak Island, Papua, Indonesia (Figure 1). In total, 14 reef sites, which are Animi, Anggaduber, Anggopi, Saba, Bakribo, Opiaref, Aryom, Soryar, Woniki, Orwer, Sareidi, Ibdi, Mandon, and Yenusi, were surveyed annually in September from 2014, 2015, and 2016 for coral cover and megabenthos conditions. Megabenthos observed were focused on the eight target taxa, including blue sea star, crown-of-thorns starfish, sea cucumber, snail Trochidae, giant clam, coral-eating snail *Drupella*, sea urchin, and lobster (Table 1). The eight taxa observed during the monitoring program were selected due to their significant role as bioindicators in coral reef ecosystems. They are to be sensitive to water quality and overfishing. Data collection was performed using SCUBA diving at shallow-water reefs.

Benthic communities from reefs were assessed using a photo-quadrat transect method. The transects were laid out at random for a 50-m length, and subsequently, the photos were taken using a digital camera, Canon PowerShot G16, with underwater housing along the transect line continuously from the starting point until the end of the transect line (Rizqi *et al*., 2019). The transect line was placed parallel to the coastline at a depth of approximately 3–5 m. Photo quadrats, framed at 44 cm x 58 cm, were taken at 1-meter intervals from meters 1 to 50 (resulting in a total of 50 pictures per transect). The frame photos were analyzed using Coral Point Count with Excel extensions (CPCe) program to estimate the coverage of the different benthic organisms (Kohler and Gill, 2006).

Table 1. Megabenthos target during the survey.

Megabenthos	Common name	Groups
Linckia laevigata	Blue sea star	Asteroidea - Echinodermata
Acanthaster planci	Crown-of-thorns starfish	Asteroidea - Echinodermata
Holothurians	Sea cucumber	Holothuroidea - Echinodermata
Trochus	Snail maculated top shell	Gastropoda - Mollusc
Tridacna	Giant clam	Bivalvia - Mollusc
Diadema	Sea urchin	Echinoidea - Echinodermata
Drupella	Coral-eating snail	Gastropoda - Mollusc
Panulirus	Lobster	Malacostraca - Crustacea

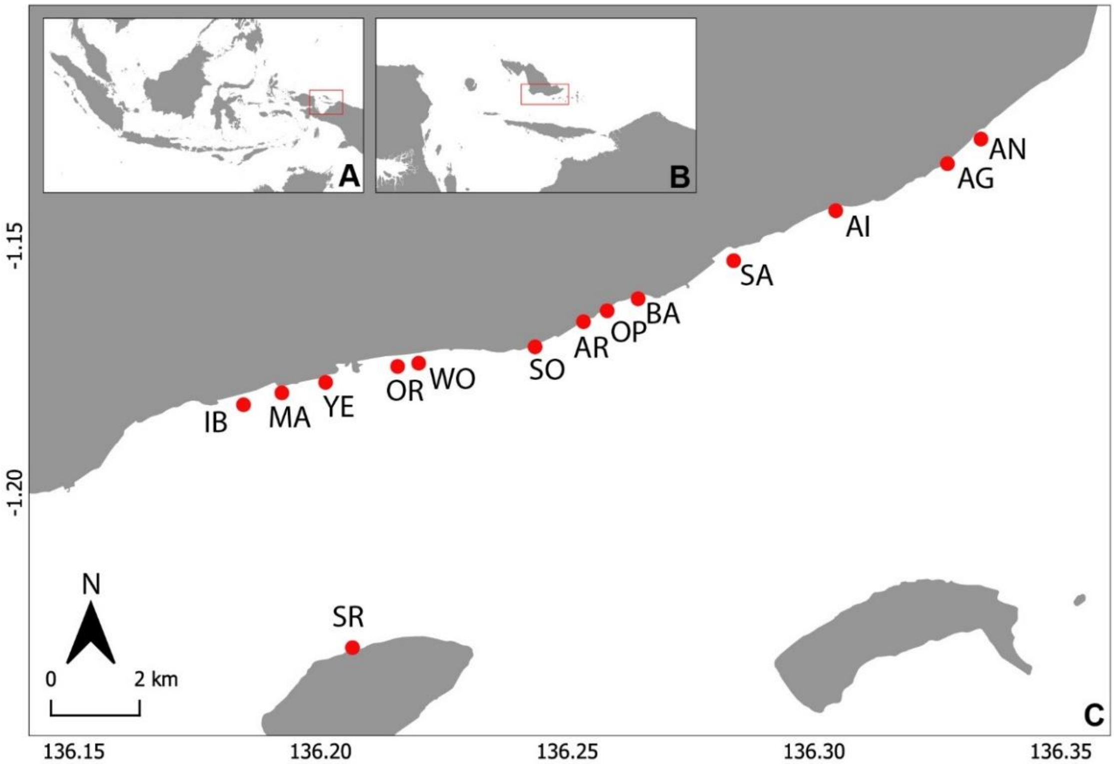

Figure 1. Sampling locations from reef ecosystems in Biak, Papua, Indonesia. (A) Indonesia. (B) Biak. (C) Survey location from 14 reef sites. Note = AN: Animi, AG: Anggaduber, AI: Anggopi, SA: Saba, BA: Bakribo, OP: Opiaref, AR: Aryom, SO: Soryar, WO: Woniki, OR: Orwer, SR: Sareidi, IB: Ibdi, MA: Mandon, YE: Yenusi.

Data collection for megabenthos was conducted using the benthos belt transect method with a transect length of 70 meters (Arbi *et al*., 2017). The occurrence of megabenthos was recorded and counted by their presence along the transect with a visual observation of 1 meter to the left and right of the transect line. Thus, the total area that was surveyed for megabenthos can be calculated. We recorded the presence of megabenthos (Table 1) and documented their image (Figure 2).

Data analysis

R software version 4.0.2 was used for all analyses. The benthic photographs from year 2016 survey were analyzed using Coral Point Count with Excel extensions (CPCe) software (Kohler and Gill, 2006). Each underwater transect image was examined to determine the percentage cover of different benthic groups. The software was configured to place 30 random points on each photo, and the benthic groups beneath them were identified. Specifically, the benthic group was classified into the following categories: hard coral, soft coral, crustose coralline algae, turf algae, sponges, macroalgae, other invertebrates, dead coral, rubble, and sand. The CPCe outputs were compiled into a single dataset and converted into percentage cover values for each benthic group per transect. Furthermore, the occurrence of megabenthos was counted from all stations in the years 2014, 2015, and 2016.

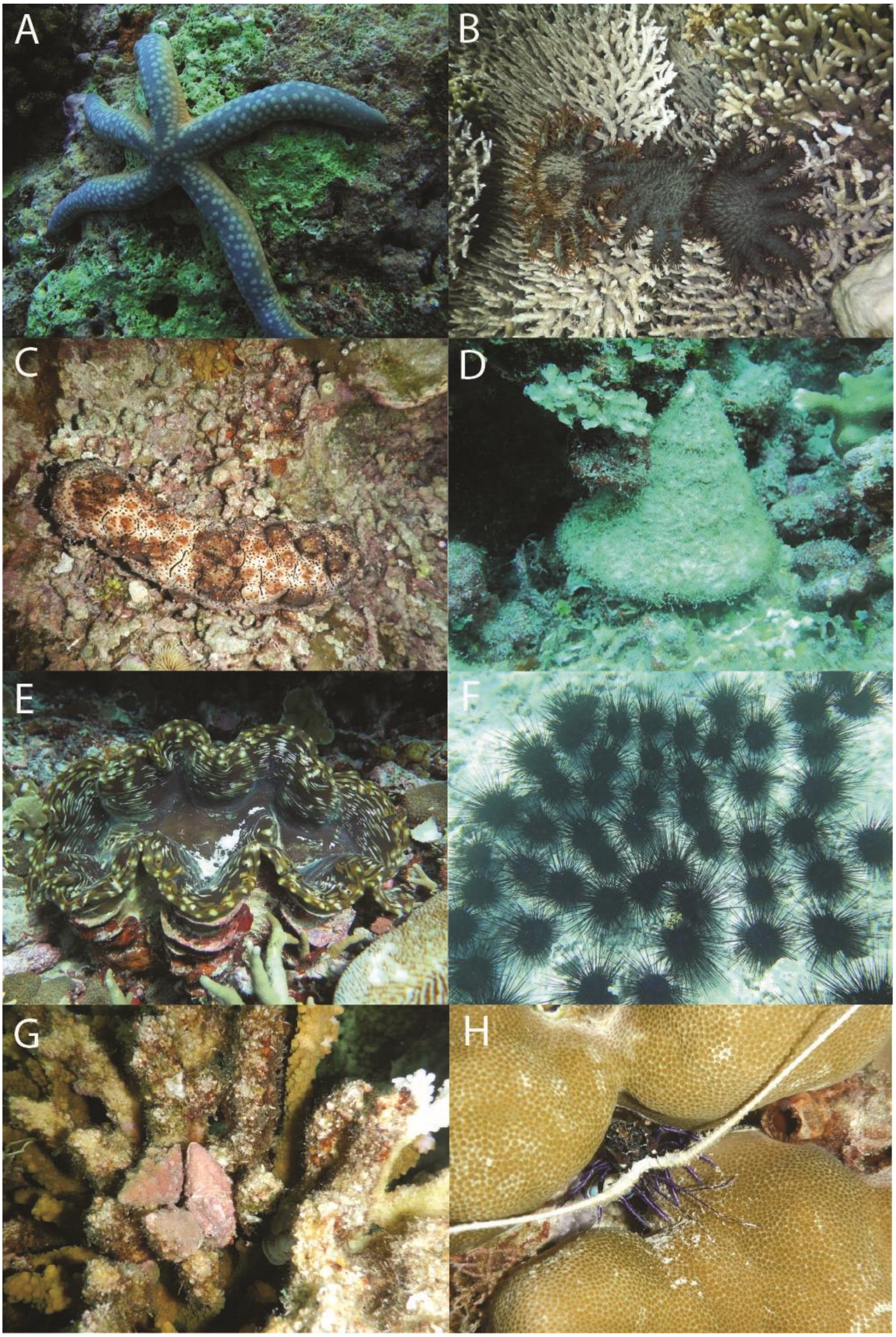

Figure 2. Representative image of megabenthos found during survey in Biak waters. A. *Linckia laevigata*, B. *Acanthaster planci*, C. Holothurian, D. *Trochus* sp., E. *Tridacna* sp., F. *Diadema* sp., G. *Drupella* sp., H. *Panulirus* sp. (Photos: Ludi Parwadani Aji)

The abundance of megabenthos per transect was counted by dividing the number of megabenthos individuals by the total area of observation (70m x 2m = 140m^2) (Aji *et al*., 2017). A stacked bar graph and boxplot were made for each megabenthos group's abundance per m^2 per station per year. This provides a visual assessment of megabenthos community composition across stations during three consecutive years of observation.

Pearson correlation tests were conducted to assess the relationship between the percentage cover of benthic groups (specifically coral and turf algae) and the total number of megabenthos individuals per station from year 2016. To visualize the differences in benthic and megabenthos community composition across stations, non-metric multidimensional scaling (NMDS) was applied. This was done using the *metaMDS* function from the vegan package (Oksanen *et al*., 2019), utilizing a Bray-Curtis dissimilarity matrix based on the total megabenthos counts. Additionally, an *envfit* analysis was conducted to assess the impact of variations in benthic group composition on megabenthos community structure among stations.

Results and Discussion

Benthic composition

The composition of benthic coral reef communities in year 2016 across sites on Biak, Papua varies (Table 2). The biotic groups occupying most of the substrate are hard coral and turf algae. The coverage of the main benthic group of reef builders, which is hard coral, ranges from 5.4% (Opiaref) to 53.7% (Animi). While the coverage of turf algae ranged between 23.9% (Ibdi) and 68% (Opiaref). Soft coral and macroalgae were observed in eight stations, with the highest coverage found in Orwer (16.8%), followed by Soryar (6%). Similarly, crustose coralline algae (CCA) were found in nine stations, with the highest coverage was 8.9% (Saba), and sponge were found in 11 stations, with coverage up to 4% (Saba). Furthermore, the highest coverage of other invertebrates was found in Anggopi, with just 8.9%. The highest coverage of abiotic benthic groups (such as dead coral, rubble, and sand) was 5.8% (Animi), 15.8% (Woniki), and 18.2% (Ibdi), respectively.

Recently, there has been concern about the shift in benthic dominance of benthic groups from coral to other non-reef building groups in coastal ecosystems due to anthropogenic stressors such as climate change and human activities (Tebbett *et al*., 2023; Aji *et al*., 2024). It was commonly reported that turf algae are one of the opportunistic major benthic groups that may overgrow coral dominance (de Bakker *et al*., 2017; Crisp *et al*., 2022). A shift from coral-dominated reefs to turf algae may have an impact on the population dynamics of megabenthos. High coral coverage or abundance, with more diverse coral species, provides habitat structural complexity (Ferreira *et al*., 2023) and habitat availability for megabenthos organisms (Aji *et al*., 2023; Becking *et al*., 2024). Subsequently, changes in benthic cover influence the abundance of megabenthos, which includes burrowing, attaching, sessile, or crawling organisms on or in the substrate of coral reef ecosystems.

Megabenthos composition and abundance

As can be seen from Figure 3, the most abundant megabenthos from all locations and years (2014, 2015, and 2016) was the sea urchin *Diadema.*

Table 2. The coverage (%) of benthic composition from 14 reefs in Biak, Papua, in the year 2016.

Sites	Hard coral	Soft coral	Turf algae	CCA	Macro algae	Sponge	Other invert	Dead coral	Rubble	Sand
Animi	53.7	2.0	31.4	3.0	0	1.6	0	5.8	0	2.5
Anggaduber	39.5	0.9	42.2	0.9	0	0	6.6	3.0	1.8	5.2
Anggopi	14.0	1.5	41.7	2.4	3.0	2.2	8.9	2.0	11.9	12.4
Saba	18.7	0.8	52.4	8.9	1.7	4.0	1.2	0.8	5.7	5.6
Bakribo	28.7	6.5	43.3	4.1	0	1.1	5.1	2.2	4.0	4.9
Opiaref	5.4	0	68.0	1.0	0	0	9.2	0	3.2	13.2
Aryom	7.0	0	58.4	3.6	0	2.3	11.1	0.8	2.6	14.2
Soryar	11.2	0	56.6	5.0	6.0	1.7	4.2	0.9	4.7	9.7
Woniki	23.7	3.7	40.8	0	0.8	2.1	0.8	2.7	15.8	9.6
Orwer	26.9	16.8	27.4	0	1.4	1.6	1.6	2.5	8.4	13.3
Sareidi	24.4	0	36.8	0	0	1.5	2.3	3.0	15.3	16.7
Ibdi	39.2	0	23.9	0.8	1.1	1.5	0.8	0.8	13.8	18.2
Mandon	30.9	2.7	37.3	0	1.5	1.3	0.8	3.2	8.6	13.5
Yenusi	42.9	0	28.6	0	1.1	0	3.1	4.3	10.6	9.5

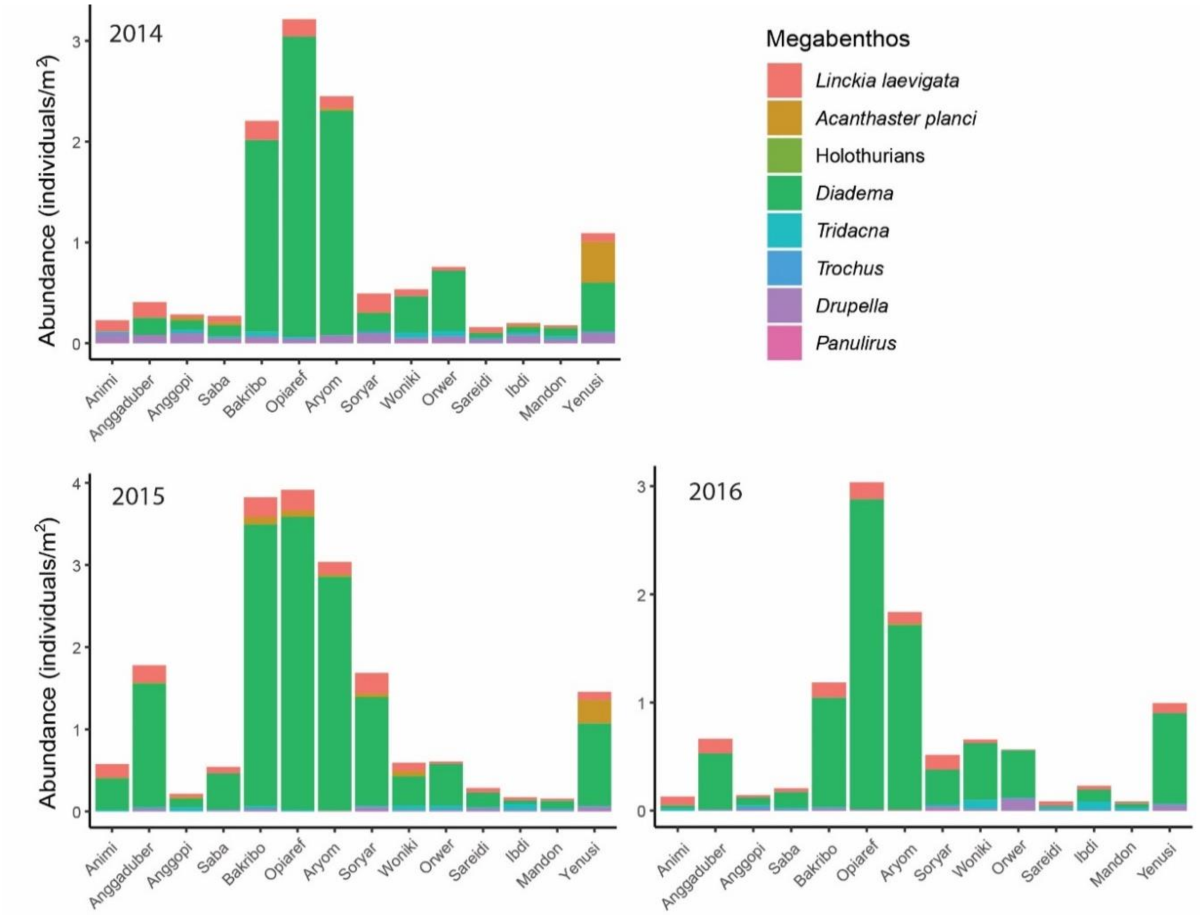

Figure 3. The abundance of megabenthos from 14 reef sites of Biak in the years 2014, 2015, and 2016.

The highest abundance of *Diadema* was found in Opiaref across years. *Diadema* was found in all stations across the years, except at Animi in 2014. Over three consecutive years of continuous observations, the second most abundant megabenthos species was *Linckia laevigata*, and the lowest abundance was holothurians. *Linckia laevigata* were found at all stations during a three-year observation period. While the presence of Holothurians has been recorded only in Ibdi (2014), Animi (2015 and 2016), and Aryom (2016). The presence of lobster *Panulirus* is also limited to only several stations across three years of observation, with 0.007 ind.m^{-2}. Furthermore, economically important megabenthos gastropod, *Trochus,* was found at more stations than holothurians and lobsters. The abundance of *Trochus* ranged from 0.007 to 0.014 ind.m^{-2}. Meanwhile, the coral polyp-eating *starfish Acanthaster planci* was found in Yenusi during the years 2014 (0.4 ind.m^{-2}) and 2015 (0.29 ind.m^{-2}), but was not present in 2016. Similarly, the abundance of snail coral polyp eater *Drupella* ranges from 0.007 ind.m^{-2} (Saba in 2015; Anggaduber, Saba, and Sareidi in 2016) to 0.107 ind.m^{-2} (Yenusi in 2014 and Orwer in 2016). Overall, our results indicate that the highest megabenthos abundance was observed for Diadema (Figure 4A), and the total megabenthos abundance across years remains relatively constant (Figure 4B).

The consistent dominance and high abundance of the sea urchin *Diadema* across all surveyed locations and years (2014–2016) indicate the availability of open space for algae due to coral mortality (*e.g.*, due to bleaching events and human activities), which increases algae cover and sea urchin colonization, a common reef phase shift (Hughes *et al*., 2003). *Diadema* may increase in abundance where coral cover is reduced, as observed in Caribbean reefs following the 1983 die-off of *Diadema antillarum* (Lessios, 1988). In the Caribbean, *Diadema antillarum* was once dominant but declined in the 1980s due to disease, resulting in algal overgrowth and reef degradation (Lessios, 1988). Monitoring *Diadema* abundance is crucial, as overabundance can lead to overgrazing, resulting in bare substrates and reef erosion (van Woesik *et al*., 2025). Moderate densities are ecologically beneficial, but very high densities can hinder coral larval settlement (Latijnhouwers *et al*., 2024).

Table 3. Megabenthos abundance (individuals per m²) in coral reef ecosystems of the Papua region.

Location	*Linckia*	*Acanthaster*	Holothurians	*Diadema*	*Tridacna*	*Trochus*	*Drupella*	*Panulirus*	Year of observation	Source of information
Biak, Biak Numfor, Papua	0.094	0.038	0.001	0.661	0.024	0.003	0.069	0.003	2014	This study
Biak, Biak Numfor, Papua	0.123	0.045	0.001	1.124	0.027	0.005	0.019	0.001	2015	This study
Biak, Biak Numfor, Papua	0.016	0.008	0.007	0.011	0.008	0.008	0.009	0.006	2016	This study
East Biak, Biak-Numfor, Papua	0.073	0.006	0.006	0.462	0.016	0.006	0.014	0.004	2015	Dharmawan *et al*., 2017
East Biak, Biak-Numfor, Papua	0.036	0.001	0.004	0.296	0.015	0.004	0.007	0.001	2016	Dharmawan *et al*., 2017
East Biak, Biak-Numfor, Papua	0.029	0.003	0.007	0.289	0.009	0.005	0.002	0.001	2017	Dharmawan *et al*., 2017
Padaido Aimando, Biak-Numfor, Papua	0.017	0.002	0.005	0.019	0.015	0.007	0.067	0.001	2015	Dharmawan *et al*., 2019
Padaido Aimando, Biak-Numfor, Papua	0.023	0.004	0.008	0.021	0.011	0.005	0.021	0.001	2019	Dharmawan *et al*., 2019
Waigeo, Raja Ampat, Southwest Papua	0.364	0.028	0.1	0.143	0.143	0.064	0.686	0.007	2015	Rizqi *et al*., 2019
Waigeo, Raja Ampat, Southwest Papua	0.257	0.007	0.078	0.036	0.2	0.05	0.1	0.014	2019	Rizqi *et al*., 2019
Raja Ampat, Southwest Papua	0.31	0.06	0.04	0.11	0.12	0.06	0.86	0	2015	Cappenberg *et al*., 2023
Raja Ampat, Southwest Papua	0.56	0	0.06	0.15	0.08	0.03	0.06	0	2016	Cappenberg *et al*., 2023
Raja Ampat, Southwest Papua	0.52	0.01	0.1	0.18	0.14	0.01	0.04	0.01	2017	Cappenberg *et al*., 2023
Raja Ampat, Southwest Papua	0.72	0	0.07	0.01	0.14	0.01	0.06	0.01	2018	Cappenberg *et al*., 2023
Raja Ampat, Southwest Papua	0.29	0	0	0.1	0.14	0.11	0.72	0	2019	Cappenberg *et al*., 2023
Raja Ampat, Southwest Papua	0.47	0	0.06	0.04	0.13	0.17	1.18	0	2021	Cappenberg *et al*., 2023

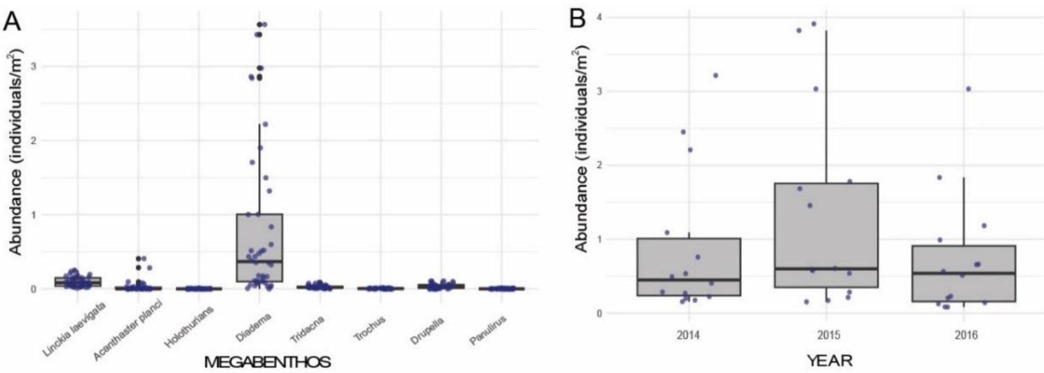

Figure 4. (A) Boxplot of the abundance of megabenthos groups from all stations and years, (B) Boxplot of the abundance of megabenthos in years 2014, 2015, and 2016.

The second most abundant megabenthos is *Linckia laevigata* because this species has good adaptation to extreme environmental stress, such as higher water temperatures, especially in shallow-water reefs (Williams *et al*., 2025). Additionally, *Linckia laevigata* is not commonly fished by local people in Biak Island, either for food or as a handicraft material. Megabenthos that are regularly fished or collected by local people include snails of the *Trochidae* family, sea cucumbers, giant clams, and lobsters because they have economic value. Our results show a lower abundance of those species compared to *Diadema* and *Linckia laevigata*. The low abundance of these megabenthos is likely more influenced by fishing pressure than ecological conditions. Molluscs *Trochidae* and giant clams are mostly fished for their shell for the button industry or as souvenirs, and their meat for human consumption (Bennett *et al*., 2025; Lionata *et al*., 2025). While sea cucumbers and lobsters are collected mainly for food because they have high nutrition value, which gives them a high market price (Lionata *et al*., 2025). Among echinoderm species, the sea cucumber is the most vulnerable to overfishing due to its ease of capture and high market demand (Setyastuti *et al*., 2018, 2024; Ramírez-González *et al*., 2020).

The abundance of *Acanthaster planci* is lower than snail *Drupella.* Both of them are coral polyp predators that can have a significant impact on decreasing coral cover if an outbreak occurs (Moerland *et al*., 2016; Tkachenko and Hoang, 2022). Those predatory corals not only negatively impact coral cover but also reduce the dominance of certain coral species in reef ecosystems. A high abundance of *Acanthaster planci* was observed only in Yenusi in 2014 and 2015, but there was no presence of *A. planci* in 2016. It happened because there was a management effort to reduce the outbreak of *A. planci* by removing them from reef ecosystems to minimize the loss of coral cover due to predatory by *A. planci* in Biak waters. Thus, the presence of *A. planci* in 2016 was found only in one station (Aryom). While the distribution of *Drupella* is wider than *A. planci,* which is found in almost all sites during three-years consecutive observations. *Drupella* often appears more abundant than *A. planci* due to its small size, continuous reproduction, ability to hide in reef structures, and persistence under varied environmental conditions (Moerland *et al*., 2016; Scott *et al*., 2017; Foo *et al*., 2024). Meanwhile, *A. planci* tends to occur in boom-and-bust cycles depending on the availability of coral and is more easily targeted by management efforts (Tkachenko and Hoang, 2022; Foo *et al*., 2024).

Regarding the comparison of megabenthos conditions between the present study and other locations in Papua, our results indicate that *Diadema* exhibited relatively high densities in Biak compared to other surveyed locations (Table 3). As a grazer, *Diadema* plays an important role in controlling algal growth and facilitating coral recruitment; however, excessively high densities may also reflect ecological imbalance, often associated with reduced predator abundance or prior reef disturbance (Latijnhouwers *et al*., 2024; van Woesik *et al*., 2025). Overall, the abundance of several taxa in the Papua region showed clear spatial and temporal variation across locations and years. When compared with other regions, Raja Ampat generally exhibited higher abundances of *Drupella*, reaching up to 1.18 ind. m^{-2} in Salawati and Batanta Islands in 2021 (Cappenberg *et al*., 2023) and up to 0.10 ind. m^{-2} in Waigeo in 2019 (Rizqi *et al*., 2019). Similarly, *Linckia* densities were consistently higher in Raja Ampat (0.29–0.72 ind. m^{-2} between 2015 and 2018 in Salawati and Batanta Islands (Cappenberg *et al*., 2023) and 0.26–0.36 ind. m^{-2} in Waigeo (Rizqi *et al*., 2019)) than those recorded in Biak (Table 3).

In contrast, economically important megabenthos, such as *Trochus*, *Tridacna*, and Holothurians, had generally lower densities in Biak than in Raja Ampat across all locations and survey years (Table 3). This pattern may reflect differences in harvesting pressure between Biak and Raja Ampat. The surveyed area in Biak is characterized by more accessible coastal areas and higher local population density, which may facilitate greater extraction of commercially valuable invertebrates. In contrast, the study area of Raja Ampat benefits from relatively lower population pressure and stronger marine conservation management, including marine protected areas and community-based regulations, which may contribute to higher densities of economically important megabenthos (White *et al*., 2022).

Megabenthos monitoring in coral reef ecosystems across Papua remains limited, with available studies restricted to Biak (Dharmawan *et al*., 2017), and Padaido and Aimando Islands (Dharmawan *et al*., 2019), as well as Salawati, Batanta, (Cappenberg *et al*., 2023) and Waigeo Islands (Rizqi *et al*., 2019) in Raja Ampat. The compiled data, therefore, highlight substantial spatial and temporal variation in megabenthos assemblages across the Papua region. Given the limited monitoring coverage, particularly in eastern Indonesia, continued and expanded megabenthos assessments are essential to improve our understanding of population trends in this relatively under-surveyed region. The present study provides an important baseline overview of megabenthos conditions in Biak. Detecting temporal increases or declines in key taxa will be critical for informing adaptive coastal and reef management strategies in the region.

Relationship between megabenthos and benthic coral and turf algae

The relationship between megabenthos abundance and coral and turf algae cover was investigated using data from year 2016 (Figure 4). Based on the tests, there was no significant correlation between coral polyp eater *Acanthaster planci* and turf algae (r= 0.36, P= 0.2) and coral (r= -0.39, P= 0.17); as well as no correlation between snail *Drupella* and turf algae (r= -0.37, P= 0.2) and coral (r= 0.067, P= 0.82). Pearson correlations showed significant correlations between *Diadema* abundance and turf algae (r= 0.66, P= 0.01) and coral (r= -0.5, P= 0.07) percent cover in the reef ecosystems; as well as significant correlation between lobster *Panulirus* and percent cover of turf algae (r= -0.69, P= 0.0059) and coral (r= 0.8, P= 0.0006). Whereas, there were no significant correlation between Holothurians and coverage of turf algae (r= 0.093, P= 0.75) and coral (r= 0.13, P= 0.67); between gastropod *Trochus* and coverage of turf algae (r= -0.27, P= 0.35) and coral (r= -0.029, P= 0.92); between bivalve *Tridacna* and turf algae (r= -0.38, P= 0.18) and coral (r= 0.2, P= 0.5) coverage (Figure 5). Overall, we only found a positive correlation between the abundance of *Diadema* and *Linckia laevigata* and turf algae cover, and a negative correlation between the abundance of *Panulirus* and coral cover.

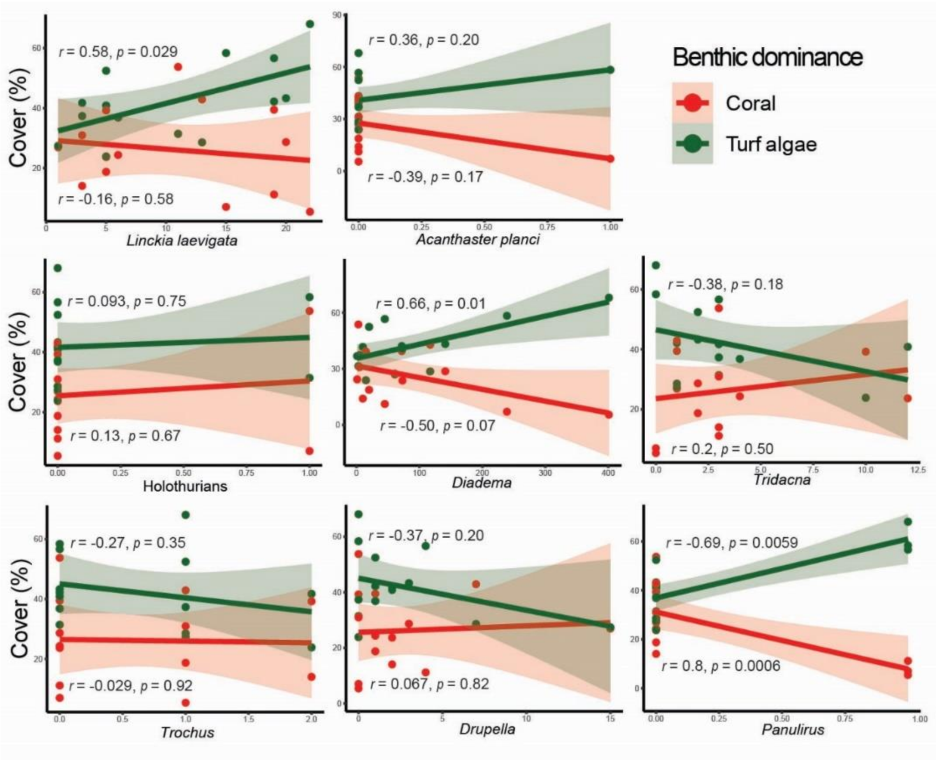

Figure 5. Correlation between the number of megabenthos individuals (*Linckia laevigata*, *Acanthaster planci*, Holothurians, *Diadema*, *Tridacna*, *Trochus*, *Drupella*, and *Panulirus*) and coral and turf algae coverage in 2016.

The distribution pattern of megabenthos is not solely due to the benthic substrate condition or the benthic group dominance in coral reef ecosystems. The lack of a statistically significant relationship between the benthic cover of corals and turf algae and the presence of megabenthos in the current analysis suggests that, within the study's temporal and spatial scope, the percentage cover of these benthic components may not directly affect megabenthos abundance. Several factors may contribute to the insignificant relationship in this study, including measurement mismatch, in which the influence of benthic cover may be more pronounced at the microhabitat or sediment chemistry level rather than in broad benthic categories such as coral and turf algae. Coral and turf algal cover may be impacted by environmental variability, including light, herbivory, nitrogen levels, and physical disturbance. It is possible that these elements will outweigh any subtle impacts of megabenthos activity. Furthermore, interactions between species, where not every megabenthos species serves the same ecological purpose. For example, some effects of holothurian activity on benthic dynamics may take longer to manifest, especially if mediated by sediment conditioning or microbial shifts, which are not immediately reflected in macroorganism abundance. Holothurian feeding behaviour and sediment turnover rates vary, which may affect their impact on benthic cover (Ennas *et al*., 2023). Overall, the lack of significant correlation highlights the complexity of reef ecosystem interactions and the potential for megabenthos ecological functions to be subtle, context-dependent, or masked by stronger drivers. Megabenthos are known to be sensitive to water quality and overfishing (Purcell *et al*., 2016; Setyastuti *et al*., 2018, 2024; Aji *et al*., 2023).

The other reason is that overfishing for economically valuable megabenthos taxa, such as lobster, giant clam, snail *Trochidae*, and sea cucumber, has occurred. The study site for our research is close to the mainland and is in shallow-water reefs, making them easily accessible to fishermen. The overfishing of megabenthos subsequently affects reef ecosystems because reducing the populations of some megabenthos groups may alter habitat conditions. For instance, sea cucumbers are crucial bioturbators and sediment processors that play a significant role in nutrient cycling and in maintaining the health of reef sediments (Purcell *et al*., 2016; Ennas *et al*., 2023). Therefore, over a long period, their indirect ecological effects such as changing microbial communities, nutrient fluxes, or sediment chemistry may result in quantifiable changes in macro-scale benthic cover (*e.g.*, coral or turf algae).

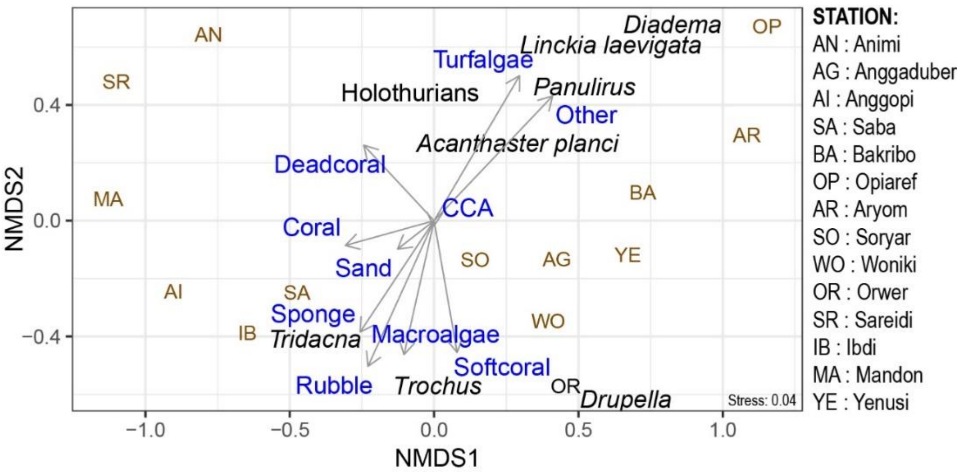

Figure 6. Non-metric Multidimensional Scaling (nMDS) ordination plot based on Bray-Curtis distance of megabenthos (*Linckia laevigata*, *Acanthaster planci*, *Diadema*, Holothurians, *Tridacna*, *Trochus*, *Drupella*, *Panulirus*) at 14 reefs with different benthic substrate composition in the year 2016. The arrows represent benthic substrate composition (Coral, Soft coral, Turf algae, CCA, Macroalgae, Sponge, Other invertebrates, Dead coral, Sand, and Rubble).

Non-metric multidimensional scaling ordination plots illustrate the variation in megabenthos assemblage composition across sampling areas in year 2016. The presence and abundance of *Diadema* (*r*= 0.83, *P*= 0.001) and *Linckia laevigata* (*r*= 0.64, *P*= 0.007) significantly influenced the composition of megabenthos community assemblages across sampling locations (Figure 6). Whereas the presence and abundance of *Acanthaster planci* (*r*= 0.19, *P*= 0.39), Holothurians (*r*= 0.26, *P*= 0.16), *Tridacna* (*r*= 0.23, *P*= 0.25), *Trochus* (*r*= 0.23, *P*= 0.22), *Drupella* (*r*= 0.36, *P*= 0.06), and *Panulirus* (*r*= 0.41, *P*= 0.06) did not significantly influenced the community assemblage of megabenthos in all 14 study areas. Furthermore, an envfit analysis indicated that there was no significant influence of benthic group (*P*> 0.05) on megabenthos composition across sampling sites (Figure 6).

Diadema has a major role in coastal ecosystems. This finding reflects both the resilience and functional significance of *Diadema* in reef ecosystems. *Diadema* are keystone herbivores in tropical reef systems, particularly *Diadema setosum* and *Diadema savignyi*. Their ecological roles include (i) grazing on algae, which prevents algal overgrowth and promotes coral recruitment and recovery (Hughes *et al*., 2007), (ii) bioerosion and sediment generation, contributing to reef carbonate cycling (van Woesik *et al*., 2025), and (iii) serving as prey for larger predatory fishes and echinoderm predators (McClanahan, 1998). *Diadema* may reflect several possible ecological dynamics, such as low predator pressure; a decline in natural predators, e.g., triggerfish, could lead to *Diadema* population growth. In addition, overfishing or habitat degradation might reduce predator abundance, indirectly favouring sea urchin proliferation (McClanahan, 1998; Ditzel *et al*., 2022). Increased nutrients from land runoff can lead to algal growth, creating more food sources for *Diadema*. However, in turn, high *Diadema* densities can suppress algae if they remain uncontrolled.

The presence of grazing *Diadema* sea urchins can suppress the overgrowth of algae, particularly the proliferation of structurally simple, two-dimensional algal forms (McClanahan, 1998). This grazing activity helps maintain the dominance of three-dimensional hard coral structures, which provide essential habitat complexity for a wide range of reef-associated organisms (Ditzel *et al*., 2022). As a result, the ecosystem supports greater species diversity, higher organismal abundance, and enhanced functional redundancy—key attributes that contribute to the overall resilience and stability of coral reef ecosystems.

Conclusion

The most dominant benthic groups in our study were coral and turf algae, with percentages of up to 53.7% and 68%, respectively. The abundance and distribution patterns of megabenthos are not solely due to benthic substrate conditions, such as high coral or turf algae cover in coral reef ecosystems. In general, we found a positive relationship between the abundance of *Diadema* and *Linckia laevigata* with turf algae cover, while *Panulirus* abundance showed a negative correlation with coral cover. Sea urchin *Diadema* spp. has the highest abundance and wider distribution from all locations across years (2014, 2015, and 2016), followed by blue seastar *Linckia laevigata,* and the lowest abundance was sea cucumber. Predatory coral polyps *Acanthaster planci* have a lower abundance and occurrence compared to the other predatory coral snail *Drupella*. There were no outbreaks of predatory coral polyps, *A. planci* and snail *Drupella*, which is considerably good for maintaining the condition of coral cover in Biak Island. In 2016, *A. planci* was found at only one site, due to management efforts by the local community to reduce the threat of predatory corals in coral reef ecosystems. Furthermore, most of the economically important megabenthos, such as the giant clam, snail Trochidae, lobster *Panulirus*, and sea cucumber, are of low abundance. The majority of local people living on Biak Island are fishermen; thus, the economically important megabenthos resources are essential for both the reef ecosystem and the local community. Our study could be used as a first overview of megabenthos conditions in Biak. By understanding temporal changes in megabenthos populations throughout the year, a better coastal management plan in Biak could be implemented. Future research on the impact of human activities, such as fishing and coastal development, on megabenthos abundance and coral coverage is considered. This information helps maintain the health of Biak's coral reef ecosystems, which play a crucial role in supporting the livelihoods and ecology of coastal areas.

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