



Recovery of Coral Reefs: Changes in Hard Coral Cover at Pulau Bidong After a Tropical Storm

Mohmad Fuad Nur Qamarina¹ · Marsya Maisarah Ahmad Zaimi² · Siti Nurtahirah Jaafar^{1,2,3} · Muhammad Hafiz Borkhanuddin^{1,2,3} · Zainudin Bachok¹ · Che Din Mohd Safuan^{1,3}

Received: 14 October 2024 / Revised: 31 October 2025 / Accepted: 16 November 2025 / Published online: 9 December 2025
© The Author(s) 2025

Abstract

Tropical storms are a natural disturbance that cause physical damage to coral reef ecosystems. In 2019, a tropical storm named Pabuk was recorded near Malaysia and caused significant damage to the coral reefs in Pulau Bidong. This study investigated the post-disturbance recovery of coral reefs at Pantai Pasir Cina, Pulau Bidong, following the impact of the Pabuk storm. Data collected from 2016 to 2023 using video sampling method were analyzed to evaluate changes in the coral reef area. No significant changes were observed after a year of post-disturbance in 2020 but a substantial increase in live coral cover was observed in 2023 where shallow water area (3 m) showed significant increase of live coral cover (from 18.21%± 10.45% SD to 79.10%± 12.12% SD) and a reduction in dead coral cover (from 76.21%± 8.45% SD to 18.19%± 12.65% SD) as compared to 2019. By 2023, the hard coral community along the transect was dominated by *Acropora–Montipora*, with many *Fungia* colonies overgrown by the faster-growing *Acropora* and *Montipora* corals. The observed recovery and maintenance of dominant coral taxa primarily reflect the success of the active restoration efforts in the study area. The findings underscore the resilience of coral reefs in the face of natural disturbances and emphasize the necessity for ongoing monitoring and conservation strategies to sustain reef health.

Keywords Coral reefs · Coral restoration · Hard coral · Resilience · South china sea

Introduction

Coral reefs are among the most crucial ecosystems on Earth. Even though many studies have been focusing on the resilience of coral reefs, more information is needed about how reefs respond to extreme weather events and major storms (Roff and Mumby 2012; Yuval et al. 2023). One of the most obvious and recurrent natural disturbances affecting the

reef communities is hurricanes and tropical storms. These natural disturbances are responsible for determining both the function (Rogers 1993; Harmelin-Vivien 1994; Gardner et al. 2005) and the structure of coral reefs (Cheal et al. 2017; Geister 1977). There are numerous studies on the severe immediate impacts of hurricanes and tropical storms documenting shifts from coral cover to turf algae and rubble post-storm in a Hawaiian island (Pascoe et al. 2021) and mass reduction in coral cover in the northern Great Barrier Reef after Cyclone Nathan (Baird et al. 2018). However, the impact could also sometimes be minimal or unapparent (Gardner et al. 2005).

Large currents and waves generated by strong mechanical forces have a direct impact on the reef (Madin et al. 2014; Perry et al. 2014; Carter et al. 2022). Mechanical damage can range from minor breakage of coral branches to the dislodgment of entire colonies (Bozec et al. 2015). Cyclones indirectly affect coral reefs by increasing riverine input and precipitation, which elevate turbidity and reduce salinity, thereby inducing physiological stress that can result in coral mortality (Haapkyla et al. 2013; Perry et al. 2014).

✉ Che Din Mohd Safuan
chedinmohdsafuan@umt.edu.my

¹ Institute of Oceanography and Environment, Universiti Malaysia Terengganu, Kuala Nerus, Terengganu 21030, Malaysia

² Faculty of Science and Marine Environment, Universiti Malaysia Terengganu, Kuala Nerus, Terengganu 21030, Malaysia

³ Research and Education on Environment for Future Sustainability, Faculty of Science and Marine Environment, Universiti Malaysia Terengganu, Kuala Nerus, Terengganu 21030, Malaysia

Runoff following storms can introduce nutrient-rich pollution, which may indirectly affect coral health by promoting microbial activity and increasing susceptibility to disease (Lamb et al. 2018). Additionally, elevated water temperatures and the prevalence of pathogenic bacteria such as *Vibrio* species are important factors that can exacerbate disease outbreaks (Akmal and Shahbudin 2020). These stressors, when combined with physical damage from tropical storms, may synergistically affect coral health and recovery in the study area (Franca et al. 2020). Inhibition of coral recruitments is highly likely as the deep water that is rich in nutrients is brought up by the strong winds or land runoff that elevates the nutrient availability and may cause macroalgal blooms (Kuffner et al. 2006; Doropoulos et al. 2014; Carter et al. 2022).

Factors influencing the patchiness of cyclone damage include the strength of waves and their length of time near specific reefs as well as the depth, location, and topography of a reef; and the state and composition of the coral community (Beeden et al. 2015). In addition, the coral colony shape and size differ in their susceptibility to the damage done by cyclones as smaller colonies with stouter growth are less vulnerable to wave damage compared to big colonies and those with fragile morphologies (Muko et al. 2013; Madin et al. 2014; Carter et al. 2022). However, the ocean warming is predicted to shorten the return interval for powerful cyclones (Knutson et al. 2020), thus, elevating their potential to cause significant ecological impacts on coral reefs ecosystems (Puotinen et al. 2020).

Resilience is defined as the degree/level of disturbance an ecosystem can withstand without changes in self-organized processes and structures (Gunderson 2000). The mixed impacts of storms on reefs include the decline of dominant coral cover, such as *Acropora*, which can reduce competition for space and allow other coral species to establish, thereby increasing overall coral diversity (Rogers 1993). One of the most severe potential impacts of storms is the alteration of reef topography, which in extreme cases may trigger cascading effects leading to ecosystem collapse (Yuval et al. 2023). The documentation of cyclone impacts on coral reefs is crucial for developing locally tailored conservation plans and ongoing adaptation efforts to a climate where humans are highly dependent on coral reefs for food security and livelihoods (Carter et al. 2022).

Coral reefs around Pulau Bidong are vulnerable to multiple stressors, including elevated sea temperatures that can lead to coral bleaching, mortality, and shifts in community composition (Reef Check Malaysia 2017, 2018). While these Reef Check Malaysia reports provide national- and regional-level assessments rather than site-specific data for Pulau Bidong, they highlight the ongoing threat of thermal stress and the importance of monitoring reef health in this

region. Back-to-back bleaching events in Peninsular Malaysia (2019–2020) have been shown to selectively affect hard coral taxa across- and within-reef scales, emphasizing the vulnerability of certain species (Szereday et al. 2024). In response to reef degradation, an active coral restoration program was initiated in 2020, involving transplantation of coral fragments in shallow water areas. While the restoration sites were located near but not directly within the monitored transects, these efforts may have contributed indirectly to coral recruitment and structural complexity, complementing natural recovery processes.

Tropical Storm Pabuk was documented near Malaysia, in January 2019. The storm created strong currents (>1 m/s) and powerful winds (>50 mph) in the region (Safuan et al. 2020), causing unusually strong physical disturbances that damaged nearby coral reefs. This study is proposed to evaluate the condition of the reef community in Pantai Pasir Cina, Pulau Bidong and assess coral reef recovery after Tropical Storm Pabuk.

As coral reefs are the house for diverse species of marine organisms, their degradation and inability to recover post-disturbance would pose a significant threat to the keystone and continuation of species. A study by Gardner et al. (2005) shows that coral reefs can recover approximately 50% of their pre-disturbance composition within 7–10 years, while recovery at some sites may take 8–13 years, depending on which coral species dominate specific locations. By examining coral recovery at Pulau Bidong following Storm Pabuk, this study aims to identify which species contribute most to reef recovery in the area, building on findings from previous studies (Safuan et al. 2020). Studies also state that changes in hard coral species composition during recovery from disturbance could result in shifts in the ecological process of the reefs. Comparing the relative abundance of dominant benthic species before and after Tropical Storm Pabuk can provide an indication of potential community shifts. By determining the current status of coral at Pantai Pasir Cina in Pulau Bidong after Storm Pabuk in 2019, the outcomes of the study could be used to evaluate the potential for recovery and to understand whether the coral communities are able to recolonize, recover, and thrive.

Methods

Study Area

Located at a latitude of $5^{\circ} 37' 16''$ N and longitude of $103^{\circ} 03' 41''$ E, Pulau Bidong is one of the many coral reef islands on the east coast of Peninsular Malaysia. It directly faces the southern part of the South China Sea (SCS) that inhabits coral reefs and diverse marine organisms. The

island is located 14 km from the mainland with surrounding waters reaching a maximum depth of 30 m. Two monsoon seasons influence the climate of the island. The northeast monsoon occurs from November to March and the southwest monsoon from April to August (Daryabor et al. 2016). Massive *Porites* and branching *Acropora* occupy the entire coral reefs of the sandy and rocky areas around the island (Safuan et al. 2021).

Pantai Pasir Cina (PPC), located on the west coast of Pulau Bidong, was selected as the survey site and is the same location reported in the first record of Storm Pabuk in the area (Safuan et al. 2020). Figure 1 illustrates the condition of the reef at PPC before and shortly after the storm. The site is not subject to substantial anthropogenic pressures. The only human presence is a nearby research station dedicated to ecological monitoring and educational activities. No fishing, coastal development, or tourism activities occur directly at the site, and local human impacts on the reef are therefore considered minimal.

Sampling Site/Sample Collection

The surveyed site was known as Pantai Pasir Cina (PPC) located on the west coast of Pulau Bidong (Fig. 2). Sampling was conducted across different years on 4th August 2016, 3rd March 2019, 31st October 2020 & 2nd May 2023. Four 100 m-transects were laid out in the study area at two depths, 3 m and 8 m to determine the difference of the reef and hard coral communities at each depth.

Coral Video Transect Method

The technique used for data collection was the Coral Video Transect (CVT) method, originally developed by English et al. (1997) and later optimized in Malaysian reefs by Safuan et al. (2015). Surveys were conducted along a

repeated transect, which was re-established annually at the same location. The transect was not permanently marked, but its placement followed consistent reference landmarks to ensure comparability over years. The data were collected along a 100 m transect tape (4×20 m segments, $n=4$). Moving slowly at a speed of 5 m/min, the reef floor was recorded using an Olympus Tough TG-6 Digital Camera. A slate board with the information on the site and transect points was captured before starting the recording process. As the recording was in progress, the elevation of the camera lens to the reef floor was maintained perpendicular to 0.5 m above the substratum. Vertical elevation was maintained by attaching a reference bar to the camera housing throughout the recording. This action ensured the focus was maintained and minimized parallax errors during video recording. Optimized CVT offers permanent, high-resolution data for precise estimation of benthic cover along with high efficiency by lesser field time and wider field area, and permanent data record compared to Line Intercept Transect (LIT) (Safuan et al. 2015).

Image Analysis

The videos were extracted into 50 non-overlapping frames for each 20 m segment using Video Image Master. (Kohler and Gill 2006). The point count method which was the 50 points/frames formerly depicted by Safuan et al. (2015) was applied. The corals were identified to the lowest taxonomic possible (genus) following the Coral Finder guidebook (Kelley 2022) and Veron et al. (2024). Apart from that, abiotic components such as dead corals were also evaluated. Dead coral with algae was recorded when algal growth was present on dead coral skeletons. Dead coral refers to corals showing no signs of life but without algal colonisation. Rubble refers to loose fragments of dead coral accumulated together. The summarization of the data was divided into

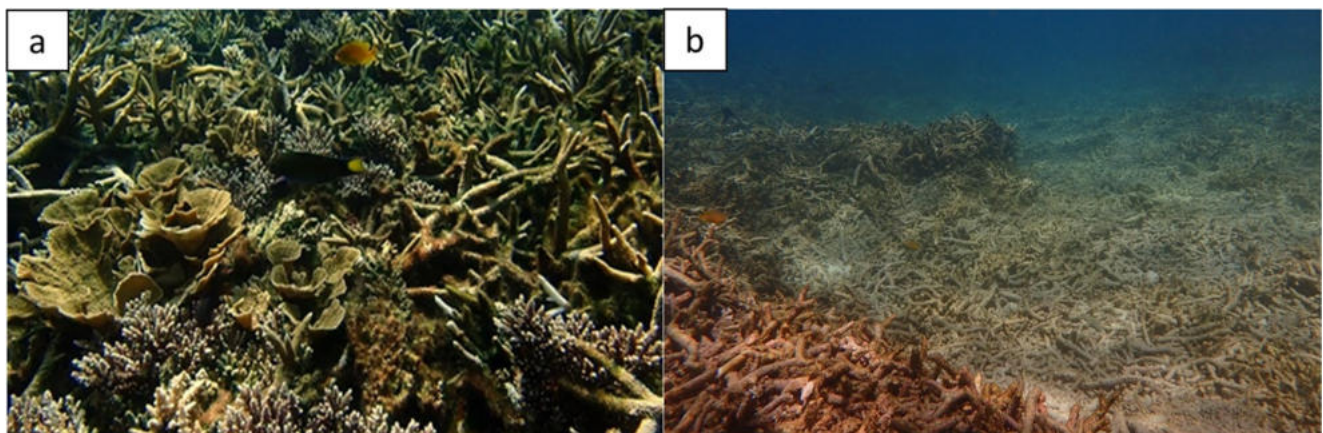


Fig. 1 Coral reef condition at Pantai Pasir Cina: (a) in 2016, showing a healthy reef, and (b) in 2020, immediately after Tropical Storm Pabuk, showing a degraded state. The images illustrate the destructive impact of the storm on hard corals

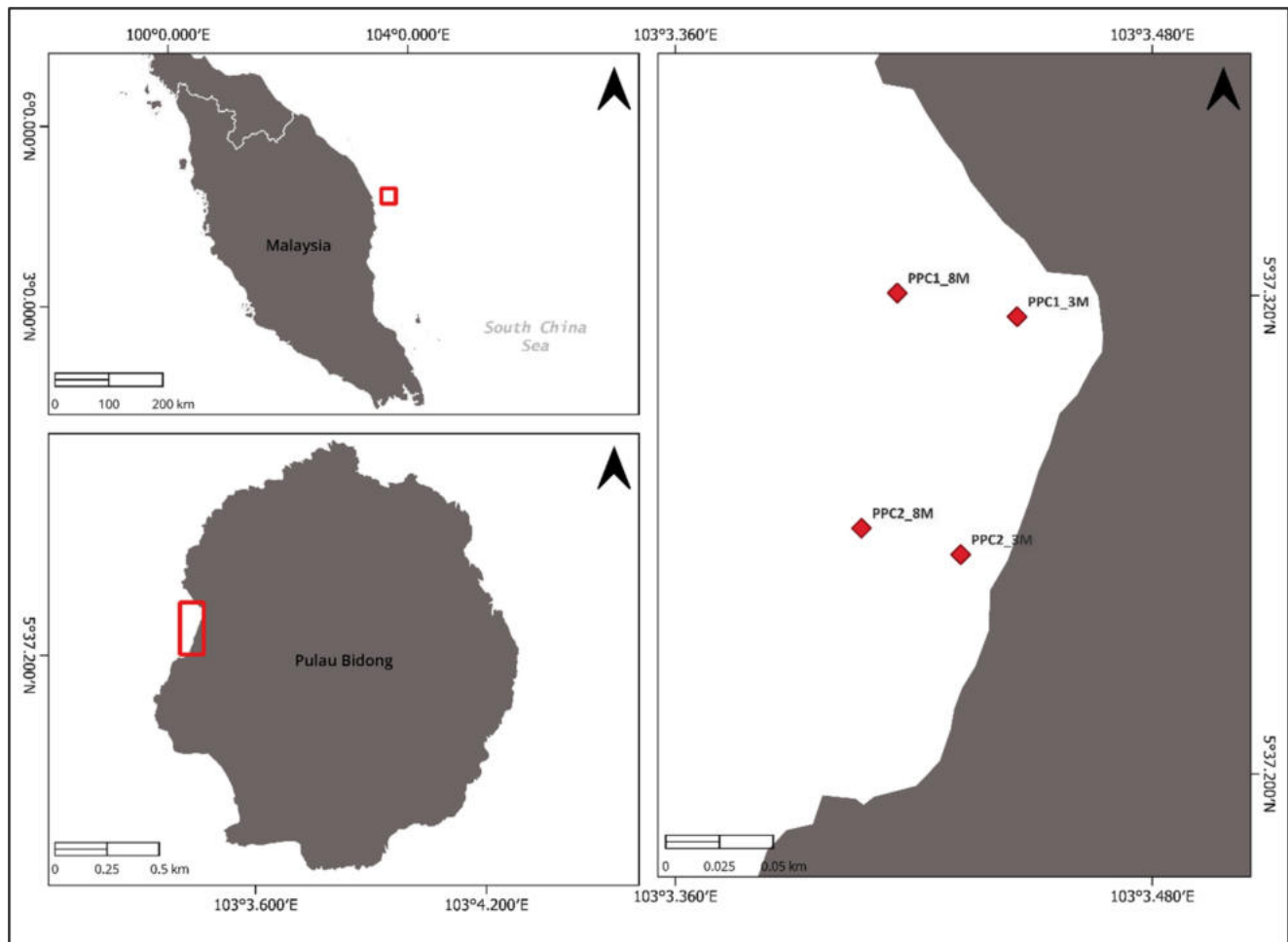


Fig. 2 Map of the study area highlighting the sampling sites around Pulau Bidong. (Top left) Map of Peninsular Malaysia showing the position of Pulau Bidong in the South China Sea. (Bottom left) Map

of Pulau Bidong with a red box indicating the study area on the west coast. (Right) Enlarged map of the study area showing four red rhombuses indicate the sampling sites at different depths (3 m and 8 m)

Table 1 The biotic and abiotic components in this study

Major categories	Subcategories
Live Coral	<i>Acropora</i> , <i>Astreopora</i> , <i>Montipora</i> , <i>Pavona</i> , <i>Turbinaria</i> , <i>Galaxea</i> , <i>Ctenactis</i> , <i>Fungia</i> , <i>Halomitra</i> , <i>Herpolitha</i> , <i>Dipsastraea</i> , <i>Echinopora</i> , <i>Favites</i> , <i>Merulina</i> , <i>Pectinia</i> , <i>Platygyra</i> , <i>Goniopora</i> , <i>Porites</i> , <i>Pachyseris</i> and <i>Pocillopora</i>
Algae	Crustose coralline algae, Other algae and Turf algae
Other invertebrates	Gorgonians, Sponges, Shells, Sea Star, Cushion Star, Giant Clam, Crown of Thorn, Ascidian, Zoanths, Anemone, Soft coral, Sea cucumber, Sea urchins and Others
Dead coral	Rubbles, Dead coral with algae and Dead coral

four different categories as percentage covers which are live coral cover, algae, dead coral, and other invertebrates (Table 1).

The classification of coral health status was used by utilizing live coral cover as a proxy of coral health following the ASEAN-Australia Living Coastal Resources Project (Chou

et al. 1994). The classification was based on the percentage of live coral cover as follows: excellent (>75%), good (51–75%), fair (26–50%) and poor (0–25%). The coral community of the study area was determined by coral taxa (genus) via their percentage cover. Previous data on the coral health status and hard coral community in Pantai Pasir Cina from 2016 to 2021 were obtained through electronic and manual literature searches (Bachok et al. 2020), including C.D.M. Safuan (personal communication, 14 April 2025). Datasets of 2016 and 2019 were obtained from Bachok et al. (2020) of a quantitative dataset of shallow water reefs in Pulau Bidong, Southern of the South China Sea as representative data before and after the tropical storm.

Statistical Analysis

To examine changes before and after Tropical Storm Pabuk, PERMANOVA (permutational multivariate analysis of variance) was conducted using PRIMER 6 to compare the

percentage cover of generic composition and benthic components. PERMANOVA was based on Bray–Curtis dissimilarity matrices for both benthic components and hard coral community datasets (Anderson 2014). For factors showing significant differences ($p < 0.05$), pairwise comparisons were performed. Non-metric multidimensional scaling (nMDS) was then used to visually represent differences among samples for the factor year. Finally, Canonical Analysis of Principal Coordinates (CAP) was employed to further test multivariate differences in benthic community composition among years.

Results

Biotic and Abiotic Components

The distribution of biotic (live coral, algae, other invertebrates) and abiotic (dead coral, sand, silt, rock) components at Pantai Pasir Cina was significantly influenced by both depth (PERMANOVA: $p = 0.001$) and year ($p = 0.001$) (Table 2). Live and dead coral were the main contributors to the observed patterns (Fig. 3). Average live coral cover

declined from $47.9 \pm 19.46\%$ SD in 2016 to $28.75 \pm 20.21\%$ SD in 2019, before rebounding to $62.3 \pm 25.12\%$ SD in 2023. Conversely, average dead coral cover exhibited the opposite trend, increasing from $26.38 \pm 14.74\%$ SD in 2016 to $64.15 \pm 23.37\%$ SD in 2020, and then decreasing to $32.04 \pm 26.81\%$ SD in 2023. Depth-related differences were also evident, live coral cover was generally higher at 3 m ($43.47 \pm 27.36\%$ SD) than at 8 m ($41.59 \pm 14.22\%$ SD), whereas dead coral cover was more prominent at 3 m ($51.58 \pm 27.67\%$ SD) compared to 8 m ($42.62 \pm 16.95\%$ SD). Pairwise comparisons with Bonferroni correction revealed significant differences between all years, except for 2019 vs. 2020 ($p = 0.247$) (Table 2). At 3 m depth, significant differences occurred across most years ($p = 0.001$), whereas at 8 m depth, differences were observed only between 2016 and 2019 ($p = 0.001$), 2016 and 2020 ($p = 0.001$), and 2016 and 2023 ($p = 0.001$) (Table 2).

Visual inspection of the reef (Figs. 4 and 5) indicated that dead coral dominated in 2019 and 2020, while live coral cover increased in 2023, with patterns differing from those observed in previous years. These observations suggest that the 2019 storm had stronger effects at shallower depths (3 m) and relatively minor impacts at 8 m.

Table 2 Results of PERMANOVA and pairwise analysis of biotic and abiotic components for factors ‘Depth’, ‘Year’ and ‘Depth x year’

Groups	PERMANOVA					
	df	SS	MS	Pseudo-F	<i>p</i> -values	perms
Depth	1	1106.7	1106.7	9.5685	0.001*	998
Year	3	8117.9	2706	23.397	0.001*	999
Depth x Year	3	3765.2	1255.1	10.852	0.001*	998
Pairwise - Year						
Groups				<i>t</i>	<i>p</i> -values	perms
2016, 2019				5.1617	0.001*	998
2016, 2020				6.3902	0.001*	999
2016, 2023				4.0885	0.001*	999
2019, 2020				1.1634	0.253	999
2019, 2023				5.2289	0.001*	999
2020, 2023				5.7457	0.001*	998
Pairwise - Depth x Year: 3 m						
Groups				<i>t</i>	<i>p</i> -values	perms
2016, 2019				4.3366	0.001*	996
2016, 2020				5.2013	0.001*	998
2016, 2023				3.6663	0.002*	998
2019, 2020				1.4866	0.139	999
2019, 2023				6.2863	0.001*	999
2020, 2023				7.9742	0.001*	997
Pairwise - Depth x Year: 8 m						
Groups				<i>t</i>	<i>p</i> -values	perms
2016, 2019				3.538	0.001*	999
2016, 2020				4.2081	0.001*	999
2016, 2023				4.3616	0.001*	998
2019, 2020				0.26123	0.945	999
2019, 2023				1.3134	0.178	999
2020, 2023				1.3672	0.191	999

* indicates $p < 0.05$

Fig. 3 Box plot showing variation of biotic and abiotic components across different (a) depth and (b) year

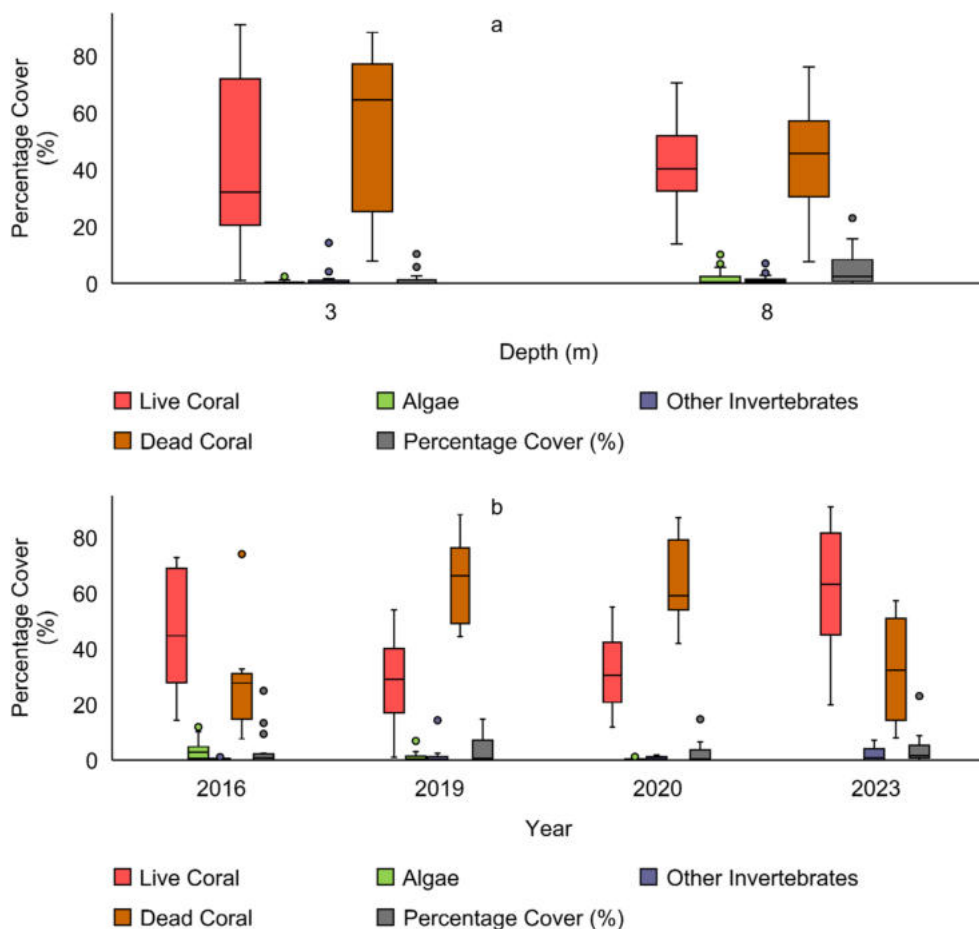


Fig. 4 Non-metric multidimensional scaling (nMDS) plot of biotic (C= live coral, ALG= Algae and OT= Other Invertebrates) and abiotic (DC= dead coral and SR= sand, silt and rock) components for factor year based on Bray-Curtis similarity. Each point represents a sample, and the distance between points reflects the dissimilarity

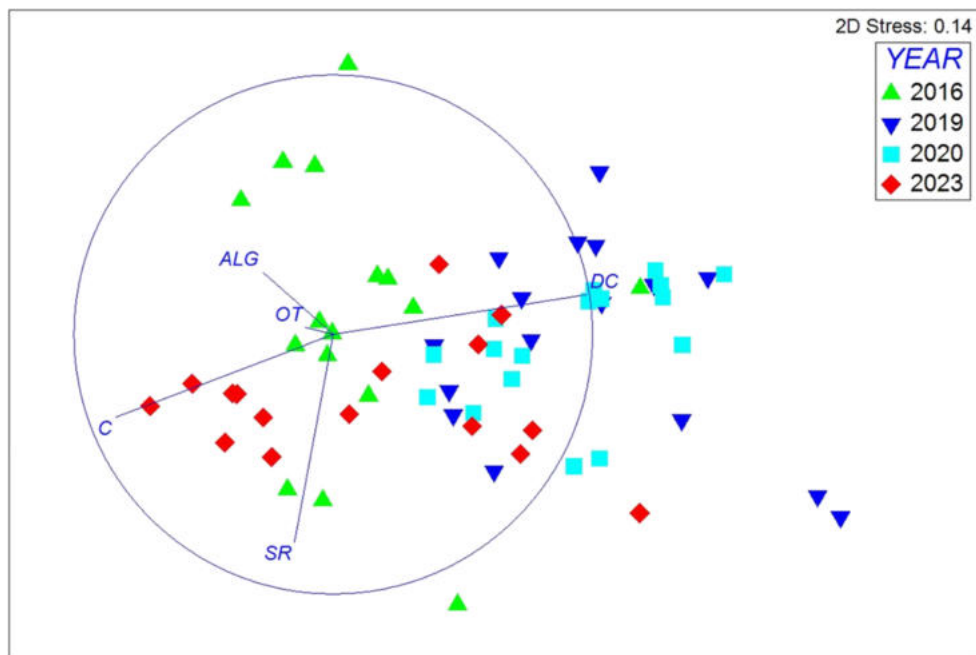


Fig. 5 Canonical analysis of principal coordinates (CAP) plot of biotic and abiotic components for factor year based on Bray-Curtis similarity. Vectors represent the components (C = Live Coral, ALG = Algae, OT = Other Invertebrates, DC = Dead Coral and SR = Sand, Silt and Rock) with significant Spearman correlations, indicating their influence on the ordination

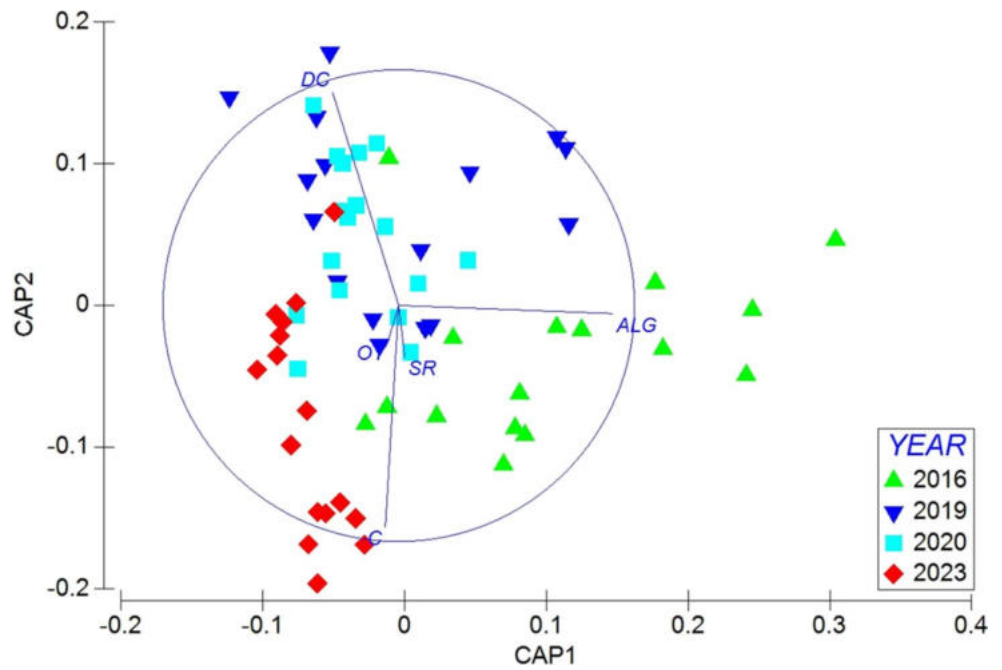
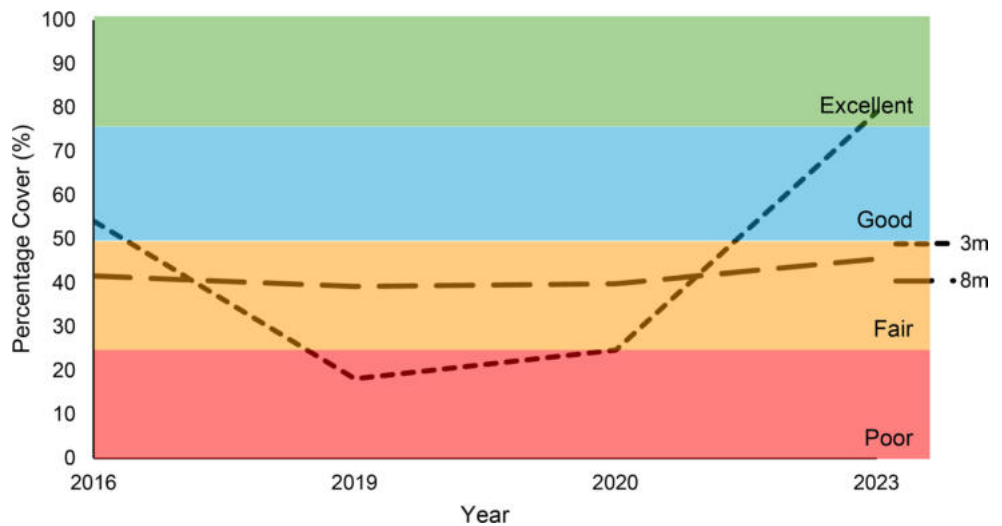


Fig. 6 Coral health status at 3 m and 8 m depth across the years 2016, 2019, 2020, and 2023, assessed according to the coral health criteria of Chou et al. (1994)



Coral Health Status

Coral health status reflected these patterns. At 3 m depth, reef condition declined from good in 2016 (54.15%) to poor in 2019 (18.21%) and 2020 (24.76%), before recovering to excellent in 2023 (79.1%) (Fig. 6). In contrast, at 8 m depth, coral health remained fair from 2016 to 2023, suggesting relative stability and resilience despite the storm (Fig. 6).

Hard Coral Genera

The hard coral community at Pantai Pasir Cina comprised 11 families and 20 genera across 2016, 2019, 2020, and 2023 (Table 3). At 3 m depth, *Acropora* has the highest coverage throughout all years. At 8 m depth, *Fungia* was dominant

before tropical storm Pabuk (2016) and in 2020 whereas *Acropora* has the most abundant coverage in 2016 and 2020. *Acropora* (27.49%), *Fungia* (9.18%), *Pocillopora* (1.71%), and *Montipora* (1.54%) were the most abundant genera across all transects (Fig. 7). Statistical analysis revealed significant differences in hard coral communities both between depths ($p=0.001$) and among years ($p=0.001$).

At 3 m depth, *Acropora* dominated with 36.28% coverage, whereas at 8 m depth, *Acropora* (18.41%) and *Fungia* (14.10%) were co-dominant (Table 3). Genus diversity was also higher at 8 m than at 3 m. Across years, *Acropora* consistently exerted the strongest influence on the hard coral community, with its coverage declining from 24.28% in 2016 to 17.61% in 2019 and 17.17% in 2020, before increasing markedly to 51.53% in 2023. In contrast, genus

Table 3 Relative percentage cover of hard coral genera across different depth and year

Family	Depth	3 m				8 m			
		Year	2016	2019	2020	2023	2016	2019	2020
Genera									
Acroporidae	<i>Acropora</i>	39.57	16.50	22.27	68.54	8.99	18.72	11.42	34.53
	<i>Astreopora</i>	0.03	–	–	–	0.09	–	0.26	–
	<i>Montipora</i>	1.57	0.11	–	0.07	1.32	0.05	–	9.44
Agariciidae	<i>Pavona</i>	0.68	0.10	0.19	1.08	0.67	0.19	0.39	0.04
Dendrophyllidae	<i>Turbinaria</i>	0.30	–	0.06	0.18	0.01	–	0.11	0.51
Euphyllidae	<i>Galaxea</i>	0.08	–	0.02	0.06	–	0.03	0.03	–
Faviidae	<i>Favia</i>	–	–	–	–	0.03	0.03	0.01	0.05
Fungiidae	<i>Ctenactis</i>	0.58	0.14	0.28	1.34	0.78	1.82	1.40	0.07
	<i>Fungia</i>	9.83	0.78	1.45	5.94	23.93	12.49	19.95	0.04
	<i>Halomitra</i>	0.07	–	–	–	0.01	0.02	–	–
	<i>Herpolitha</i>	–	0.01	–	–	0.06	0.06	0.08	–
Merulinidae	<i>Echinopora</i>	0.09	0.01	0.01	0.06	–	0.60	1.25	–
	<i>Favites</i>	–	–	–	–	0.02	–	–	0.11
	<i>Merulina</i>	–	0.13	–	–	–	–	–	–
	<i>Pectinia</i>	0.16	–	–	0.12	0.07	–	0.02	–
Meandrinidae	<i>Platygyra</i>	0.01	–	0.17	–	0.11	–	–	–
Poritidae	<i>Goniopora</i>	–	–	–	–	0.02	–	0.01	–
	<i>Porites</i>	0.17	–	0.04	0.05	0.48	0.06	0.03	0.06
Pachyseridae	<i>Pachyseris</i>	0.03	–	–	–	–	–	0.03	–
Pocilloporidae	<i>Pocillopora</i>	0.98	0.07	0.28	1.48	4.57	2.23	3.71	0.52
Number of genera		15	9	10	11	16	12	15	10

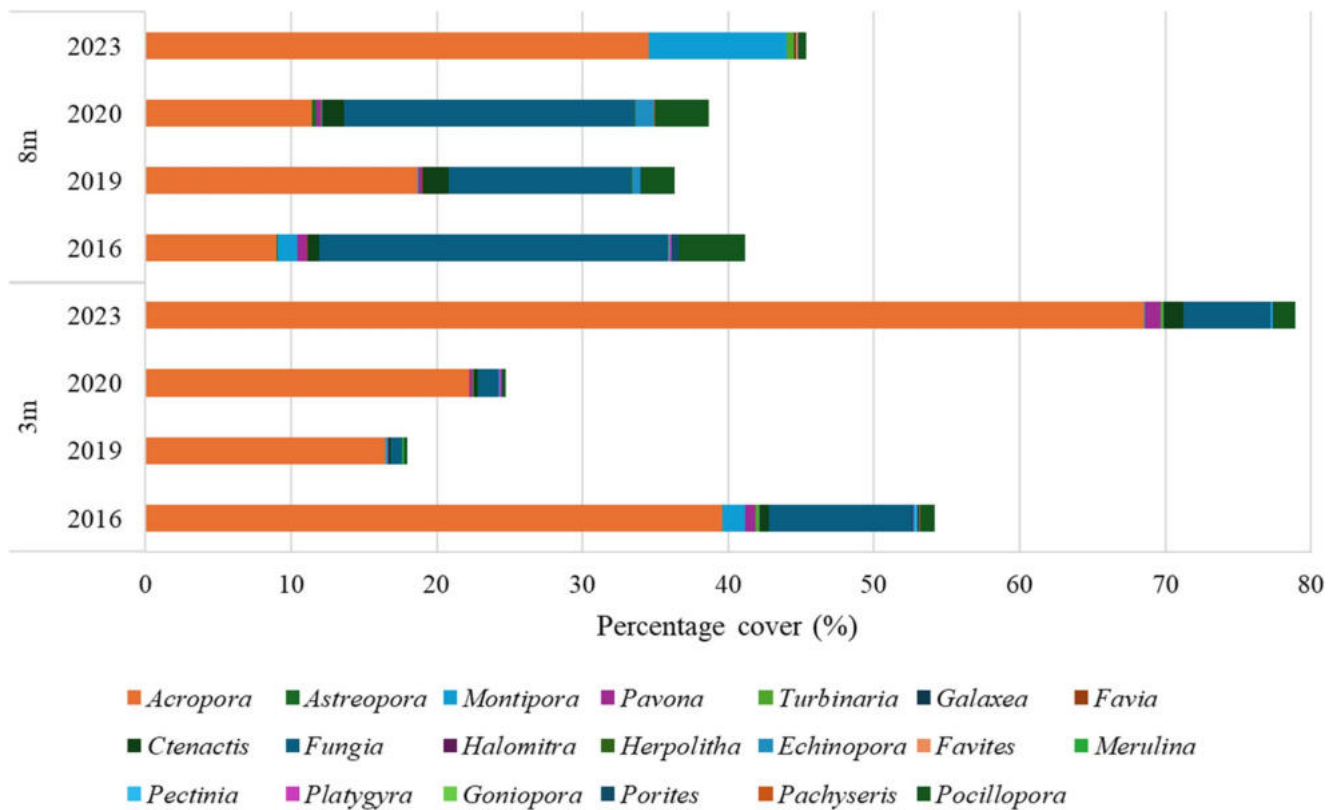


Fig. 7 Percentage cover of hard coral genera at 3 m and 8 m depth across the years 2016, 2019, 2020, and 2023

diversity declined steadily from 19 genera in 2016 to 13 genera in 2023, with several genera absent from records in the most recent survey (Table 3).

Pairwise comparisons between years indicated significant differences among all groups (Table 4), suggesting continuous changes in hard coral communities over the eight-year period. At 3 m depth, however, further pairwise analysis showed high similarity only between 2016 and 2023, suggesting partial recovery at shallow depths. These temporal dynamics were also evident in the multivariate analyses. The nMDS (Fig. 8) and CAP (Fig. 9) ordinations showed that samples from 2019 to 2020 overlapped substantially, while those from 2016 to 2023 displayed partial overlap. Most samples clustered along the *Acropora* vector, reflecting its dominant and persistent influence on community structure, whereas *Montipora* contributed only modestly. Together, these results highlight the central role of a few dominant genera in shaping community trajectories over time.

Discussion

Changes in Hard Coral Cover

Tropical storm Pabuk developed in January 2019 in the southern region of the South China Sea and was the first tropical storm recorded to pass near the waters of the East Coast of Peninsular Malaysia (ECPM) (Safuan et al. 2020). In the ECPM, physical disturbance such as the northeast monsoon could influence the coral reef community structure (Toda et al. 2007; Safuan et al. 2020). As compared to the NE monsoon, Pabuk generated stronger cyclonic winds (>50 mph), leading to intensified currents (>1 m/s), significant wave heights ($H_s > 4$ m), and lower sea surface temperatures (SST) by 1 °C (Safuan et al. 2020). These extreme changes of hydrodynamic conditions resulted in a pronounced loss of live coral cover where shallower reef flats (3 m) experiencing significantly greater damage than the deeper forereef (8 m) (Safuan et al. 2020).

A year after being struck by the tropical storm, no significant difference occurred in the coral reef condition in the study area when comparing data from 2019 to 2020. The slow recovery of live coral cover and persistently high

Table 4 Results of PERMANOVA and pairwise analysis of hard coral communities for factors 'Depth', 'Year' and 'Depth x year'

Groups	PERMANOVA					
	df	SS	MS	Pseudo-F	p-values	perms
Depth	1	8364.3	8364.3	13.085	0.001*	999
Year	3	14,169	4723.1	7.389	0.001*	997
Depth x Year	3	15,504	5168	8.0849	0.001*	998
Pairwise - Year						
Groups				t	p-values	perms
2016 Vs 2019				2.3544	0.001*	997
2016 Vs 2020				1.8033	0.017*	999
2016 Vs 2023				3.6504	0.001*	999
2019 Vs 2020				1.5943	0.028*	999
2019 Vs 2023				2.903	0.001*	999
2020 Vs 2023				4.2498	0.001*	998
Pairwise - Depth x Year: 3 m						
Groups				t	p-values	perms
2016 Vs 2019				2.0418	0.006*	998
2016 Vs 2020				1.9275	0.01*	999
2016 Vs 2023				1.1314	0.26	998
2019 Vs 2020				1.4595	0.045*	999
2019 Vs 2023				3.0039	0.001*	997
2020 Vs 2023				3.2263	0.002*	999
Pairwise - Depth x Year: 8 m						
Groups				t	p-values	perms
2016 Vs 2019				1.8603	0.011*	998
2016 Vs 2020				1.2761	0.181	999
2016 Vs 2023				4.4339	0.001*	999
2019 Vs 2020				1.6068	0.021*	999
2019 Vs 2023				4.2923	0.001*	998
2020 Vs 2023				5.6943	0.001*	999

* indicate $p < 0.05$

Fig. 8 Non-metric multidimensional scaling (nMDS) plot of hard coral communities (ACP = *Acropora*, FUN= *Fungia*, MON= *Montipora* and POCL= *Pocillopora*) for factor Year based on Bray-Curtis similarity. Each point represents a sample, and the distance between points reflects the dissimilarity

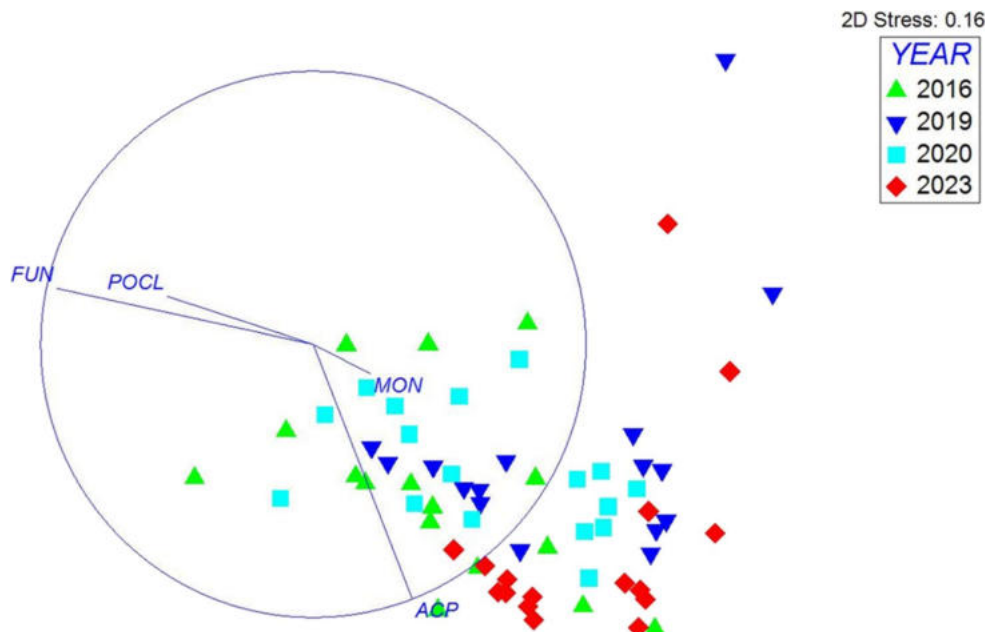
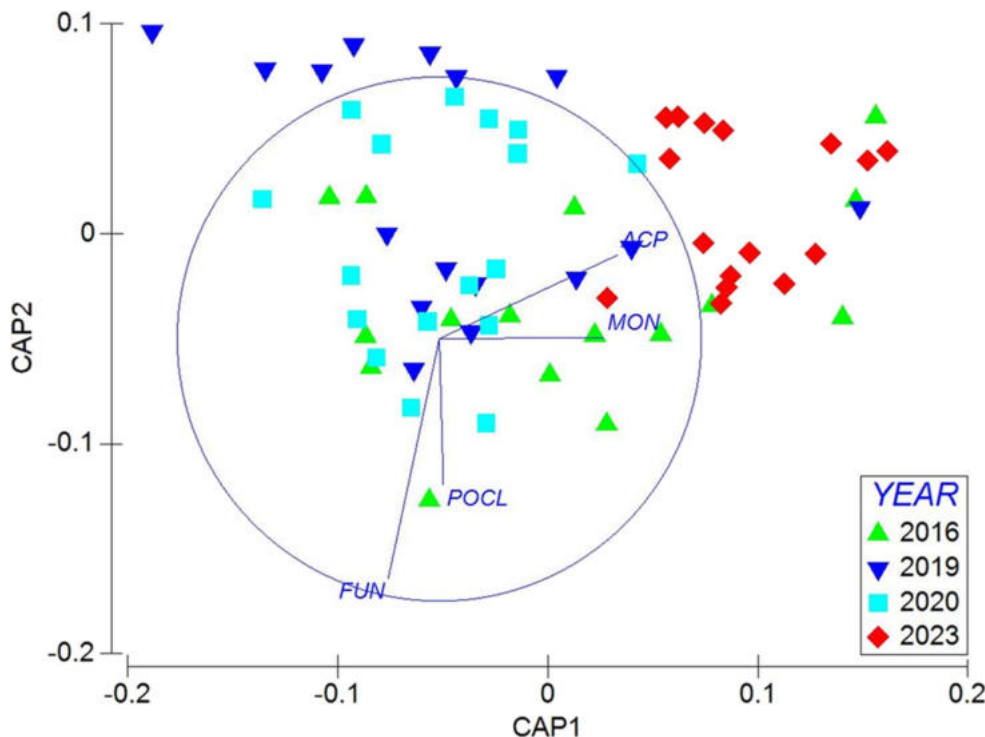


Fig. 9 Canonical analysis of principal coordinates (CAP) plot of hard coral communities for factor year based on Bray-Curtis similarity. Vectors represent four hard coral genera with the highest average percentage cover (ACP = *Acropora*, FUN= *Fungia*, MON= *Montipora* and POCL= *Pocillopora*) with significant Spearman correlations, indicating their influence on the ordination



levels of dead coral cover in 2019 and 2020 suggest that storm-impacted corals may have prioritized energy allocation toward physiological repair and tissue regrowth (i.e., non-reproductive recovery), rather than reproduction (Baird et al. 2018). Corals, like all organisms, have a finite pool of energy resources, and following physical disturbances such as tropical storms, they often prioritize vital processes like tissue repair and skeleton rebuilding. This redirection of energy away from reproduction could partly explain

the reduced live coral cover (Padilla-Gamino et al. 2024). However, recovery also depends on larval supply, which may originate from both local coral and distant reefs. Some *Acropora* species, for instance, produce larvae that can remain in the water column for extended periods, enabling long-distance dispersal and recruitment (Connolly and Baird 2010). Therefore, the slow recovery observed may reflect a combination of local limitations and regional connectivity processes.

The substantial increase in live coral cover in 2023 likely reflects a combination of natural recovery processes and the effects of the ongoing coral restoration program in the study area. The findings indicate that live coral cover increased drastically in 2023 where an area with high dead coral in 2019 have been replaced by live coral. It is estimated that the coral cover increased by 8.39% per year from $28.75 \pm 20.21\%$ SD in 2019 to $62.30 \pm 25.12\%$ SD in 2023. This drastic change can be seen in shallow water area (3 m) as compared to deeper area (8 m). The tropical storm in early 2019 preceded the mass bleaching event later that year. Although bleaching and other stressors such as disease outbreaks, predation, and water quality changes can influence coral recovery, no published data report bleaching events specifically at Pulau Bidong between 2016 and 2023 (Reef Check Malaysia 2017, 2018). Our observations did not reveal evidence of widespread disease or other acute disturbances. Therefore, the increase in live coral cover from 2019 to 2023 primarily reflects recovery from storm damage, but the potential roles of these other factors cannot be fully ruled out and deserve further study. Studies have shown that coral reefs can recover from physical damage, although this recovery can be influenced by several factors, including the frequency and intensity of disturbances and the presence of other stressors (Adjeroud et al. 2018; Rodgers et al. 2021).

Coral recovery in our shallow water area may have been supported by an active coral restoration program initiated in 2020 and funded by industrial partners. The restoration sites were located within the broader study area but outside the monitored transects. Although specific survival and growth rates of transplanted corals were not assessed, the restoration efforts may have contributed indirectly to recovery by enhancing coral recruitment and structural complexity. Therefore, the observed increase in live coral cover in 2023 likely reflects a combination of natural recruitment and the effects of the restoration program, although their individual contributions cannot be fully distinguished. Reefs restoration activities are known to be ‘expensive’ (Suggett et al. 2024), hence the contribution of other entities, particularly on funding, is significantly helping in the active coral restoration in impacted area. This project involves multiple coral species with varying morphologies, which can promote diverse responses to environmental conditions and enhance reef resilience by reducing the risk of widespread coral loss from a single disturbance event (Shaver et al. 2022). This restoration effort may have contributed to the observed coral recovery alongside natural processes. A study by Lange et al. (2024) indicates that the rapid growth of transplanted corals significantly contributes to the recovery of coral cover and carbonate production.

Another notable finding is the ability of the coral to return to its original condition. In 2016, coral condition in the study area was classified as ‘fair’ condition and change into ‘poor’ condition in 2019 after being struck by the tropical storm. However, following the natural recovery and active coral restoration, the condition has been returned to ‘fair’ condition. Surprisingly, a better condition was observed in the restoration area with recovery rate of 6.71%/year within four years, shifting the reef condition from ‘fair’ to ‘excellent.’ The use of fast-growing branching corals such as *Acropora* is useful for promoting rapid recovery after large-scale disturbances (Shaver et al. 2022). Besides, algae cover in the study area was low, showing no indication of phase shift from coral dominant to algae dominant reef. This indicates a successful recovery and highlights the resilience of corals at the study site in facing physical damage caused by natural disturbances. A resilient coral reef lies in its ability to both weather disturbances and bounce back to a state rich in diverse coral morphology (Marshall and Schuttenberg 2006). In this case, Pulau Bidong also has minimal human disturbances as compared to other islands in the ECPM (Safuan et al. 2021). Therefore, the recovery of the coral reef in PPC likely reflects a combination of natural processes and local efforts, though the specific drivers remain unclear.

Hard Coral Communities

The changes in dominant coral taxa from *Acropora-Fungia* in 2016 to *Acropora-Montipora* in 2023 at deeper depth can be closely linked to the impacts of the 2019 tropical storm and the subsequent recovery of reef structural complexity. Tropical storms can significantly alter the shape and structure of coral reefs and have lasting effects on the types of coral present and how they are spaced out on the reef (Harmelin-Vivien and Laboute 1986; Scheffers and Scheffers 2006; Cheal et al. 2017; Baird et al. 2018). The recovery of *Acropora* dominance in 2023, alongside the persistence of *Montipora*, suggests that post-disturbance assemblages at Pantai Pasir Cina retain the capacity for structural recovery and ecological resilience over time (Graham and Nash 2013). The study by Yuval et al. (2023) underscores the importance of structural complexity in supporting these recovery processes and maintaining coral biodiversity and ecosystem function.

This recovery phase likely involved a shift towards taxa that are more adaptable to changing conditions and disturbances. For instance, faster-growing, branching corals such as *Acropora* (Dullo 2005) tend to outcompete and become the dominant coral type more readily, compared to slow-growing corals such as *Favites* (Guest et al. 2023) and other massive corals (Edinger and Risk 2000). The domination

of fast growing *Acropora* particularly at shallow water area significantly contribute to the high coral cover in the study area. Quantitative data showed a lower percentage cover of *Fungia* at 8 m depth compared to 3 m. This difference may reflect natural depth-related variation in their distribution, although some colonies may also have been obscured by overgrown branching corals such as *Acropora*. Fungiid corals are also known to move or migrate to avoid burial or overgrowth, as observed in Okinawa, Japan (Ohara et al. 2021), which could further influence cover estimates. These factors highlight the need for complementary approaches, such as targeted searches, to better capture the abundance of cryptic or mobile coral species in future monitoring. Overall, our findings underscore the vulnerability of coral assemblages at Pantai Pasir Cina and highlight the need for continued long-term monitoring to detect future shifts in community structure and resilience potential.

Conclusion

The investigation into coral reef recovery at Pulau Bidong following Tropical Storm Pabuk reveals significant recovery and resilience responses within the coral community. The increase in live coral cover and reduction in dead coral cover by 2023 underscore the reef's capacity to recover from severe disturbances. The ability to return to the previous condition (fair condition in 2016) and maintain the dominant coral taxa (*Acropora-Fungia* community) indicates the resilience of the coral reef to return back to its original condition. At 8 m depth, the apparent shift from *Acropora-Fungia* to *Acropora-Montipora* dominance may reflect changes in the visible coral assemblage, potentially influenced by the overgrowth of branching corals. However, this pattern should be interpreted with caution, as the presence of cryptic species such as *Fungia* may have been underestimated due to methodological limitations. Additionally, the role of active coral restoration for coral recovery is particularly noteworthy, as it accelerates the natural recovery processes, aiding in the re-establishment of coral cover and the stabilization of the reef structure. This study underscores the critical need for proactive and adaptive coral reef management strategies that focus on enhancing resilience. Such strategies should integrate active restoration efforts with long-term monitoring and protection measures to support coral reefs in adapting to and recovering from both natural and anthropogenic stressors. These efforts are imperative for maintaining the ecological functions and services provided by coral reefs, securing their role in supporting marine life and human livelihoods in the face of climate change and other ongoing threats.

Acknowledgements The authors would like to express their gratitude to all the researchers and staff for their invaluable assistance during the study period. This study was funded by the Talent and Publication Enhancement-Research Grant (TAPE-RG) sponsored by Universiti Malaysia Terengganu (UMT/TAPE-RG 2022/VOT 55404) and supported by the Ministry of Higher Education Malaysia under research grant of Higher Institution Centre of Excellence (HICoE, Vot no. 56059), Institute of Oceanography and Environment, Universiti Malaysia Terengganu.

Author Contributions M.F.N.Q. – Writing - Review & Editing, Visualization, Formal Analysis. M.M.A.Z. – Writing - Original Draft, Formal Analysis. S.N.J. - Conceptualization, Investigation. M.H.B – Conceptualization, Investigation. Z.B – Investigation, Funding Acquisition. C.D.M.S. – Conceptualization, Investigation, Writing - Original Draft, Writing - Review & Editing, Funding Acquisition, Project Administration.

Funding Open access funding provided by The Ministry of Higher Education Malaysia and Universiti Malaysia Terengganu. This study was funded by the Talent and Publication Enhancement-Research Grant (TAPE-RG) sponsored by Universiti Malaysia Terengganu (UMT/TAPE-RG 2022/VOT 55404) and supported by the Ministry of Higher Education Malaysia under research grant of Higher Institution Centre of Excellence (HICoE, Vot no. 56059), Institute of Oceanography and Environment, Universiti Malaysia Terengganu.

Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

References

- Adjeroud M, Kayal M, Iborra-Cantonnet C, Vercelloni J, Bosserelle P, Liao V, Penin L (2018) Recovery of coral assemblages despite acute and recurrent disturbances on a South central Pacific reef. *Sci Rep* 8(1):9680
- Akmal KF, Shahbudin S (2020) Baseline assessment of coral health and disease in Tioman Island marine Park, Malaysia. *Community Ecol* 21:285–301
- Anderson MJ (2017) Permutational Multivariate Analysis of Variance (PERMANOVA). In: Balakrishnan N, T Colton, B Everitt, W Piegorisch, F Ruggeri, JL Teugels, editors. Wiley StatsRef: statistics

- reference online. <https://doi.org/10.1002/9781118445112.stat07841>
- Bachok Z, Safuan CDM, Roseli NH, Akhir MF (2020) Quantitative dataset of shallow water reef in Pulau Bidong, Southern of South China sea during pre and post of tropical storm (Pabuk-January 2019). *Data Brief* 32:106182
- Baird AH, Álvarez-Noriega M, Cumbo VR, Connolly SR, Dornelas M, Madin JS (2018) Effects of tropical storms on the demography of reef corals. *Mar Ecol Prog Ser* 606:29–38
- Beeden R, Maynard J, Puotinen M, Marshall P, Dryden J, Goldberg J, Williams G (2015) Impacts and recovery from severe tropical Cyclone Yasi on the Great Barrier Reef. *PLoS One* 10(4):e012127
- Bozec YM, Alvarez-Filip L, Mumby PJ (2015) The dynamics of architectural complexity on coral reefs under climate change. *Glob Change Biol* 21(1):223–235
- Carter AL, Gilchrist H, Dexter KG, Gardner CJ, Gough C, Rocliffe S, Wilson A (2022) Cyclone impacts on coral reef communities in Southwest Madagascar. *Frontiers in Marine Science* 9:753325
- Cheal AJ, MacNeil MA, Emslie MJ, Sweatman H (2017) The threat to coral reefs from more intense cyclones under climate change. *Glob Change Biol* 23:1511–1524. <https://doi.org/10.1111/gcb.13593>
- Chou LM, Chou LM, Ang PO (1994) ASEAN-Australia Living Coastal Resources Project: coral reef monitoring. ASEAN-Australia Marine Science Project, Singapore
- Connolly SR, Baird AH (2010) Estimating Dispersal Potential for Marine Larvae: Dynamic Models Applied to Scleractinian Corals. *Ecology* 91(12):3572–83
- Daryabor F, Ooi SH, Samah AA, Akbari A (2016) Dynamics of the water circulations in the Southern South China sea and its seasonal transports. *PLoS ONE* 11(7):e0158415
- Doropoulos C, Roff G, Zupan M, Nestor V, Isechal AL, Mumby PJ (2014) Reef-scale failure of coral settlement following typhoon disturbance and macroalgal bloom in Palau, Western Pacific. *Coral Reefs* 33:613–623
- Dullo WC (2005) Coral growth and reef growth: a brief review. *Facies* 51(1):33–48
- Edinger EN, Risk MJ (2000) Reef Classification by Coral Morphology Predicts Coral Reef Conservation Value. *Biol Conserv* 92(1):1–13
- English S, Wilkinson C, Baker V (1997) Survey manual for tropical marine resources. Australian Institute of Marine Science, Townsville
- França FM, Benkwitt CE, Peralta G, Robinson JP, Graham NA, Tylananakis JM, Robinson JPW, Graham NAJ, Berenguer E, Lees AC, Ferreira J, Louzada J, Barlow J (2020) Climatic and local stressor interactions threaten tropical forests and coral reefs. *Philos Trans R Soc Lond B Biol Sci* 375(1794):20190116
- Gardner TA, Côté IM, Gill JA, Grant A, Watkinson AR (2005) Hurricanes and Caribbean coral reefs: impacts, recovery patterns, and role in long-term decline. *Ecology* 86(1):174–184
- Geister J (1977) The influence of wave exposure on the ecological zonation of Caribbean coral reefs. In: *Proc 3rd Coral Reef Symp*, vol 1, pp 23–29
- Graham NA, Nash KL (2013) The Importance of Structural Complexity in Coral Reef Ecosystems. *Coral Reefs* 32(2):315–26
- Guest J, Baria-Rodriguez MV, Toh TC, Cruz dela, Vicentuan D, Gomez K, Edwards E, A (2023) Live slow, die old: larval propagation of slow-growing, stress-tolerant corals for reef restoration. *Coral Reefs* 42(6):1365–1377
- Gunderson LH (2000) Ecological resilience—in theory and application. *Annu Rev Ecol Syst* 31(1):425–439
- Haapkylä J, Melbourne-Thomas J, Flavell M, Willis B (2013) Disease outbreaks, bleaching and a cyclone drive changes in coral assemblages on an inshore reef of the Great Barrier Reef. *Coral Reefs* 32:815–824
- Harmelin-Vivien ML (1994) The Effects of Storms and Cyclones on Coral Reefs: A review. *J Coastal Res* 12:211–23
- Harmelin-Vivien ML, Laboute P (1986) Catastrophic Impact of Hurricanes on Atoll Outer Reef Slopes in the Tuamotu (French Polynesia). *Coral Reefs* 5(2):55–62
- Kelley R (2022) Coral finder 2022 – Indo Pacific coral finder, 5th edn. BYOGUIDES, Townsville, Australia
- Knutson T, Camargo SJ, Chan JC, Emanuel K, Ho CH, Kossin J, Wu L (2020) Tropical cyclones and climate change assessment: part II: projected response to anthropogenic warming. *Bull Am Meteorol Soc* 101(3):E303–E322
- Kohler KE, Gill SM (2006) Coral Point Count with Excel Extensions (CPCe): A Visual Basic program for the Determination of Coral and Substrate Coverage using Random Point Count Methodology. *Comput Geosci* 32(9):1259–69
- Kuffner IB, Walters LJ, Becerro MA, Paul VJ, Ritson-Williams R, Beach KS (2006) Inhibition of coral recruitment by macroalgae and cyanobacteria. *Mar Ecol Prog Ser* 323:107–117
- Lamb JB, Willis BL, Fiorenza EA, Couch CS, Howard R, Rader DN, Harvell CD (2018) Plastic waste associated with disease on coral reefs. *Science* 359(6374):460–462
- Lange ID, Razak TB, Perry CT, Maulana PB, Prasetya ME, Lamont TA (2024) Coral restoration can drive rapid reef carbonate budget recovery. *Curr Biol* 34(6):1341–1348
- Madin JS, Baird AH, Dornelas M, Connolly SR (2014) Mechanical vulnerability explains size-dependent mortality of reef corals. *Ecol Lett* 17(8):1008–1015
- Marshall, P. & Schuttenberg, H. 2006. Adapting coral reef management in the face of climate change. In: *Coral Reefs and Climate Change: Science and Management*, 61, 223–241
- Muko S, Arakaki S, Nagao M, Sakai K (2013) Growth form-dependent response to physical disturbance and thermal stress in acropora corals. *Coral Reefs* 32:269–280
- Ohara T, Hoeksema BW, Wee HB, Reimer JD (2021) Downslope migration of free-living corals (Scleractinia: Fungiidae) in typhoon-exposed reef habitats at Okinawa, Japan. *Mar Environ Res* 170:105445
- Padilla-Gamino J, Timmins-Schiffman E, Lenz E, White SJ, Axworthy J, Potter A, Wang F (2024) Coral long-term recovery after bleaching: implications for sexual reproduction and physiology. *BioRxiv* 2024–2004. <https://doi.org/10.1101/2024.04.09.588789>
- Pascoe KH, Fukunaga A, Kosaki RK, Burns JH (2021) 3D assessment of a coral reef at Lalo Atoll reveals varying responses of habitat metrics following a catastrophic hurricane. *Sci Rep* 11(1):12050
- Perry CT, Smithers SG, Kench PS, Pears B (2014) Impacts of cyclone Yasi on nearshore, terrigenous sediment-dominated reefs of the central Great Barrier Reef, Australia. *Geomorphology* 222:92–105
- Puotinen M, Drost E, Lowe R, Depczynski M, Radford B, Heyward A, Gilmour J (2020) Towards modelling the future risk of cyclone wave damage to the world's coral reefs. *Glob Change Biol* 26(8):4302–4315
- Reef Check Malaysia (2017) Status of coral reefs in Malaysia, 2016. Reef Check Malaysia, Malaysia, p 90
- Reef Check Malaysia (2018) Status of coral reefs in Malaysia, 2019. Reef Check Malaysia Survey Report, Reef Check Malaysia
- Rodgers K, Donà A, Stender Y, Tsang A, Han J, Weible R, Prouty N, Storlazzi C, Graham A (2021) Rebounds, regressions, and recovery: a 15-year study of the coral reef community at Pila'a, Kaua'i after decades of natural and anthropogenic stress events. *Mar Pollut Bull* 112306. <https://doi.org/10.1016/j.marpolbul.2021.112306>
- Roff G, Mumby PJ (2012) Global disparity in the resilience of coral reefs. *Trends Ecol Evol* 27(7):404–413
- Rogers CS (1993) Hurricanes and coral reefs: the intermediate disturbance hypothesis revisited. *Coral Reefs* 12:127–137

- Safuan CDM, Ashraf ARM, Tan CH, Jaafar SN, Yusop PAM, Lai RK, Bachok Z (2021) Coral health status assessment in Malaysia islands; looking towards Marine Spatial Planning. *Ocean & Coastal Management* 213:105856
- Safuan CDM, Roseli NH, Bachok Z, Akhir MF, Xia C, Qiao F (2020) First record of tropical storm (Pabuk-January 2019) damage on shallow water reef in Pulau Bidong, south of South China Sea. *Reg Stud Mar Sci* 35:101216
- Safuan M, Boo WH, Siang HY, Chark LH, Bachok Z (2015) Optimization of coral video transect technique for coral reef survey: comparison with intercept transect technique. *Open J Mar Sci* 5:379–397
- Scheffers, A. & Scheffers, S. 2006. Documentation of the impact of Hurricane Ivan on the coastline of Bonaire (Netherlands Antilles). *Journal of Coastal Research*, 22(6), 1437–1450
- Shaver EC, McLeod E, Hein MY, Palumbi SR, Quigley K, Vardi T, Wachenfeld D (2022) A roadmap to integrating resilience into the practice of coral reef restoration. *Glob Change Biol* 28(16):4751–4764
- Suggett DJ et al (2024) Restoration as a meaningful aid to ecological recovery of coral reefs. *Npj Ocean Sustain* 3(1):20
- Szereday S, Voolstra CR, Amri AY (2024) Back-to-back bleaching events in Peninsular Malaysia (2019–2020) selectively affect hard coral taxa across-and within-reef scales. *Mar Biol* 171:183. <https://doi.org/10.1007/s00227-024-04567-8>
- Toda T, Okashita T, Maekawa T, Alfian BAAK, Rajuddin MKM, Nakajima R, Terazaki M (2007) Community structures of coral reefs around Peninsular Malaysia. *J Oceanogr* 63:113–123
- Veron JEN, Stafford-Smith MG, Turak E, DeVantier LM (2024) Corals of the world. Retrieved May 15, 2024, from <https://www.coralsoftheworld.org/>
- Yuval M, Pearl N, Tchernov D, Martinez S, Loya Y, Bar-Massada A, Treibitz T (2023) Assessment of storm impact on coral reef structural complexity. *Sci Total Environ*. 891 <https://doi.org/10.1016/j.scitotenv.2023.164493>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.