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Anthony Montagne, Odile Naim, Catherine Tourrand, Bernard Pierson, David D. Menier. Status of Coral Reef Communities on Two Carbonate Platforms (Tun Sakaran Marine Park, East Sabah, Malaysia). *Journal of Ecosystems*, 2013, 2013, 15 p. 10.1155/2013/358183 . hal-00879576

**HAL Id: hal-00879576**

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Submitted on 4 Nov 2013

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## Research Article

# Status of Coral Reef Communities on Two Carbonate Platforms (Tun Sakaran Marine Park, East Sabah, Malaysia)

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Received 12 March 2013; Revised 29 May 2013; Accepted 26 August 2013

Academic Editor: Luiz E. Aragao

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This study concerns three sites, located on carbonate platforms, east Sabah: Gaya West, Gaya East, and Mantabuan. At each site, the dominant coral shapes and their health were recorded (lagoons and outer slopes). Densities of echinoderms, *Tridacna*, and nudibranchs were recorded while fish density was estimated. Generally, the coral vitality is low ( $\leq 50\%$  living corals). Massive corals dominate all sites, except the Gaya West-outer slope where coral coverage and diversity are the highest. On the Mantabuan-mesh reef, a diverse *Acropora* assemblage dominates the landscape. On the reef flat of Gaya East, monospecific circa 10 meter coral patches occur. Primary producers are scarce on all sites. Sea urchins, dominated by *Diadema*, are abundant on the Gaya East-reef flat and the Gaya West-mesh reef. Sea stars and holothurids are the most prevalent in Gaya West-outer slope, although they remain scarce. Crinoids are only abundant in Mantabuan. *Stegastes* damselfish highly characterizes the sites of Gaya East (reef flat and inner slope) and the Mantabuan-mesh reef. On the Mantabuan-outer slope, parrotfish and other fishes are plentiful. No sign of eutrophication has been detected and natural hypersedimentation and/or eventual ancient bleaching events appear to be the direct principal causes of coral death or coral degradation.

## 1. Introduction

An exceptionally high biodiversity prompted the creation of the Tun Sakaran Marine Park (TSMP) in the western part of the Celebes Sea, east of Semporna, Sabah, Malaysia, as the site supports a greater diversity of marine species than recorded elsewhere in Malaysia. The site is therefore of regional, national, and local importance.

Marine and coastal habitats include (1) mangroves, (2) seagrass beds, (3) lagoons, (4) fringing, patch and bank reefs and (5) open water. Studies show that the diversity of marine species in the proposed park is very high. There are over 600 species of fish and at least 250 species of corals [1, 2]. Harborne et al. [3], summarizing fragmented studies of coral species' richness around Malaysia, reported a total of 323 species. Around the reefs, 265 species of molluscs occur [4],

and there may be as many as 140 species of sponges, 70 species of soft corals, and at least 50 species of gorgonians [5, 6]. In addition, a high diversity of echinoderms exists, with a total of 109 species recorded [5, 7, 8]. Several of the sponges and soft corals found in the Gaya lagoon are new undescribed species. One sponge is very unusual and possibly endemic to the Semporna reefs [9]. Also, Allen [1] found two new species of damselfish.

The preliminary results of the Semporna Marine Ecological Expedition [10] ([http://awsassets.panda.org/downloads/smee\\_factsheet\\_dec\\_2010.pdf](http://awsassets.panda.org/downloads/smee_factsheet_dec_2010.pdf)) indicate that Semporna may have one of the world's highest marine biodiversity. For example, the expedition's fish counts demonstrated that Semporna is one of the richest areas within the Coral Triangle (844 species of fish encountered). Also, the expedition yielded

a record number of 43 species of mushroom corals (the previous highest recorded richness in this family was 40 species in Indonesia and Papua New Guinea). Furthermore, some new species were discovered (two species of shrimp and possibly a number of gall crabs).

In Semporna, the island of Bodgaya was first gazetted in 1933 as a forest reserve, and the island of Boheydulang was proposed as a bird sanctuary. Then in 1977, proposals were made to establish a state park. Later, in 1998, a collaboration (known as the Semporna Islands Project) was set up between the Marine Conservation Society (MCS), Sabah Parks, WWF Malaysia, and Nature Link. In 2004, the Tun Sakaran Marine Park (TSMP), the seventh gazetted area under Sabah Parks, was established.

Over 2,000 residents, that is, Suluk, Bajau, and Bajau Laut, live in the TSMP. This unique mix of people adds a further dimension to the area through their cultures, lifestyles, legends, and skills. Most of the islands have settlements made up of semipermanent houses, shacks, and permanent structures. The main activities consist of fishing, gardening, and seaweed cultivation. The natural products harvested are fish, shellfish, medicinal plants, fruits, and timber. Tourism is currently almost nonexistent, although 21 prestigious scuba diving sites are reported [11].

Herein, reticulated reefs, commonly known as mesh reefs, are particularly studied. Complex cellular patterns of coral reef walls or “reticulated/mesh reefs” often occupy the small fringing reefs and the internal lagoons of several modern platforms in the Tun Sakaran Marine Park. They are networks, with intervening depressions, of linear or polygonal reef framework. The cellular patterns are of different sizes and scales: cells 20 m in diameter, larger cells 200 m in diameter, and the largest (on Selakan Bank) about 1 km in diameter [12, 13]. These reef patterns may occur (1) on *fringing reefs*, notably in the Arabian Gulf, in the Red sea [14, 15], and in Madagascar [16], (2) on *barrier reefs* in New Georgia [17], in Belize [18], on the Great Barrier Reef [19–21], and in Mayotte [16], and (3) on *atolls* in Hawaii (Maro reef, [22]), in Fiji, in French Polynesia [23, 24], and in Kiribati (Caroline/Millennium, [25]). According to Montaggioni [23] and Purkis and Riegl [15], the reticulated shape of the mesh reef could mimic a preexisting karst topography, inherited from an episode of lower sea level.

The aim of the study is to analyze the health and stage of development (old corals or recovery after mortality) of coral communities in two islands (reticulated reefs in lagoons and outer slopes). The density of associated organisms, echinoderms, gastropods, bivalves, and fishes, are coanalyzed.

## 2. Material and Methods

**2.1. General Environmental Setting.** Sabah is a tropical country characterized by uniform temperatures, high humidity, and copious rainfalls. Situated between roughly 4°N and 7°N, under the monsoon and typhoon belt, Sabah is often referred to as “the Land below the wind.” Generally two seasons are distinguished: the rainy and the dry seasons although it is hot and humid (85–95%) almost all year round, except at

highaltitude. In most parts of Sabah, the wet season starts in November with the onset of the Northeast Monsoon (winter monsoon) and ends towards March. During the months of April to November, the drier season occurs (southwest monsoon or summer monsoon), and southwesterly winds over the northwest coast of Sabah may strengthen, reaching 40 km·h<sup>-1</sup> or more. In Semporna, temperatures rarely rise above 32°C during the day and rarely drop below 23°C at night. Seawater is almost at a constant temperature (26–29°C).

Tun Sakaran Marine Park (TSMP), also known as Semporna Islands Park, lies off the east coast of Sabah, Malaysia, at the entrance to Darvel Bay (latitude 4°33'N to 4°42'N and longitude 118°37'E to 118°51'E) (Figure 1). It is the largest marine Park in Malaysia and one of the prime coral reef sites of the country. It includes eight islands and associated reefs (Bodgaya, Boheydulang, Sebangkat, and Selakan, the sand cays of Maiga, Sibuan, and Mantabuan, the patch reefs of Church and Kapikan) and covers an area of approximately 340 km<sup>2</sup> of sea and coral reefs and 10 km<sup>2</sup> of land. The large, central high islands are formed of volcanic rock and are unique in Sabah. The outlying islands are low limestone and carbonate sand cays. Their windward margin, where coral reefs develop, faces the dominant northeast trade winds.

In the studied area, the maximum high tide recorded in the tide tables for Semporna (Darvel Bay) is 2.1 m and the minimum tide, 0.1 m (<http://www.mareespeche.com/as/malaysia/semporna-darvel-bay>).

**2.2. Studied Sites.** Three monitoring sites were selected on Gaya and Mantabuan Banks (Figure 1). Gaya Bank is a true atoll, about 8 km in diameter, with a perimeter of 30 km. An extinct volcano, at the core of the bank, forms two high relief islands, Pulau Bodgaya and Pulau Boheydulang. A reef complex and associated facies mainly developed on the seaward side of the volcanic islands. The deep lagoon may represent the crater of the extinct volcano. Intricate, polygonal patterns of reef walls, or mesh reefs of different sizes occupy the lagoon. Mantabuan is a smaller bank, 8 km in perimeter, located in the NE of Gaya bank.

The studied sites (Figure 2) display different types of reef habitats occurring on the carbonate platforms: (1) site GE includes a fringing reef exposed to currents (reef flat and internal slope), (2) site GW includes a part of a large mesh reef, a reef rim, and an outer slope, (3) site M, an outer, clear-water site, includes a part of the mesh reef, a reef rim, and an outer slope. As the coral coverage decreases sharply below 15 m in depth, slopes were explored up to this depth (Figure 3).

In the results, we will often separate one site into two subsites: the lagoon or reef flat and the slope. Methods are detailed in Table 1.

**Survey I: Reef Zonation and Major Benthic Categories.** To provide information on reef zonation, the habitat was observed and the major components were analyzed. The surveyor measured depth, current speed and recorded the abundance of main components of the sessile benthic community.

TABLE 1: The three surveys.

	Aim of the study	Stations	Method	Period
Survey 1	Sessile fauna: estimation of coverage and species composition of major benthic categories	At each site, LITs are parallel to the reef front	Line-Intercept-Transsect = 10 m LIT	2011, May
Survey 2	Sedentary fauna: estimation of densities of echinoderms, <i>Tridacna</i> , and nudibranchs	1 belt-transect, 0.5 m apart the 50 m LIT	Belt-transect (50 m by 1 m)	2011, May
Survey 3	Fishes: abundance index for: (1) Damselfish <i>Stegastes</i> (2) Parrotfish (3) Other fishes	1 belt-transect, 0.5 m apart the 50 m LIT	Belt-transect (50 m by 1 m)	2011, May

LIT: Line-Intercept-Transsect.

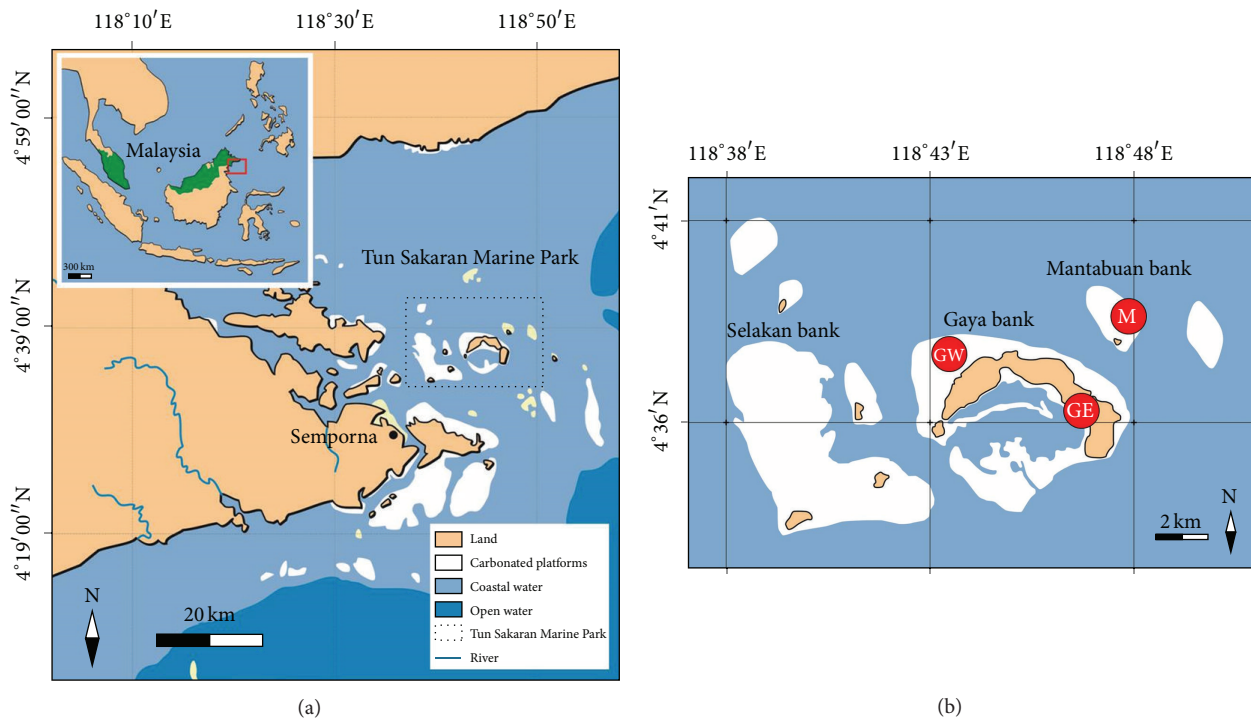


FIGURE 1: (a) Location of the Tun Sakaran National Park in Malaysia; (b) focus on the three studied sites: Gaya West (GW), Gaya East (GE), and Mantabuan (M).

Using the Line-Intercept-Transsect (LIT) method [26, 27], an estimation of the coverage (in %) of major benthic sessile categories (such as primary producers, living and dead corals, soft corals, sponges, rock, sand, and rubble) was made at a 5-centimeter resolution. LITs, 50 m in length, parallel to the front of the reef, were run at different intervals (Figure 2).

Primary producers are cyanophytes and benthic algae; bare dead corals are the dead substrates that are not covered by any living organism visible to the naked eye.

The different forms of corals have been noted as follows: ACB: branching *Acropora*; ACBB: bottlebrush *Acropora*; ACCOR: corymbose *Acropora*; ACST: stout *Acropora* (*A. palifera*); ACTAB: tabular *Acropora*; CB: branching non-*Acropora* (such as branching *Porites*, *Pocillopora*, *Stylophora*, and *Seriatorpora*); CENC: encrusting Non-*Acropora*; CF: foliaceous corals (such as some *Montipora*, some *Pavona*,

and *Turbinaria*); CM: massive Non-*Acropora* (such as massive *Porites*, Faviidae); CMR: mushroom corals (*Fungia*, *Cycloseris*, *Herpolitha*, etc.); CSM: submassive corals (some *Montipora*, *Psammocora*, etc.); CST: stout branching non-*Acropora*.

In the lagoon, LITs had to be located on the upper part of the mesh rims and not at random, because of the great height of the coral rims (Figure 3).

Unlike in a classical reef check, we analyzed all the layers of the communities (Figure 4), for example, the dead substratums, on which young corals are settled, young corals on which perhaps algae are settled, and so forth.

*Survey 2: Densities of Echinoids, Holothurids, and Stegastes.* Densities of Echinoderms (echinids, asterids, holothurids, crinoids), *Tridacna*, and nudibranchs were censused in belt-transects, 0.5 m strip on either side of each 50 m LIT (50 m<sup>2</sup>).

TABLE 2: Description of the three radial lines on the three sites, Gaya West, Gaya East, and Mantabuan, from the lagoon to the reef rim and the outer slope.

(a)		
Gaya West	Depth, turbidity, and currents	Description of the general morphology
The mesh reef in the lagoon (stations GW1 to GW5)	Depth: -7 m. The water is very turbid. Current speed is low.	In the lagoon, corals form a mesh reef made of large coral strips, 4-7 m high and 4-5 m wide. These coral rims rise from the seabed like large walls, surrounded by a sandy plain (Figure 5). The upper part of the strips never emerges at low tide. Coral vitality is low.
The transition from the lagoon to the reef rim	Depth: -2 m. It is possible to walk on this part of the reef at low tide. Currents are very strong, and, as a consequence, the area has not been analyzed.	From the lagoon toward the reef rim, the depth decreases sharply. In this transition zone, corals occur as circa metric patch reefs with great vitality. These patches are scattered in a large sandy area. Coral colonies are likely massive and submassive and few <i>Acropora</i> are visible.
The reef rim	Depth: 0 m.	The reef rim is the highest part of the intertidal portion of the reef, reaching a few centimeters above the upper level of coral growth. Here it is half-necrotic and is less than 10 m wide. Coralline algae cements the upper surface of the rim.
The outer slope (stations GW6 and GW7)	From 0 to 15 m, turbidity is not important, and coral diversity is the highest observed at Gaya West.	The outer slope is very steep and displays luxuriant hard corals, dominated by large heads of non- <i>Acropora</i> corals.
The sandy plain	Depth: -15 m. Turbidity is very important.	At -15 m depth appears a plain characterized by slightly muddy fine sediment.
(b)		
Gaya East	Depth, turbidity, and currents	Description of the general morphology
The back reef (GE1 station)	This part of the reef is made of sand. The currents may be high during tides.	No hard coral is visible. Some scarce starfish occurs there.
The reef flat (GE2 to GE5 stations)	Depth: -4 to -2 m. The water is not turbid. Because of the location behind a corridor occurring between the two islands, Pulau Bodgaya and Pulau Boheydulang, the currents may be violent during tides.	The reef flat is characterized by monospecific, circa 10 m in diameter, stands of branching <i>Acropora</i> , <i>foliaceous Montipora</i> , <i>cf florida</i> , or <i>Pavona cactus</i> . These large stands alternate with more diversified and smaller patches of branching, submassive, and massive non- <i>Acropora</i> ( <i>Pocillopora</i> , <i>Stylophora</i> , <i>Seriatopora</i> , <i>Psammocora</i> , <i>Favia</i> , <i>Favites</i> , etc.).
The reef rim	Depth increases slowly.	There is no reef rim visible.
The inner slope (GE6 and GE7 stations)	From -2 to -15 m. First the slope gently goes down from -2 to -7 m for 50 meters and then becomes steeper from -7 to -17 m.	The two stations GE6 and GE7 are located in the steep area (-10 and -15 m).
The sandy plain	Depth: -17 m Turbidity is not important.	At -17 m appears a plain made of fine sediment.
(c)		
Mantabuan	Depth, turbidity, and currents	Description of the general morphology
The mesh reef into the lagoon (M1 to M4 stations)	Depth: -1 to -5 m The water is not turbid.	Into the lagoon, corals form a mesh reef. But the strips, 4 m high and 3 m wide, are less developed than in the Gaya West lagoon. The coral community is diverse, and <i>Acropora</i> is abundant. The upper parts of the strips are subtidal.

(c) Continued.

Mantabuan	Depth, turbidity, and currents	Description of the general morphology
The transition from the lagoon to the reef rim	Depth: -2 m, high speed currents.	Toward the reef rim, the depth decreases, and an area made of very fine sand occurs with small coral patches of great vitality. Corals occurring there are likely massive and submassive, but <i>Acropora</i> is much more abundant than in the similar zone of Gaya West.
The reef rim	Depth: 0 m.	The reef rim appears as a subtidal area.
The outer slope (M5 to M7 stations)	Depth: from -2 to -15 m. Low turbidity and high current speed.	First the slope gently goes down from -2 to -7 m (M5 station) and then becomes steep from -7 to -15 m (M6 and M7 stations). The diversity in corals is less important than in Gaya West outer slope.
The sandy plain	Depth: -15 m. Low turbidity.	At -15 m appears a plain made of fine sediment.

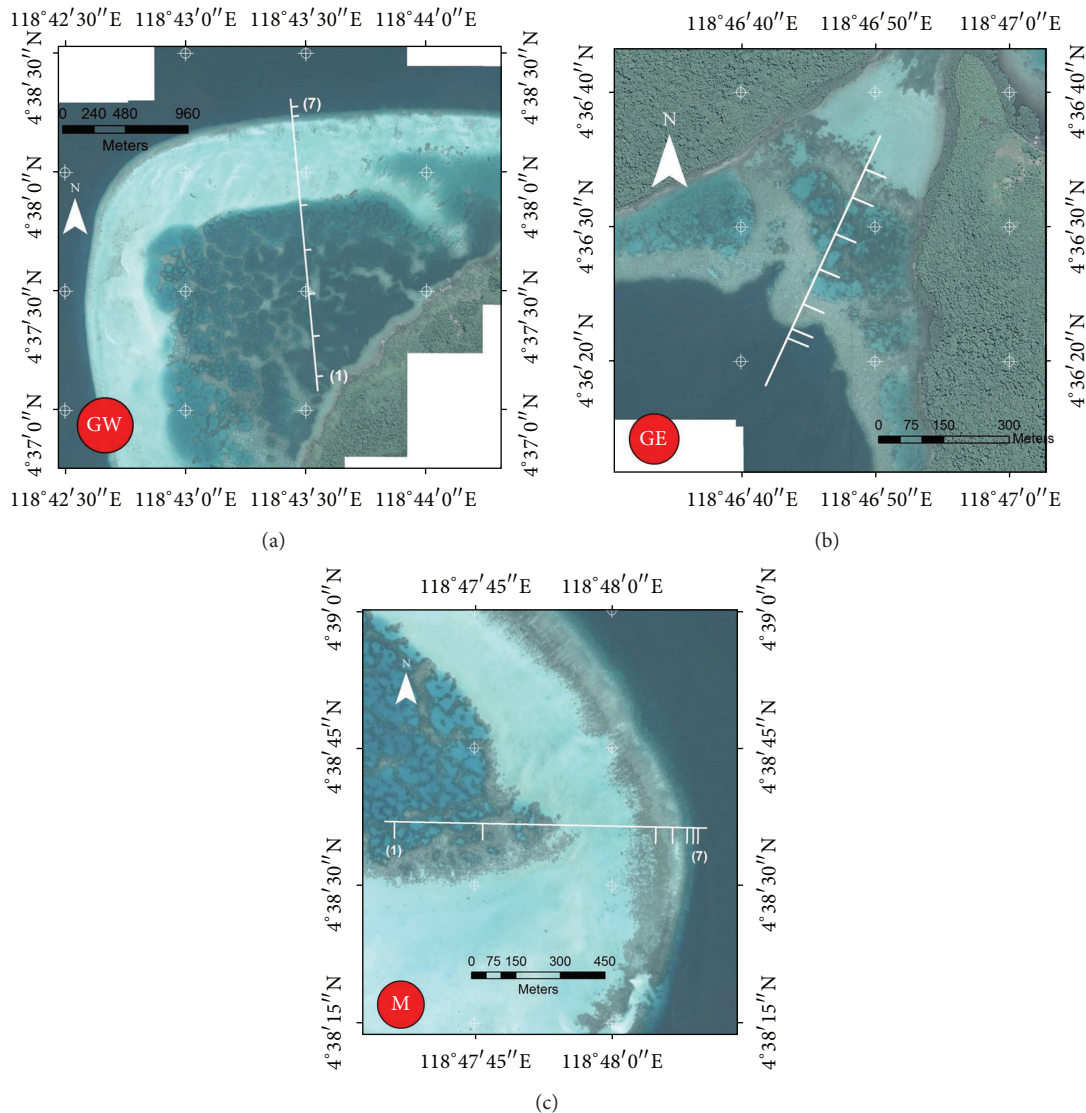


FIGURE 2: Aerial photography of the three sites with the radial lines and LITs. We can see on aerial photographs of (a) Gaya West (GW), the mesh reef, the rim, and the outer slope, (b) Gaya East (GE), the reef flat and the inner slope, and (c) Mantabuan (M), the mesh reef, the reef rim, and the outer slope.

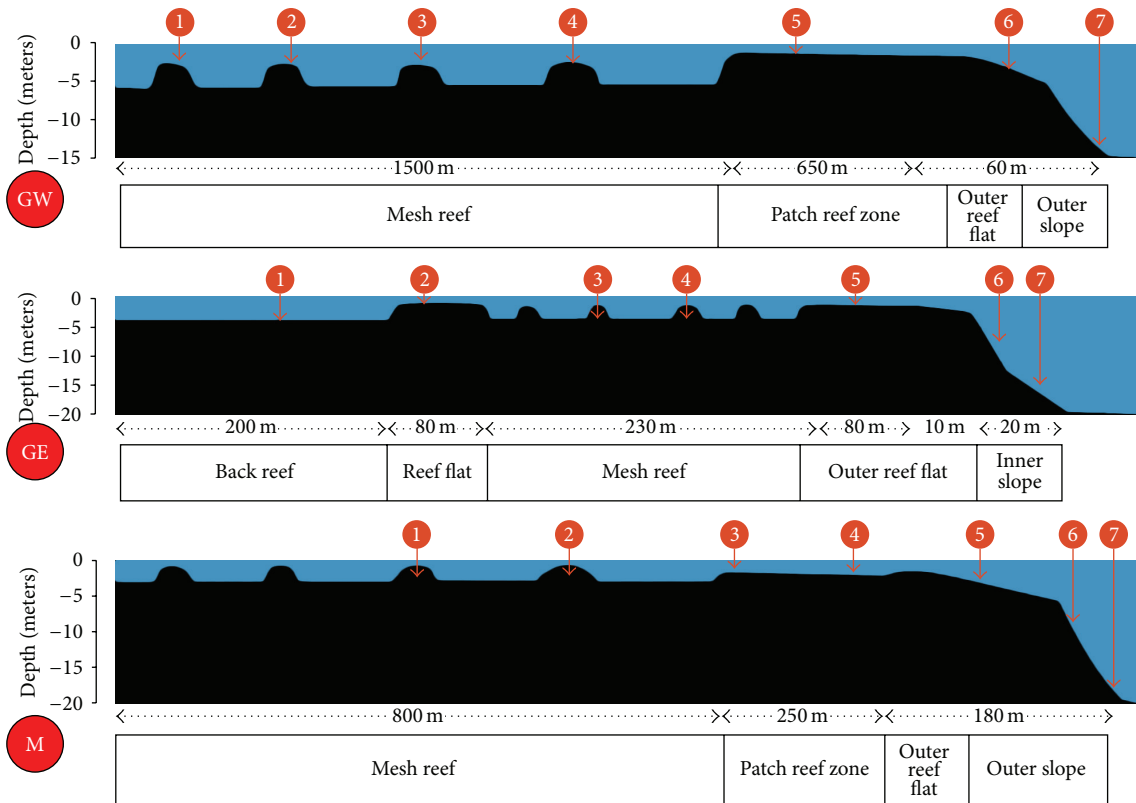


FIGURE 3: The reef profile along the three radial lines, Gaya west (GW), Gaya east (GE), and Mantabuan (M), and the location of the LITs on the different geomorphological zones (not to scale).

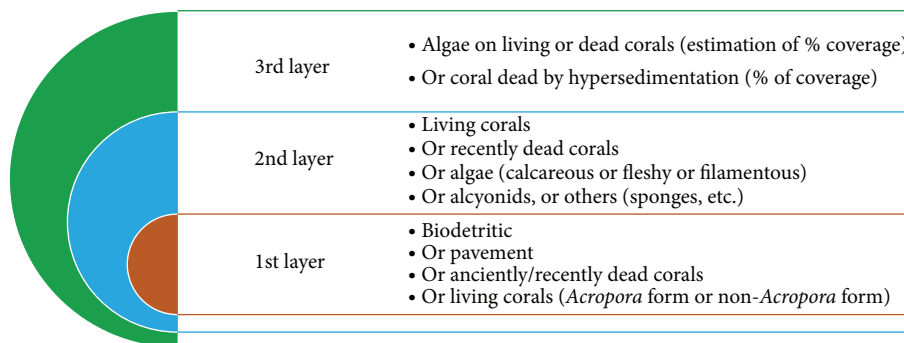


FIGURE 4: The analysis on a LIT: three layers (or more) can occur: all are noted.

All animals, visible from a vertical position as well as those hiding underneath ledges and in crevices, were counted.

**Survey 3: Fish Abundance.** Fishes are classified into three categories: (1) the territorial damselfish *Stegastes*, (2) parrotfish, and (3) other fishes. Before echinoderm counting, an abundance index is given to each of the three categories occurring in the 50 m by 1 m belt (abundance index 1= 2-3 individuals; 2 = 5-16 individuals; 3 = 17-64 individuals; 4 = 65-250 individuals; 5 = more than 250 individuals).

**2.3. Data Analysis.** Mean and standard deviation (SD) of sessile fauna data for sites (Gaya West, Gaya East, and Mantabuan) and subsites (reef flat, mesh reef, and inner and

outer slope) are calculated by taking one 10 m LIT as a sample. For sedentary fauna and fish, the sample is the 50 m by 1 m belt, thus 50 m<sup>2</sup>. Due to the multispecies nature of the data and the design of the survey, the most appropriate analyses are multivariate [28]. To assess patterns in benthic data from all stations during all years of survey, we used the principal component analysis (PCA).

### 3. Results

A first description of the radial lines was made to highlight the different subzones (Table 2) and to decide where the LITs have to be settled.

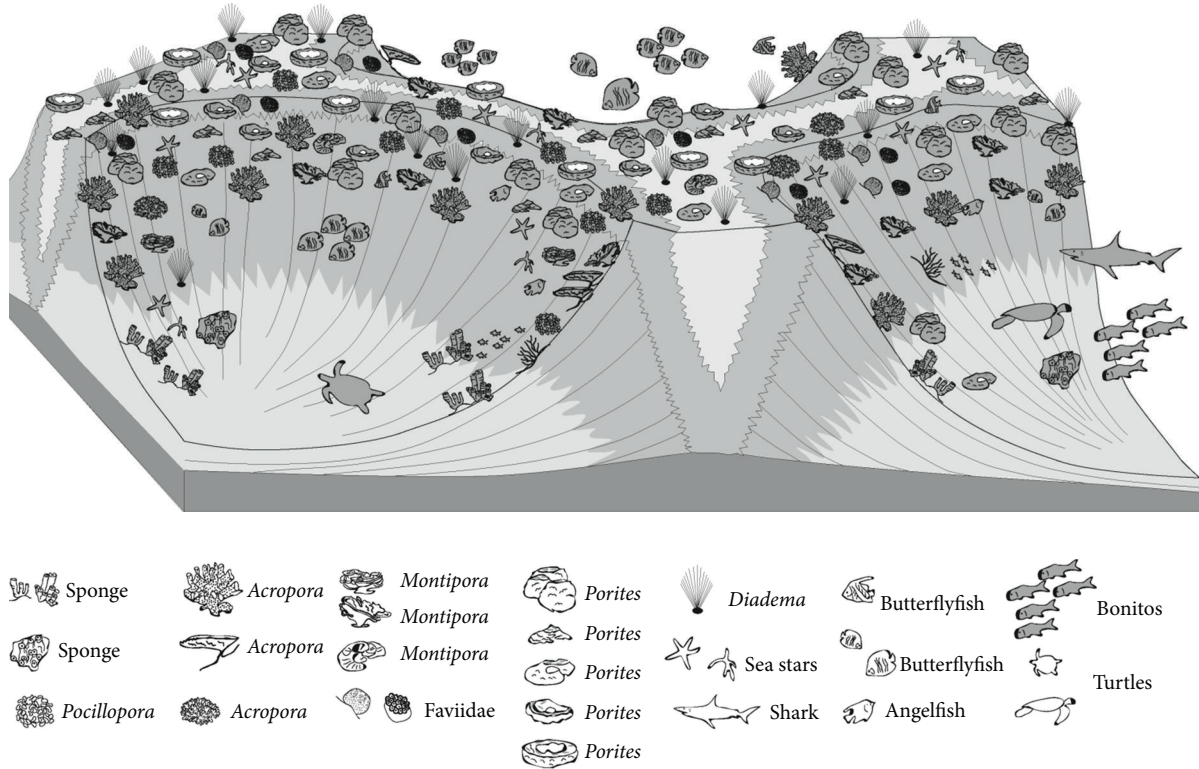


FIGURE 5: Gaya West lagoon: a part of the mesh reef with associated fauna (no scale).

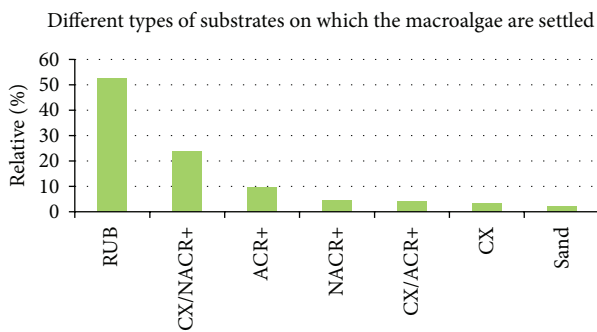


FIGURE 6: Substrates on which are settled the macroalgae. All stations together. RUB: rubble; ACR+: dead *Acropora*, NACR+: dead non-*Acropora*; CX/ACR+: dead *Acropora* settled on dead substrates; CX/NACR+: dead non-*Acropora* settled on dead substrates.



FIGURE 7: Gaya West, upper part of the mesh reef, *Caulerpa racemosa* crawling between living and dead *Acropora*.

**3.1. Primary Producers.** Among primary producers, the encrusting calcareous algae are not recorded. Although they are ubiquitous, their abundance is below the threshold of the measurement.

The total coverage of filamentous and macroalgae is very low (below 5%), except on the Gaya East-reef flat (Table 3), where they can be abundant in places (turfs in damselfish territories or macroalgae patches).

Figure 6 shows that the macroalgae are mainly settled on rubble, indicating that few living corals are in competition

with primary producers. On Gaya West-mesh reef, *Caulerpa racemosa* is abundant, its vesicle-like branchlets along the erect axes crawling between corals (Figure 7). On Gaya East-reef flat, large Ochrophytes, such as *Sargassum* and *Turbinaria*, occur on rubble.

**3.2. Bioconstructed Substrates.** At each site, the studied radial lines spread into the lagoon, the reef rim, and the outer or inner slopes (Figures 2 and 3). Into the lagoon, corals are organized into a reticulated reef in Gaya West and Mantabuan



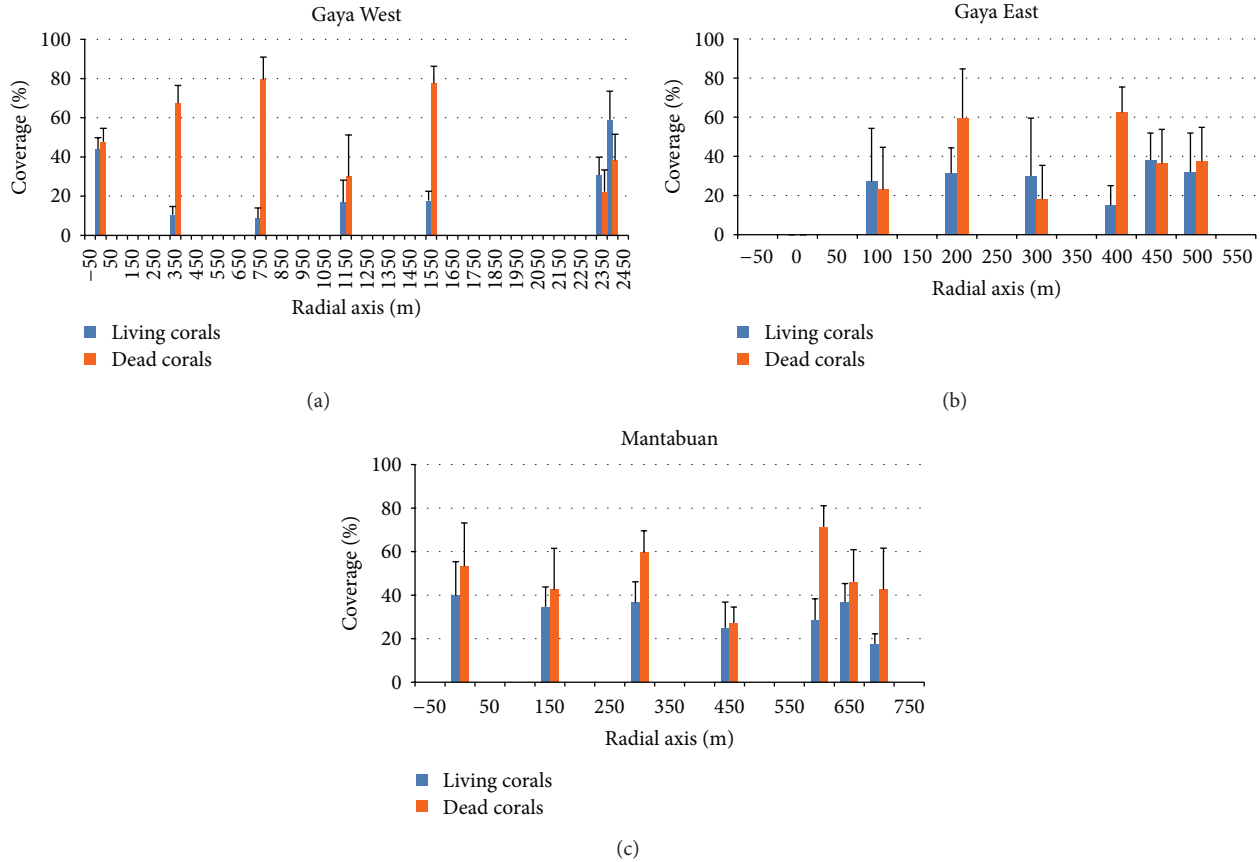


FIGURE 8: Mean percentage (and SD) of coverage of living and dead corals at each station. In Gaya West (a) and Gaya East (b) sites, the two last stations on the right are located on the outer slope. In Mantabuan (c), the three last stations on the right are located on the outer slope.

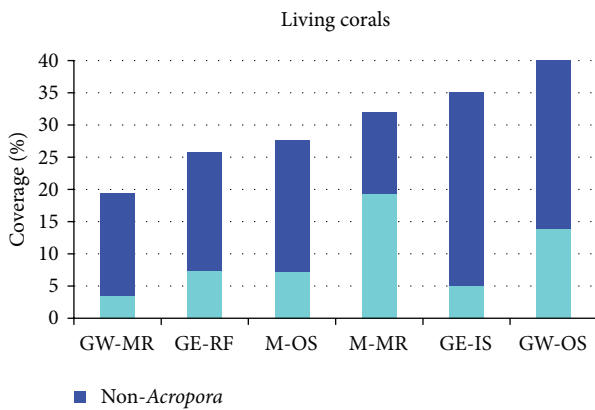


FIGURE 9: Increasing mean percentage of coverage of living corals, with *Acropora* and non-*Acropora*, in lagoons (MR: mesh reef and RF: reef flat) and slopes (IS: inner slope and OS: outer slope). Sites: GW: Gaya West, GE: Gaya East, and M: Mantabuan.

while they form a reef flat in Gaya East (Table 2). In Gaya West and Mantabuan lagoons, LITs were placed on the upper parts of the mesh reef rims, which is why the bioconstructed mean coverage reaches almost 80% (Table 4). Although other LITs were placed randomly on the outer slopes and on the fringing

TABLE 3: Percentage of coverage of primary producers (macroalgae and filamentous algae). Mean (SD).

Sites	Primary producers
Gaya West-mesh reef	3.1 (4.5)
Gaya West-outer slope	0.0 (0.0)
Gaya East-reef flat	8.1 (23.6)
Gaya East-inner slope	2.7 (8.5)
Mantabuan-mesh reef	4.0 (7.5)
Mantabuan-outer slope	2.7 (5.4)

reef of Gaya East (reef flat and inner slope), the percentage of coverage of “bioconstructed” substrates is exceptionally high, generally around 70%.

**3.3. Vitality of Corals.** The living coral coverage is approximately  $\leq 50\%$  of the bioconstructed substrates on the three sites. Considering the different subsites (Table 4), the vitality of corals is the highest in the Gaya West outer slope and the Gaya East inner slope (resp., almost 60 and 50% of living corals within the bioconstructed substrates).

When all the different stations are taken into consideration (Figure 8), it appears that dead corals dominate over living corals in almost all the stations, except on the outer

TABLE 4: Percentage of coverage of living and dead corals on the different geomorphological zones and vitality (relative percentage of living corals/totality of bioconstructed substrates). Mean (SD).

Site-subzone	Living corals	Dead corals	Bioconstructed substrates	Vitality (%)
Gaya West-mesh reef	19.6 (14.2)	60.5 (21.2)	80.0 (22.2)	24.5
Gaya West-outer slope	44.8 (19.9)	30.3 (11.3)	75.1 (26.0)	59.7
Gaya East-reef flat*	25.9 (7.5)	40.8 (23.5)	66.7 (35.6)	38.8
Gaya East-inner slope	35.0 (4.3)	37.0 (0.7)	72.0 (19.7)	48.6
Mantabuan-mesh reef	34.0 (6.4)	45.6 (14.2)	79.6 (21.4)	42.7
Mantabuan-outer slope	27.7 (9.7)	53.4 (15.7)	81.1 (21.2)	34.1

\* Except LIT GE1 totally sandy. Vitality = Living corals/Dead corals \* 100.

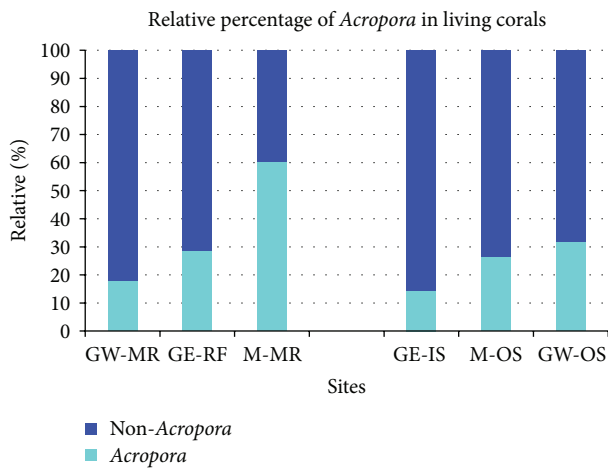


FIGURE 10: Increasing mean relative percentage of coverage of living *Acropora*: left, in lagoons (MR: mesh reef and RF: reef flat) and right: on slopes (IS: inner slope and OS: outer slope). GW: Gaya West, GE: Gaya East, and M: Mantabuan.

TABLE 5: Percentage of coverage of corals affected by hypersedimentation in the different geomorphological zones. Mean (SD).

Site-subzone	Corals affected by hypersedimentation
Gaya West-mesh reef	4.5 (3.4)
Gaya West-outer slope	2.0 (3.6)
Gaya East-reef flat*	13.2 (17.9)
Gaya East-inner slope	7.4 (8.8)
Mantabuan-mesh reef	0.5 (1.4)
Mantabuan-outer slope	4.3 (8.2)

\* Except LIT GE1 without corals.

slope of Gaya West and on one station of the Gaya East-reef flat. The stations located on Gaya West-mesh reef have the lower vitality.

### 3.4. Living Corals

**3.4.1. *Acropora* versus Other Corals.** As shown in Figure 9, the living coral coverage is maximal on the outer slope of Gaya West and on the inner slope of Gaya East. It is minimal on Gaya West-mesh reef whereas LITs have been spread only on the upper part of coral rims.

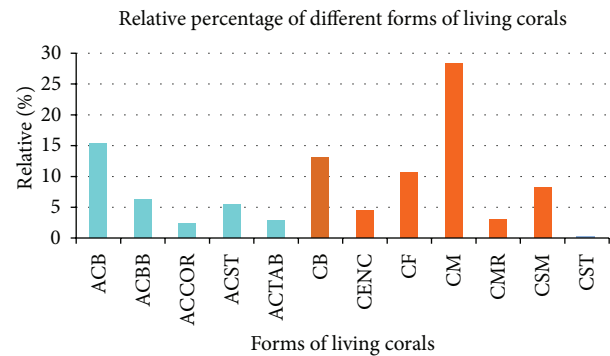


FIGURE 11: Living corals, all sites together. Relative percentage of the different coral forms occurring on the three sites. ACB: branching *Acropora*; ACBB: bottlebrush *Acrop.*; ACCOR: corymbose *Acrop.*; ACST: stout *Acrop.*; ACTAB: tabular *Acrop.*; CB: branching non-*Acrop.*; CENC: encrusting corals; CF: foliaceous corals; CM: massive corals; CMR: mushroom corals; CSM: submassive non-*Acrop.*; CST: stout non-*Acrop.*

*Acropora* colonies constitute 19 and 14% of the total coverage in Mantabuan-mesh reef and Gaya West-outer slope, that is, 60% and 30%, respectively, of the relative coverage of living corals (Figure 10). In the other sites, *Acropora* coverage is always lower than 30% of the living corals and even lower than 20% on Gaya West-mesh reef.

**3.4.2. Living Corals: The Different Forms.** Considering all the stations together (Figure 11), the dominant living coral forms are (1) the massive corals (-CM-, notably here massive *Porites* and *Faviidae*), (2) the branching *Acropora* -ACB-, (3) the branching non-*Acropora* (-CB-, represented here by branching *Porites*, *Pocillopora*, *Stylophora*, *Seriatopora*, etc.), and (4) the foliaceous corals -CF-, such as *Montipora cf florida*, *Pavona cf cactus*.

Considering now each subsite (Figure 12), it appears that the highest diversity in coral forms is reached in the Gaya West-outer slope where the living coral coverage is the highest: massive and foliaceous corals dominate, along with branching *Acropora*.

The diversity of forms is also high in the Mantabuan-mesh reef (with a dominance of branching *Acropora*) and in the Gaya East-reef flat where large monospecific stands of *Montipora cf florida*, branching *Acropora sp.* or *Pavona cf*

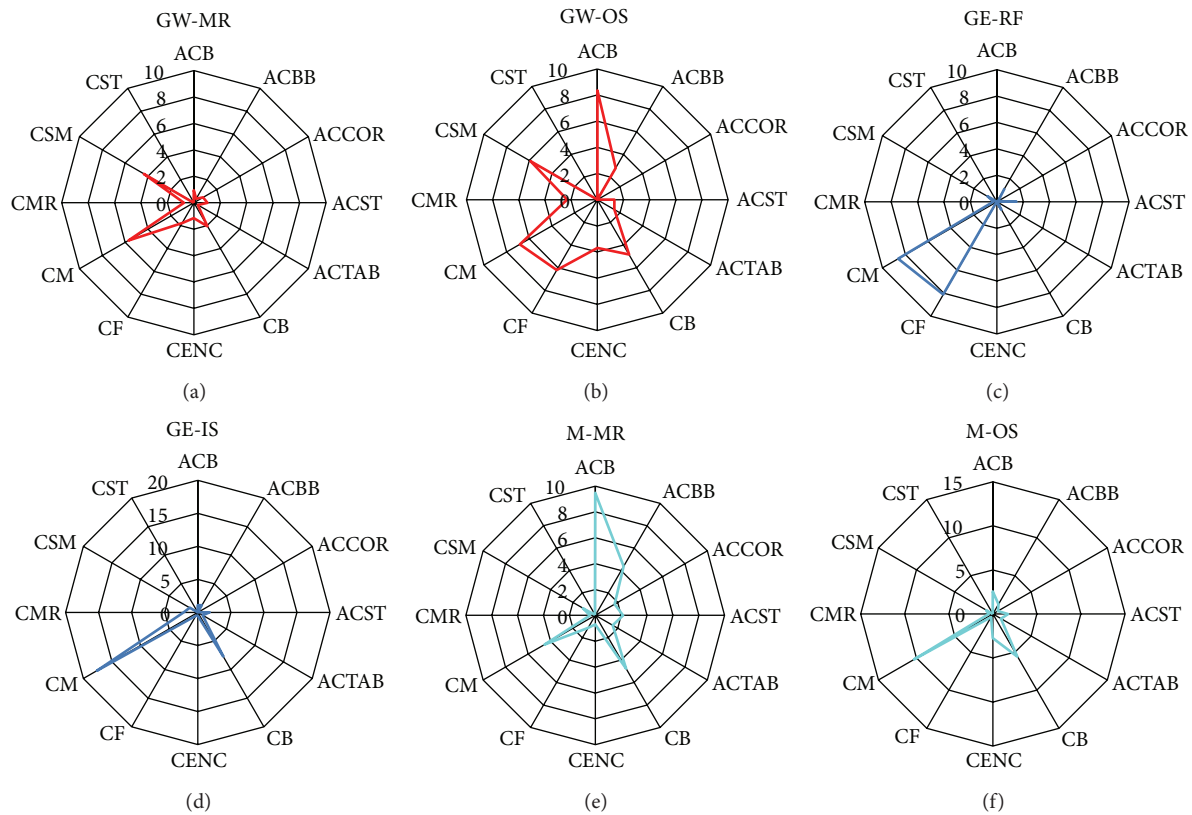


FIGURE 12: Percentage of coverage of different forms of living corals on each site (GW: Gaya West; GE: Gaya East; M: Mantabuan; MR: mesh reef; RF: reef flat; OS: outer slope; IS: inner slope). ACB: branching *Acropora*; ACBB: bottlebrush *Acrop.*; ACCOR: corymbose *Acrop.*; ACST: stout *Acrop.*; ACTAB: tabular *Acrop.*; CB: branching non-*Acrop.*; CENC: encrusting non-*Acrop.*; CF: foliaceous corals; CM: massive corals; CMR: mushroom corals; CSM: submassive corals; CST: stout non-*Acrop.*

TABLE 6: Number of individuals per 10 m<sup>2</sup> in the different subsites. Mean (SD).

Site-subzone. <i>N</i> ind./10 m <sup>2</sup>	Echinids	Asterids	Holothurids	Crinoids	<i>Tridacna</i>	Nudibranchs
Gaya West-mesh reef	10.0 (21.7)	0.6 (0.9)	0.2 (0.5)	0.2 (0.5)	0.1 (0.2)	0.5 (0.3)
Gaya West-outer slope	0.4 (0.6)	1.4 (0.3)	0.6 (0.8)	0.4 (0.6)	0.2 (0.3)	1.4 (0.3)
Gaya East-reef flat*	15.4 (13.9)	0.4 (0.3)	0.2 (0.3)	0.4 (0.8)	2.0 (1.0)	0.1 (0.1)
Gaya East-inner slope	7.5 (7.5)	0.1 (0.1)	0.0 (0.0)	3.1 (2.7)	0.9 (1.0)	0.2 (0.3)
Mantabuan-mesh reef	4.2 (3.5)	0.7 (0.7)	0.0 (0.0)	7.4 (13.7)	1.1 (1.3)	0.0 (0.0)
Mantabuan-outer slope	3.8 (0.5)	0.7 (0.0)	0.5 (0.1)	10.5 (4.5)	0.7 (0.8)	0.1 (0.1)

\* Except LIT GE1 exclusively sandy.

TABLE 7: Estimation of the number of individuals per 100 m<sup>2</sup> in the different subsites, using abundance index. Mean (SD).

Site-subzone. <i>N</i> ind./100 m <sup>2</sup>	<i>Stegastes</i>	Parrotfish	Other fish
Gaya West-mesh reef	71.1 (84.5)	6.0 (7.0)	171 (22.3)
Gaya West-outer slope	34.5 (29.7)	34.5 (29.7)	110.3 (151.7)
Gaya East-reef flat*	233.8 (18.8)	4.1 (6.4)	5.6 (5.3)
Gaya East-inner slope	233.8 (23.0)	8.3 (7.4)	136.5 (114.6)
Mantabuan-mesh reef	185.1 (72.4)	48.0 (94.9)	26.1 (27.2)
Mantabuan-outer slope	34.5 (29.7)	152.8 (137.5)	>250 (0.0)

\* Except LIT GE1 exclusively sandy.

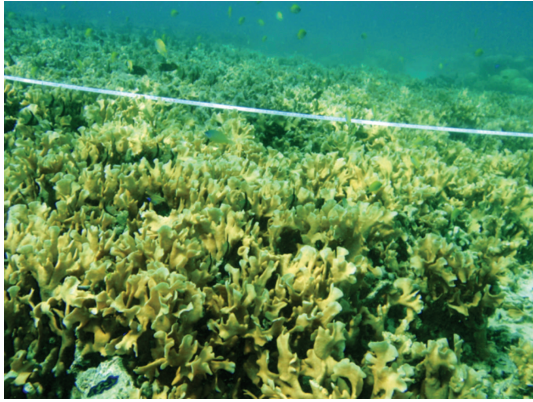


FIGURE 13: Gaya East-reef flat: large monospecific stand of *Pavona*.

*cactus*, occur (Figure 13). These stands alternate with patches rich in massive corals, made of large *Porites cf lobata* and numerous Faviidae (*Favia*, *Favites*, *Goniastrea*, etc.).

The last three subsites, Gaya West-mesh reef, Gaya East-inner slope, and Mantabuan-outer slope, show a low diversity in coral forms and are dominated by massive corals.

**3.5. Principal Component Analysis on Benthos Data (PCA).** PCA on data shows that axes 1 and 2 explain 48.1% of the variance. Factor 1 (PC1) accounting for 27.7% of the variance is largely determined by the opposition between the occurrence of a high coverage of living corals, mostly foliaceous and branching *Acropora* in stations GE2, GE4, and GE6, against the occurrence of juvenile living corals settled on bare substratums (thus a facies of recovery) in M1 and M5 (Figure 14(a)). The coral communities on Gaya East-fringing reef are then more ancient than in Mantabuan.

Factor 2 (F2) accounting for 20.4% of the variance depends mainly on the opposition between a high coverage of foliaceous corals (GE2) and a high coverage of massive corals in GE6 and GE7.

Factor 3 (13.9% of var.) opposes young branching *Acropora* settled on dead substratums in M1 and young submassive corals settled on dead substratums on GW1 and GW7 (Figure 14(b)), both facies of recovery.

**3.6. Corals Affected by Hypersedimentation.** Corals affected by hypersedimentation do not represent a high percentage of coverage (Table 5). The higher percentage is observed on the fringing reef of Gaya East, reef flat and inner slope.

**3.7. Echinoderms, *Tridacna*, and Nudibranchs.** Echinids (or sea urchins), mostly *Diadema*, are numerous on Gaya East-reef flat (more than 1.5 individual per m<sup>2</sup>) and on Gaya West-mesh reef (1 individual per m<sup>2</sup>) (Table 6). They are surprisingly not abundant on Mantabuan-mesh reef (0.4 individual per m<sup>2</sup>).

Asterids (or sea stars) and holothurids (or sea cucumbers) are scarce and are the most abundant on Gaya West-outer slope (0.1 individual per m<sup>2</sup> resp.).

Crinoids are the most abundant on Mantabuan-mesh reef and -outer slope: 0.7 and 1.0 individual per m<sup>2</sup>, respectively.

*Tridacna* are abundant on the reef flat of Gaya East (0.2 individual per m<sup>2</sup>), on Mantabuan-mesh reef, and on Gaya East-inner slope (0.1 individual per m<sup>2</sup>).

The gastropods nudibranchs are abundant in Gaya West-outer slope and -mesh reef (0.1 and 0.05 individual per m<sup>2</sup>, resp.).

Considering the sedentary fauna on the whole (Figure 15), it appears that the two subsites of Gaya East and the subsite of Gaya West-mesh reef are dominated by sea urchins, while Mantabuan (mesh reef and outer slope) is much more dominated by crinoids. The subsite Gaya West-outer slope is the only one where the six groups of fauna are slightly dominated by starfish and nudibranchs.

**3.8. Fish.** The damselfish *Stegastes* is particularly abundant on Gaya East-reef flat and -inner slope, while parrotfish are the most abundant in Mantabuan-outer slope and more moderately abundant on the mesh reef (Table 7). The other fish are very abundant (>250 ind. per m<sup>2</sup>) on the Mantabuan-outer slope.

Regarding the total fish community (Figure 16), it appears that the Mantabuan-outer slope and the Gaya East-inner slope encompass numerous fishes, but the Gaya East fish community is dominated by *Stegastes* while the Mantabuan fish community is much more diversified and includes numerous parrotfish.

## 4. Discussion

**4.1. Primary Producers.** The fast growth and turnover rates of fleshy algae highlight their value as early warning indicators of reef degradation. Except in some places on the reef flat of Gaya East and the upper parts of strips of Gaya West, primary producers are scarce. Thus, not a single sign of eutrophication has been recorded, and algae cannot be considered as a potential danger to living corals in the studied areas. Nevertheless, further investigations during the hot and very wet season are needed to better understand the role of the primary producers on these reefs.

**4.2. Coral Vitality.** In the studied stations, the bioconstructed coverage (living and dead corals) is exceptionally high (67–81% of mean coverage). However, the coral vitality varies. It reaches 60% on the Gaya West-outer slope (“fair” condition), 49% on the Gaya East-inner slope, 43% on the Mantabuan-mesh reef, and 24% on the Gaya West-mesh reef (“poor” condition).

On the Gaya West-mesh reef, LITs have been spread only on bioconstructed substrates. Nevertheless, the bioconstructed coverage is relatively low because large basins of sand and rubble occur on the upper parts of the coral rims.

Reticulated reefs display very different facies and vitality levels in Gaya and Mantabuan: in the Gaya West lagoon, coral rims (4–7 m high, 4–5 m wide) occur in a very turbid environment and have a vitality of 24%. In the Mantabuan lagoon, corals are organized in smaller rims (4 m high, 3 m

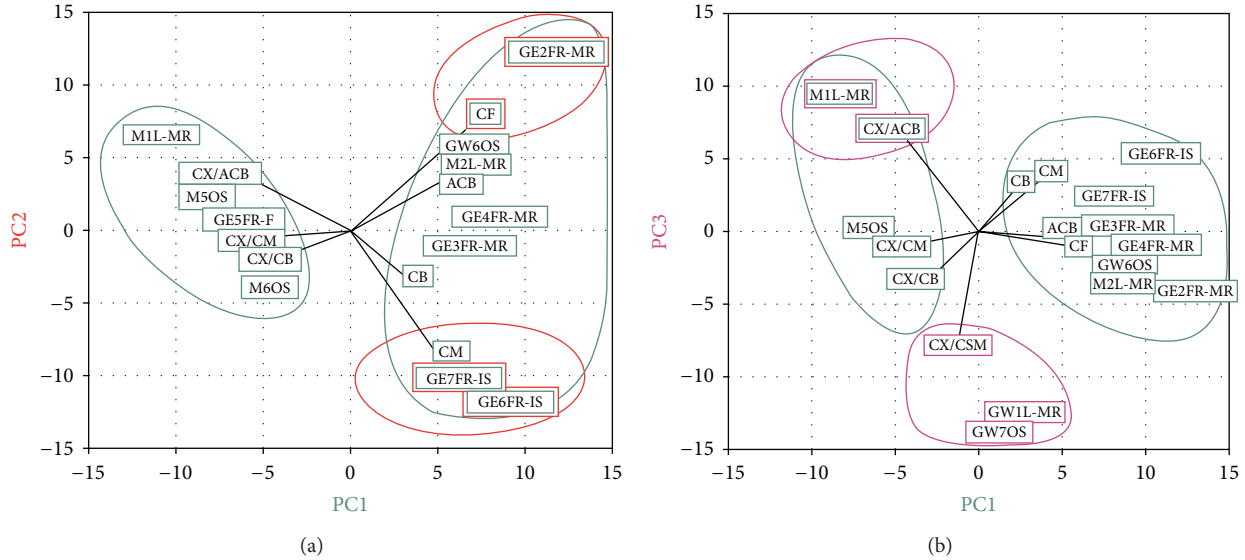


FIGURE 14: PCA on all data (GW: Gaya West; GE: Gaya East; M: Mantabuan; MR: mesh reef; RF: reef flat; OS: outer slope; IS: inner slope). ACB: branching *Acropora*; ACBB: bottlebrush *Acropora*; ACCOR: corymbose *Acropora*; ACST: stout *Acropora*; ACTAB: tabular *Acropora*; CB: branching non-*Acropora*; CENC: encrusting non-*Acropora*; CF: foliaceous corals; CM: massive corals; CMR: mushroom corals; CSM: submassive corals; CST: stout branching non-*Acropora*; CX/ACB: branching *Acropora* sur dead substrate, CX/ACBB: etc.

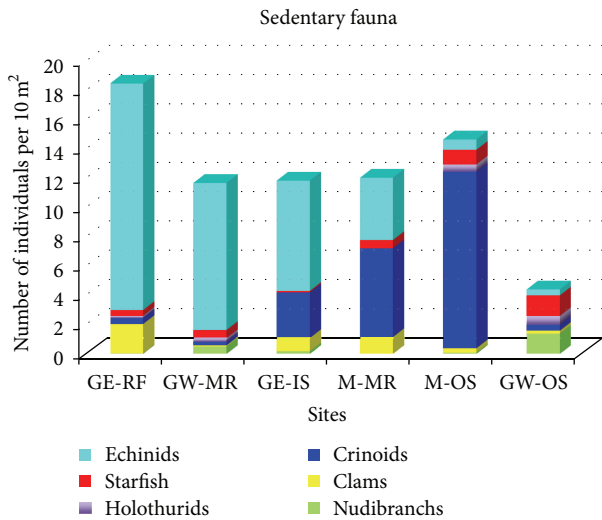


FIGURE 15: Mean of number (nb) of individuals of sedentary fauna recorded on each site. Continuum from dominance of sea-urchins on the left to dominance of crinoids on the right (GW: Gaya West; GE: Gaya East; M: Mantabuan; MR: mesh reef; RF: reef flat; OS: outer slope; IS: inner slope).

wide) and occur in clear water; the vitality is 43%, and *Acropora* forms 60% of the living corals. According to Edinger and Risk [29], the occurrence of abundant *Acropora* is linked to good health, as *Acropora* is an r-strategist and a very sensitive form of coral. Generally, the *Acropora*-dominated reefs harbor a high diversity of associated fish [30].

On the Gaya East-fringing reef (reef flat and inner slope), we observed the highest percentage of corals affected by hypersedimentation. It is likely that the funnel shape of the

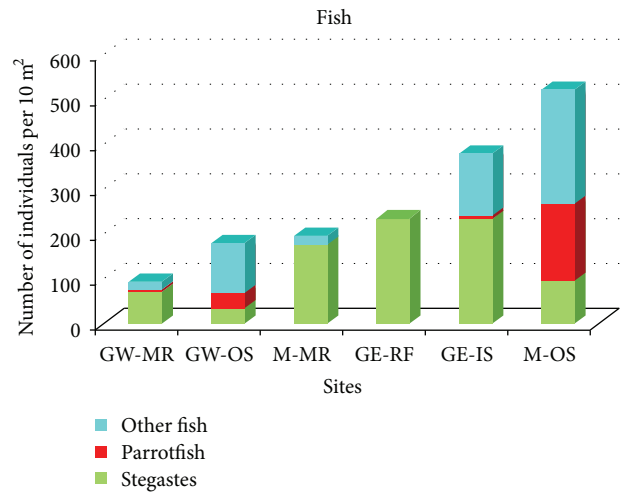


FIGURE 16: Mean of increasing abundance of fish (GW: Gaya West; GE: Gaya East; M: Mantabuan; MR: mesh reef; RF: reef flat; OS: outer slope; IS: inner slope).

fringing reef and the strong current occurring between the two islands are at the origin of this increased sedimentation. On the reef flat, the station GE2 (Gaya East-reef flat) is highly characterized by foliaceous corals (such as *Pavona cf cactus* and *Montipora cf florida*) that develop in monospecific stands (circa 10 m wide). On the other hand, the Gaya East-inner slope is highly characterized by massive corals. Gaya East (reef flat and inner slope) is also characterized by a high density of *Stegastes* damselfish (more than 200 per 100 m<sup>2</sup>). This is an indication of coral degradation.

In Peninsular Malaysia, one of the major reasons for the “poor” to “fair” conditions of hard corals may be due to increases in sedimentation [31]. Along the west coast of Peninsular Malaysia, heavy sedimentation has caused serious siltation problems in some river mouths and harbors [32]. Millions of tons of sediment are transported annually by major rivers of the east coast of Sumatra and the west coast of Peninsular Malaysia to the coastal waters of the Malacca Straits [33]. In many localities, these huge amounts of sediment have changed the physical, chemical, and biological environment of the coral reefs. Therefore, coral vitality is very low in the area [34].

In our study, coral communities display a different state of evolution: corals in the lagoon of the Mantabuan-mesh reef are in state of recovery while on the Gaya East-reef flat they have reached a mature status. Thus, large bleaching/mortality events may have affected some reefs of the Tun Sakaran Marine Park such as the Mantabuan ones.

**4.3. Sea Urchins.** Sea urchins, such as *Diadema*, are highly represented on the Gaya East-reef flat and the Gaya West-mesh reef. On the Gaya West-mesh reef, macroalgae such as *Caulerpa* spp. occur within corals; on Gaya East, large Ochrophytes occur as metric sporadic stands. These primary producers can attract *Diadema*, a big consumer of seaweed.

On the Mantabuan-mesh reef, the sea urchins are scarce. As the corals are at the stage of recovery, the sea urchin populations may have been affected by the same mortality as the corals. This would explain the low density of sea urchins on this reef. Nevertheless, the primary producers remain very scarce in this area; thus, they may be controlled by herbivorous organisms. Additional investigations are needed on sea urchin and fish herbivory to better understand the functioning of this beautiful area.

**4.4. Fishes.** The fish community is thriving on the Mantabuan-outer slope where a myriad of fish exist around corals. In the three lagoons, but also on the Gaya East-inner slope, the *Stegastes* damselfish dominates. On Mantabuan, parrotfish are particularly abundant on the outer slope. They are also present into the lagoon around the mesh reef.

**4.5. Coral Degradation.** Concerning the low vitality observed in the Gaya West-mesh reef, Bell and Galzin [24], studying reticulated reefs (Mataiva atoll, Tuamotu Archipelago, and French Polynesia), explained that several “lagoon basins” somewhat closed by the coral rims were entirely or partially dead (the cause of mortality was uncertain). Perhaps this “closing” process of the mesh reefs explains the coral degradation into the lagoons (i.e., Mataiva or Gaya bank).

Bodgaya is an inhabited island with a significant fishing pressure inside the lagoon (particularly on Gaya West). This pressure might explain the scarcity of fish. Thus, an overfishing might speed up a disequilibrium in the ecosystem via (1) the reduction of fish (and perhaps sea urchin) herbivory and/or (2) the demise of key species. Further studies are needed (1) to estimate the impact of fishing and harvesting by the local population, (2) to identify the target species, and

(3) to research potential new species that could bring food or money to the locals. If fishing by the local population impacts too much on the lagoon communities, a range of measures (such as aquaculture) have to be proposed to reduce fishing pressure and allow overexploited fish populations to recover and ensure the maintenance of healthy populations.

Experiments are also needed to estimate the real impact of local populations and tourism (mostly divers). For example, restoration via coral nubbins may be attempted on some degraded parts of the Gaya lagoon, which would be protected from human impact. Also, the Mantabuan lagoon may be an ideal control site for experimentation.

## 5. Conclusion

TSMP belongs to the Coral Triangle region. Known as the “Amazon of the Seas” and one of the world’s most diverse and threatened marine ecosystems, the Coral Triangle encompasses ocean areas in six countries in Southeast Asia and the Pacific (Indonesia, Malaysia, Papua New Guinea, Philippines, Solomon Islands, and Timor-Leste). This region is recognized as the global centre of marine biodiversity [35] and a global priority for conservation [36]. Covering 5.7 million square kilometers of ocean waters, it contains at least 500 species of reef-building corals in each ecoregion [37]. More than 2,200 species of fish (including the largest fish species, the whale shark, and the coelacanth) live there. It also provides a habitat to six out of the world’s seven marine turtle species.

The coral fauna of the TSMP shows a clear affinity with that found on Indonesian reefs, and several species (including some rare species of *Acropora* and the uncommon caryophylliid *Nemenezophyllia turbida* [2]) are new to Malaysia. A number of the sponges and soft corals found in the Gaya lagoon are new undescribed species. One sponge is reported to be very unusual and possibly endemic to the Semporna reefs [9]. Also, Allen [1] found two new species of damselfish there.

Tun Sakaran Marine Park provides as much as 21 prestigious scuba diving sites, for example, Tabah Siramba (Church Reef), Kapikan Reef, Ribbon Reef, Mantabuan, and Sibuan Reef. Divers and snorkelers enjoy various attractive marine lives such as turtles, eagle rays, barracudas, bumphead parrotfish, nudibranchs, and recently discovered sponges. It is difficult to describe the thrills that divers experience when they encounter marine macrolife in the Bodgaya lagoon. It is therefore important that something be done to prevent further degradation of this natural wonderland.

## Acknowledgments

This research project, carried out at the South-East Asia Carbonate Research Laboratory (SEACARL), is financed by a Shell grant to Universiti Teknologi Petronas (Malaysia), French Embassy (Malaysia), University of South-Brittany (France), the Bretagne Region (CARBASIA project), and the Conseil Général du Morbihan. The authors wish to thank Sabah Parks for granting them a research permit to work

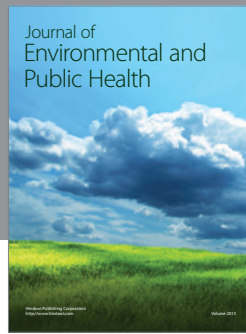
in Tun Sakaran Marine Park. They wish to express their gratitude to the staff of Sabah Parks Kota Kinabalu, Semporna, and Boheydulang station for their invaluable help and support during the field visits to Tun Sakaran Marine Park. The authors also wish to thank the staff of the Oceanography Institute of Universiti Malaysia Terengganu for their help with the acquisition of the bathymetry data. Thanks are also due to Lawrence Schwarz for improving the English language of the paper.

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