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Puerto Morelos Coral Reefs, Their Current State and Classification by a Scoring System

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Abstract: Marine protected areas have been established as essential components for managing and protecting coral reefs to mitigate natural and anthropogenic stressors. One noteworthy example within the Mexican Caribbean is the Arrecife de Puerto Morelos National Park (APMNP), where several studies on the coral communities have been carried out since 2006. In June 2019, we conducted a study in eight sites of the APMNP applying a coral reef assessment method based on biological indicators of both the benthos and the fish communities. In this paper, we present the quantitative results of our study and provide a qualitative criterion assessing seven condition indexes through a scoring system. We also present a statistical comparison with a previous study carried out in 2016. The general status of coral reefs was classified as regular due to the low values of coral recruitment rate and biomass of key commercial fish species. However, living coral cover average was above 20%, with a slight dominance of framework building coral species and the presence of low values of fleshy algae cover, these being positive indicators. Our study found a higher proportion of reef promoter elements and a lower proportion of detractors, compared to a previous study carried out in 2016.

Keywords: biological indicators; marine protected areas; coral reefs; Mexico

1. Introduction

Since the late 20th century, there has been an accelerated decline in the health of coral reefs of the Caribbean Sea [1,2]. This situation has been attributed to the synergistic effects of local and regional pressures from a combination of natural and anthropogenic disturbances such as hurricanes, diseases, increased sea temperature, increased nutrient concentrations, and overfishing [3–7]. The continued loss of coral cover has been significant [1,8], particularly due to the decline of framework building corals as *Acropora sp*. [9] and *Orbicella sp*. [10], which has caused a decrease in reef structural complexity [11]. The decline of the populations of the black sea urchin *Diadema antillarum* [12] and the increase of macroalgal cover has also been significant [13]. Overfishing has led to abrupt population decline of herbivores and commercial fish species [2,14].

Implementation of marine protected areas (MPAs) has been one of the main strategies used to mitigate the effects of natural and anthropogenic disturbances that affect coral reefs [15]. MPAs safeguard marine biodiversity, conserve essential habitats, and promote the increased application of regulations, management actions, and educational activities [16–19]. There are fifteen MPAs in the Mexican Caribbean. The Arrecife de Puerto Morelos National Park (APMNP) is located in this region and includes relevant coral communities [20]. This ecosystem is one of the most important resources for the local community, mostly sustained by tourism and subsistence fishing. As in the rest of the Caribbean, coral communities in this MPA have experienced drastic coral cover declines [21], but since the mid-2000s there have been some signs of recovery [22,23]. However, from 2018, two significant alterations have been reported in the APMNP: massive arrivals of pelagic species of the brown algae Sargassum and its subsequent decomposition along the shoreline [24], and the outbreak of the stony coral tissue loss disease (SCTLD), which ravaged populations of many coral species [21,25].

In consideration of the effort made in the Mexican Caribbean, and with the idea of standardizing existing methodologies, the National Commission for the Knowledge and Use of Biodiversity (CONABIO), leads a coral reef monitoring program [19]. This program aims to collect field information in order to feed a structured database and incorporate it into the interactive web platform: Marine-Coastal Information and Analysis System (SIMAR) <https://simar.conabio.gob.mx> [26]. One of SIMAR's goals is to carry out a comprehensive assessment of the health and resilience of coastal marine ecosystems and facilitate comparisons between sites within the region. All of the above will allow the implementation of operational alert systems for decision-making and the generation of knowledge for sustainable management, in a context of climate change.

In June 2019, we conducted an assessment of the coral reef condition in the APMNP through a quantitative analysis based on biological indicators with the aim of (1) producing a qualitative classification of the reef sites based on a scoring system (indexes) from the main condition indicators; and (2) to compare how reef condition had changed after the impact of the Sargassum bloom and the SCTLD outbreak by comparing data from 2016 and 2019. Our results, which follow up on previous studies carried out in the APMNP, allow us to assess factors that influence coral reef structure and to estimate possible future changes. They will be integrated into the SIMAR online platform, to contribute to decision-making on coral reef management and conservation in the Mexican Caribbean region.

2. Materials and Methods

2.1. Study Zone

The APMNP is located at the northeast portion of Quintana Roo state, Yucatán Peninsula, Mexico. The reef extends parallel to the shore, with crest segments, a reef lagoon covered by seagrass beds, and adjacent mangroves [27]. The sampling took place at eight sites located in the back-reef zone, at depths from 2 to 5 m (Figure 1, Supplementary Table S1). The reefs sampled are fixed sites of the monitoring carried out by the managers of the APMNP. The study area has zones of continual hard substrate with presence of *Acropora palmata*; and coral head patches surrounded by sand and dominated by species of *Orbicella*, *Pseudodiploria*, and soft corals (Supplementary Figure S1a–c). The study was conducted between 28 June and 3 July, 2019.

In the APMNP, there is a well-established marine zoning that limits the activities carried out in each area and establishes strict regulations for each type of activity allowed [28]. All the studied sites, except Limones, are for tourist use for diving and snorkeling. Limones has been closed to tourist activity since 2014, so only scientific activity is allowed. Fishing is not allowed in any of the reef areas, but the activity is carried out in neighboring areas.

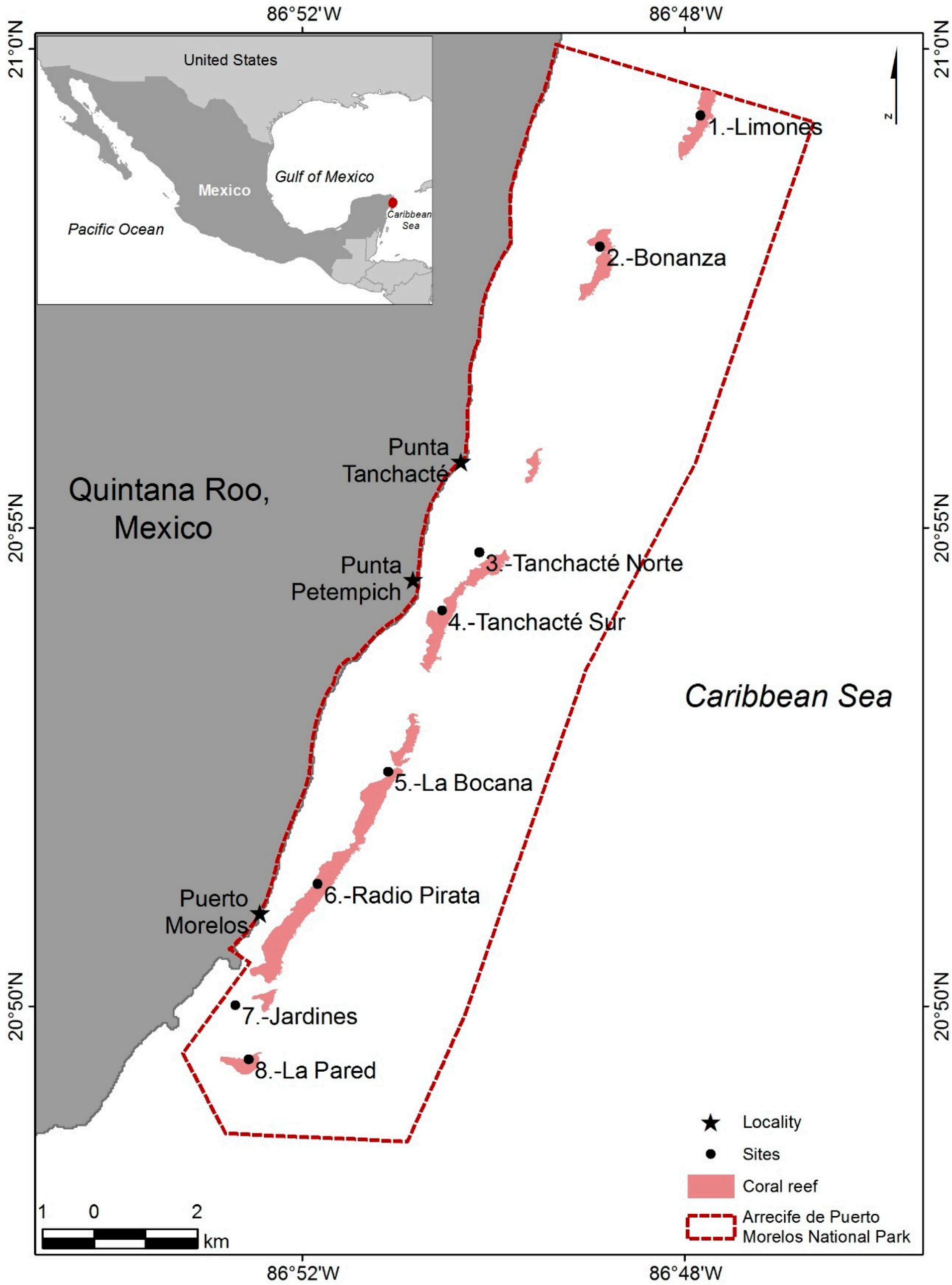

Figure 1. Map of the geographical location of the sampling sites within the Arrecife de Puerto Morelos National Park.

2.2. Sampling Methodology

At the back-reef zone at each site, a sampling method was applied based on biological indicators for corals, algae, black sea urchin, and fish species. The bottom cover (%) was calculated by using the 10 m-long point-intercept transect (8–11 transect lines per site) as in the AGRRA protocol, version 2016-18 [29]. At each point (separated by 10 cm), the type of substrate was recorded according to 14 categories outlined below:

- Living coral: for scleractinian corals and hydrocorals (coral species were identified).
- Recent mortality coral: was defined as any non-living part of a coral in which the corallite structures were still visible and were not covered by any other organism.

- Old mortality coral: was defined as any non-living part of a coral in which the corallite structures were either gone or covered over by any other organisms (algae, sponges).
- Fleshy algae: included leafy, filamentous, globose and corticated macroalgae.
- Articulated calcareous algae: included calcareous macroalgae.
- Crustose coralline algae: included coralline encrusted algae.
- Turf: included cespitose algae with appreciable thickness.
- Cyanobacteria.
- Pavement: bare hard substrate, or hard substrate with very thin and spaced turf.
- Rubble: gravel, very deteriorated and loose dead corals.
- Sand: substrate covered with sand of appreciable thickness.
- Soft corals: Any octocoral species.
- Aggressive invertebrates: included encrusting sponges and other bioeroder invertebrates.
- "Others": anemones, zoanthids.

From each coral colony ≥ 5 cm located below the transect line, the following data were recorded: species, maximum diameter, percent of colony surface with old and/or recent mortality, signs of disease, and bleaching. Maximum diameter was defined as the maximum dimension of the colony seen from above.

A 25 cm quadrat frame was used as a sampling unit to quantify coral recruits (colonies < 5 cm). Five frames, each separated by 2 m, were located along each transect. The individuals of *D. antillarum* observed within 1 m width along the transect line were recorded.

The chain transect method was used to quantify the reef structural complexity (rugosity index), calculated by dividing the total length of the chain (3 m) by the length of the chain in contact with the substrate. Ten replicates per site were conducted.

To quantify the number of individuals of key herbivorous and commercial fish [29], a 30 × 2 m linear track (six per site) was used as a sampling unit. As key herbivorous fish, only Scaridae and Acanthuridae families were included. As key commercial fish, only Serranidae and Lutjanidae families were included. Total length of each individual was estimated using length classes (cm) in ranges of 0–5, 5–10, 10–20, 20–30, 30–40, and >40.

2.3. Data Processing Methodology

2.3.1. Quantitative Analysis of Biological Indicators

General values of bottom cover were represented using scatterplots graphs with the median as a measure of central tendency, and the mean of each site as a measure of variability. Cover of each substrate type, density, size, and mortality of coral colonies, coral recruit density, rugosity, and fish biomass, were represented using box plot graphs, with the mean as a measure of central tendency and the standard deviation as a measure of variability. A relative abundance of coral species (predominance according to their cover values) and fish families (predominance according to their biomass values), were presented by bar graphs.

Statistical differences among sites with respect to these indicators, permutational analysis of variance (PERMANOVA) [30] were performed, using "sites" as a fixed factor (one-way factorial design). Euclidean distance index with 9999 permutations and 0.05 of significance was applied. The magnitude of effects was assessed by the estimates of components of variation.

2.3.2. Qualitative Integral Assessment of the Coral Reef Condition

A qualitative integral evaluation of the coral reef condition was made applying a scoring system with seven indexes (based in the previous indicators) for the benthos and ichthyofauna: "reef promoter", "reef detractors", coral condition, coral recruitment, rugosity, key herbivorous fish biomass, and key commercial fish biomass.

According to Lang et al. [31] criteria, the "reef promoter" index was calculated by adding the percentages of living coral cover, crustose coralline algae cover, and pavement cover. "Reef detractors" index was calculated by summing the percentages of fleshy and articulate calcareous algae cover, turf cover, cyanobacteria cover, and aggressive invertebrates cover. Coral condition index was defined by the formula: 100 − (% recent coral mortality + % old coral mortality). The rest of the indexes coincide with the respective indicator's name.

Each index was scored representing qualitative condition according to a defined range of values associated to qualitative criteria of condition: critical (1), poor (2), regular (3), good (4), and very good (5). The indexes and associated values range for their scoring, were chosen by criteria of the authors, based on the studies of Lang et al. [31], Alcolado and Durán [32], Dahlgren et al. [33], and McField et al. [34]. Finally, an integral index of the reef condition was obtained, from the average of indexes previously described (Table 1).

Table 1. Scoring system for the coral reef integral assessment from seven indicators for the benthos and ichthyofauna.

	Classification and Score				
Indexes	**Critical (1)**	**Poor (2)**	**Regular (3)**	**Good (4)**	**Very Good (5)**
"Reef promoter"	<15.0	15.0–29.9	30.0–59.9	60.0–80.0	>80.0
"Reef detractors"	>80.0	60.0–80.0	30.0–59.9	15.0–29.9	<15.0
Coral condition	<30.0	30.0–49.9	50.0–69.9	70.0–90.0	>90.0
Coral recruitment	<2.0	2.0–3.9	4.0–7.9	8.0–16.0	>16.0
Rugosity	1.00–1.19	1.20–1.49	1.50–1.99	2.00–2.50	>2.50
Key herbivorous fish biomass	<20.0	20.0–39.9	40.0–59.9	60.0–80.0	>80.0
Key commercial fish biomass	<10.0	10.0–29.9	30.0–69.9	70.0–90.0	>90.0
Reef Integral condition	1.0–1.8	1.9–2.6	2.7–3.4	3.5–4.2	4.3–5.0

2.3.3. Temporal Variability Analysis

Our results were statistically compared with a study (using the AGRRA methodology) carried out at the same sites, in December 2016.

We compared the indexes "reef promoter" and "reef detractors". Results per site were represented using scatterplots graphs with the median as a measure of central tendency, and the mean of each site, as a measure of variability.

For coral species composition, we applied a non-metric multidimensional scaling ordination (nMDS), looking for similarity patterns in coral assemblage structure across sites based on species cover values. The matrix of species cover per site was shortened by selecting only the species that individually contribute at least to the 5% of the total cover. The similarities among sites were calculated using the Bray–Curtis similarity index [30].

Coral species predominance was visualized through a bar graph. Corals were grouped in: framework building coral species (*Acropora* and *Orbicella*), according to Precht et al. [35], and Perry et al. [36]; opportunistic coral species (*Agaricia, Siderastrea*, and *P. astreoides*), according to Yakob and Mumby [37], and Perry et al. [36]; other branched coral species (*Porites* and *Madracis*); brain corals (*Pseudodiploria* and *Diploria*); and "others".

Differences of metrics were tested by a PERMANOVA analysis, using a similarity matrix based on Euclidean distances, with 9999 permutations and 0.05 of significance. A two-way balanced design was applied, using "sites" and "year" as fixed factors. The magnitude of effects was assessed by the estimates of components of variation.

3. Results

3.1. Quantitative Analysis of Biological Indicators

In general, bottom cover was dominated by 4 categories according their median values: living coral (23.3%), soft coral (17.3%), fleshy algae (12.5%), and turf (11.5%). The median value of the remaining categories separately did not exceed 6.1% (Figure 2).

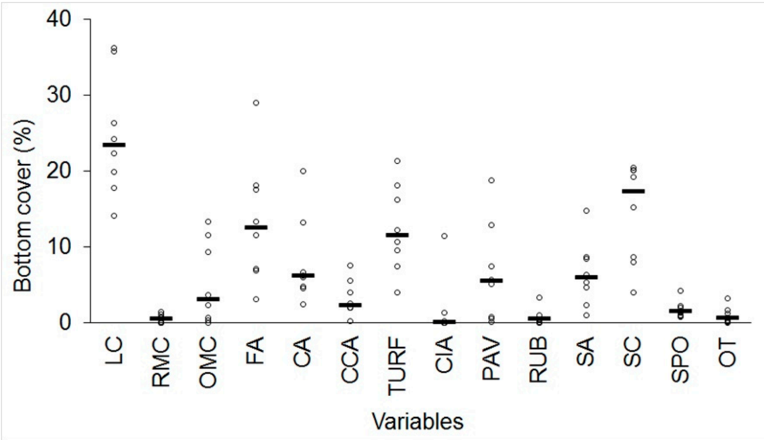

Figure 2. Bottom cover values for the APMNP. Bars represent the median value for the reef, and circles represent means values of each site. Abbreviations of the categories: LC, living coral; RMC, recent mortality coral; OMC, old mortality coral; FA, fleshy algae; CA, articulate calcareous algae; CCA, crustose coralline algae; TURF, thick cespitose algae; CIA, cyanobacteria; PAV, pavement; RUB, rubble; SA, sand; SC, soft corals; SPO, aggressive invertebrates; and OT, "others."

Cover of living coral, fleshy algae, articulated calcareous algae, turf and crustose coralline algae, showed significant differences among sites (Table 2). The highest values of living coral cover were observed in Radio Pirata and Limones (mean of 36 and 35%, respectively). In the remaining sites the average was between 27% and 14% (Figure 3A, Supplementary Table S2). We identified 20 species of stony corals with a variable number and distribution per site (Table S3). The dominant species were *A. palmata* (26%), *Agaricia tenuifolia* (17%), *Orbicella annularis* (12%), *O. faveolata* (10%), and *Porites astreoides* (10%), together accounting for 76% of the total cover (Figure 3B). Radio Pirata and Limones showed higher predominance of *A. palmata* than the other sites. *A. tenuifolia* was dominant in Jardines and Tanchacté Sur. *Orbicella* was more abundant in Bonanza, La Pared, and Radio Pirata, and *P. astreoides* was more abundant in Tanchacté Norte. Mean of turf and articulated calcareous algae cover were below 21% in all sites (Figure 3C,D). The mean value of fleshy algae cover was highest in Jardines (29%), and in the rest of the sites it did not exceed 20% (Figure 3E). Crustose coralline algae were scarce in all sites with means below 10% (Figure 3F).

Recent coral mortality and coral recruit density did not show significant differences across sites, whereas the remaining benthic metrics did present differences (Table 2). Limones and La Pared had the highest coral density values with means of over 10 colonies per transect (Figure 4A). Radio Pirata and La Bocana had the largest corals with mean values above 100 cm (Figure 4B). The percentages of old mortality had mean values below 32% (Figure 4C). Tanchacté Sur showed the highest percentage (3.8%) of coral colonies with recent mortality signs, while in all other sites that value was equal or less than 2.6% (Figure 4D). Recent mortality in corals was mostly due to the incidence of SCTLD, which mostly affected massive colonies of *Pseudodiploria, Orbicella*, and *Siderastrea* (Figure S2). Overall percentage of diseased colonies was 5.2, and the most affected sites were Bonanza (12.5) and Tachanté Sur (11.5) (Supplementary Table S4A,B). Recruits coral density did not exceed 4 colonies m^{-2} in any site (Figure 4E). We identified eight genera, of which *Agaricia, Siderastrea*, and *Porites* were dominant (Supplementary Table S5). The black urchin *D. antillarum* was only observed in Limones, Tanchacté

Sur, and Radio Pirata, with densities of 4 or less individuals 10 m^{-2} (Table S2). The reef structural complexity index varied among sites, with La Bocana, Radio Pirata, and Limones, presenting the highest rugosity (Figure 4F).

Table 2. Results of the permutational analysis of variance (PERMANOVA one way) for biological trait data for sites. Significant differences at $p < 0.05$ in bold type. ECV (estimates of components of variation), perms (permutations).

Indicator	Pseudo-F	p (Perm)	ECV (%)	Perms
Living Coral Cover	7.563	**0.0001**	21.9	8959
Fleshy Algae Cover	15.184	**0.0001**	29.2	8193
Crustose Coralline Algae Cover	4.273	**0.0004**	16.5	5123
Articulated calcareous Algae Cover	14.412	**0.0010**	28.6	9958
Turf Cover	5.876	**0.0010**	19.4	9984
Coral Species Predominance	4.086	**0.0001**	37.8	9897
Coral Density	6.935	**0.0001**	45.7	4945
Coral Maximun Diameter	13.397	**0.0001**	30.7	9950
Old Coral Mortality	8.407	**0.0001**	25.4	9929
Recent Coral Mortality	1.101	0.3378	3.8	9933
Coral Recruit Density	1.566	0.1403	10.6	2235
Rugosity Index	6.620	**0.0001**	42.8	9461
Key Herbivorous Fish Biomass	1.540	0.1320	23.1	9896
Key Commercial Fish Biomass	1.105	0.3539	11.7	9913

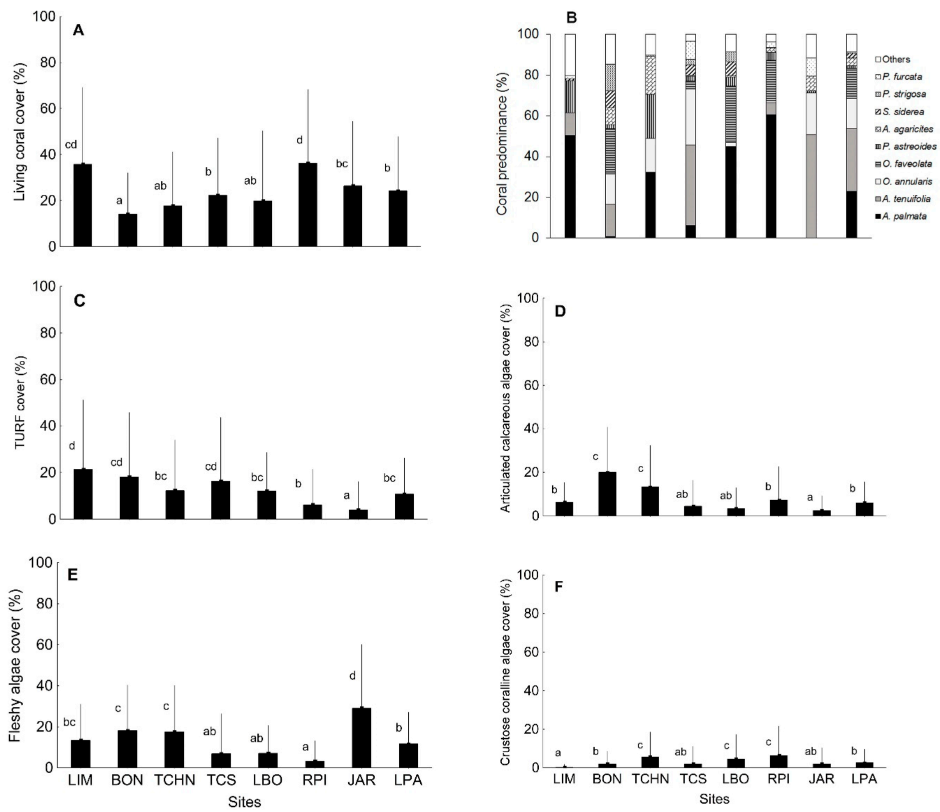

Figure 3. Quantitative values (mean, bars; ± standard deviations, lines) of different categories of the bottom cover. (**A**) Living coral cover, (**B**) Coral species predominance according their living cover, (**C**) Turf cover, (**D**): Articulated calcareous algae cover, (**E**): Fleshy algae cover, (**F**). Crustose coralline algae cover. Letters represent significant differences among sites. LIM: Limones, BON: Bonanza, TCHN: Tanchacté Norte, TCHS: Tanchacté Sur, LBO: La Bocana, RPI: Radio Pirata, JAR: Jardines, LPA: La Pared.

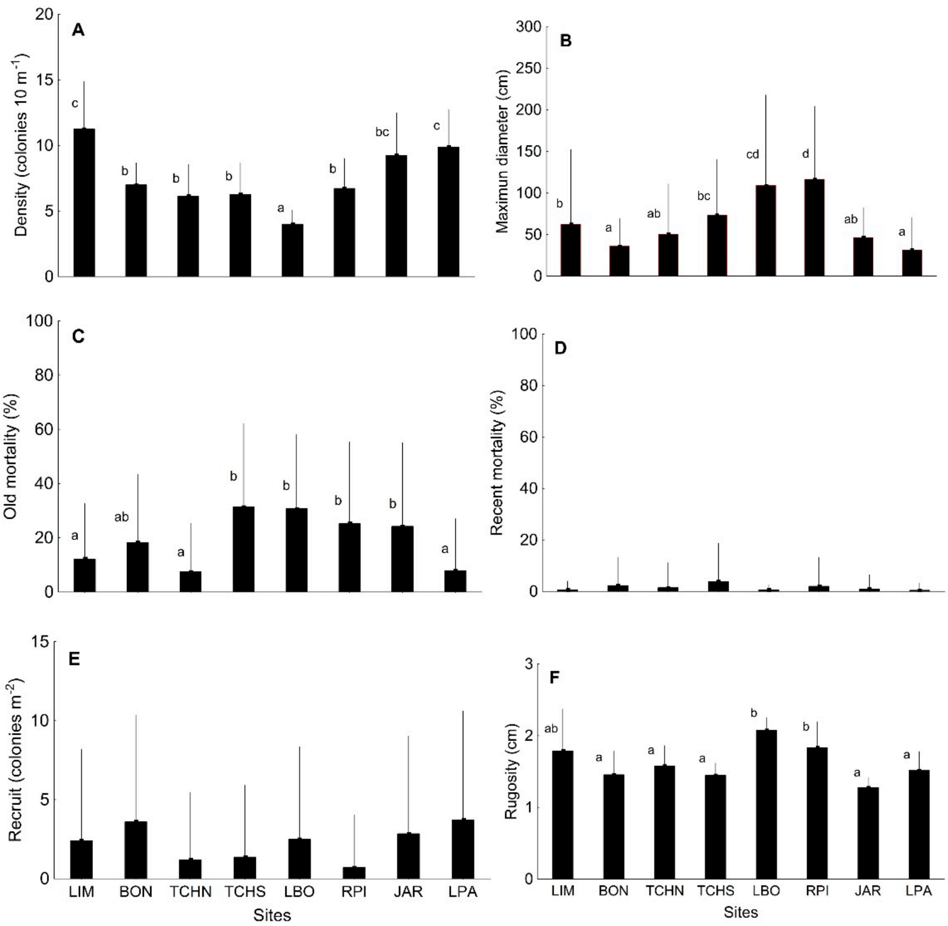

Figure 4. Coral reef condition variables by site (mean, bars; ± standard deviations, lines). (**A**) Coral density, (**B**) Maximum diameter of colonies, (**C**) Old mortality in the surfaces of colonies, (**D**) Recent mortality in the surfaces of colonies, (**E**) Density of coral recruits, (**F**) Coral reef structural complexity index (rugosity). LIM: Limones, BON: Bonanza, TCHN: Tanchacté Norte, TCHS: Tanchacté Sur, LBO: La Bocana, RPI: Radio Pirata, JAR: Jardines, LPA: La Pared.

Fish biomass did not present significant differences among sites (Table 2). Bonanza and Radio Pirata had averages of key herbivorous fish biomass above 100 g $\times$ m^{-2} (Figure 5A). At the rest of sites, the biomass was below 71 g $\times$ m^{-2}. Key commercial fish biomass means did not surpass 30 g $\times$ m^{-2} in any site (Figure 5B). Bonanza and Radio Pirata had highest proportion of Acanthuridae family, and *Acanthurus coeruleus* was the most abundant species. Scaridae family had more predominance in Limones, La Bocana, Jardines, and La Pared (Figure 5C), and *Sparisoma viridis* was the predominant species. Key commercial fish mainly comprised Lutjanidae (Figure 5D), with *Lutjanus mahogoni* and *L. analis* predominating. See all fish species composition in Table S6.

The sites had high variability with respect to the density and rugosity variables, presenting ECV (%) values of 45.7 and 42.8 respectively. Density of coral recruits was the variable with the lowest EVC (%) (Table 2).

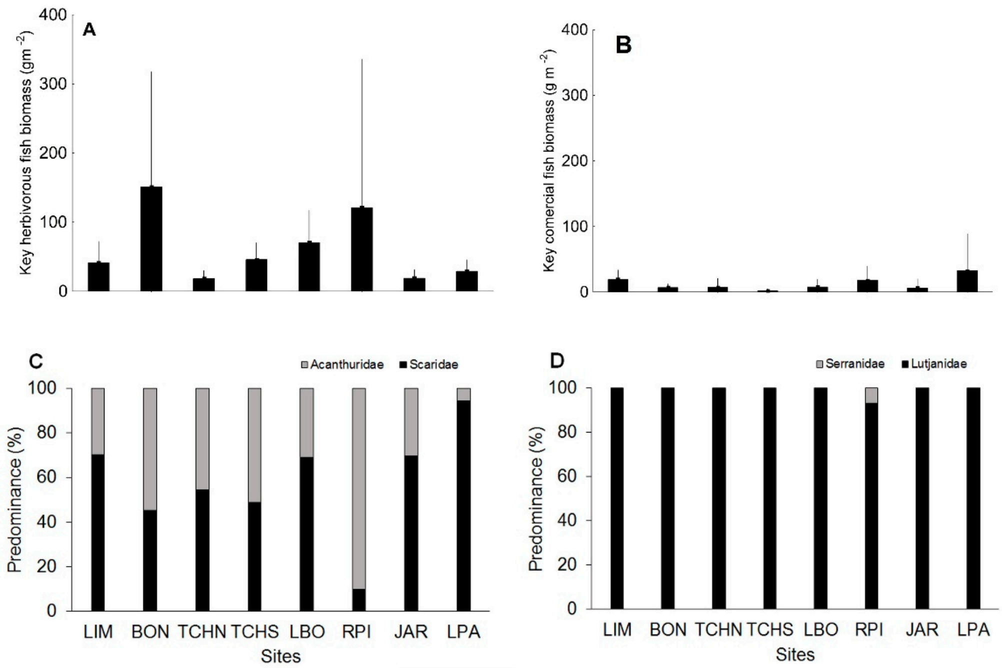

Figure 5. Fish variables results (mean, bars; ± standard deviations, lines). (**A**) Key herbivorous fish biomass, (**B**) Key commercial fish biomass, (**C**) Predominance of the herbivorous fish families according their biomass, (**D**) Predominance of the commercial fish families according to their biomass. LIM: Limones, BON: Bonanza, TCHN: Tanchacté Norte, TCHS: Tanchacté Sur, LBO: La Bocana, RPI: Radio Pirata, JAR: Jardines, LPA: La Pared.

3.2. Qualitative Integral Assessment of the Coral Reef Condition

The integral assessment of the coral reefs of the APMNP according to the qualitative analysis based on the seven indexes, resulted in score category regular (2.7). The sites with better results of the integral assessment were: Radio Pirata (3.1), La Bocana (3.0), La Pared (3.0), and Limones (2.9). The indexes contributing higher scoring for the reef were coral condition (4) and key herbivorous fish biomass (4). The indexes with low scoring for the reef were: coral recruitment (2) and key commercial fish biomass (2) (Table 3).

Table 3. Results of the integral qualitative assessment of the APMNP reef sites, based on the indexes described in Table 1. Reef integral condition index calculated by the average of the sum of each individual index. LIM: Limones, BON: Bonanza, TCHN: Tanchacté Norte, TCHS: Tanchacté Sur, LBO: La Bocana, RPI: Radio Pirata, JAR: Jardines, LPA: La Pared.

	Sites								
Indexes	**LIM**	**BON**	**TCHN**	**TCHS**	**LBO**	**RPI**	**JAR**	**LPA**	**APMNP**
"Reef Promoter"	3	2	2	3	3	3	2	3	**3**
"Reef Detractors"	3	2	3	4	4	4	3	3	**3**
Coral Condition	4	4	5	3	3	4	4	5	**4**
Coral Recruitment	2	2	1	1	2	1	2	2	**2**
Rugosity	3	2	3	2	4	3	2	3	**3**
Key Herbivorous Fish Biomass	3	5	1	3	4	5	1	2	**4**
Key Commercial Fish Biomass	2	1	1	1	1	2	1	3	**2**
Reef Integral condition	**2.9**	**2.6**	**2.3**	**2.4**	**3.0**	**3.1**	**2.1**	**3.0**	**2.7**

3.3. Temporal Variability Analysis

"Reef promoter" and "reef detractors" indexes, and coral species composition, showed significant differences among the factors "sites," "year," and the interaction "sites x year." The lower ECV (%) was found to "year" from "reef promoter" (Table 4). See pair-wise test result in Supplementary Table S8.

Table 4. Results of the permutational analysis of variance (PERMANOVA two way) for biological trait data for sites and years, in the comparison between studies of 2016 and 2019 at APMNP. Significant differences at $p < 0.05$ in bold type. ECV (estimates of components of variation), perms (permutations). "Reef promoter" (% living coral cover + % crustose coralline algae cover + % pavement). "Reef detractors" (% fleshy algae cover + articulated calcareous algae cover + % turf cover + % Cyanobacteria cover + % aggressive invertebrates cover).

Indicator	Source	Pseudo-F	*p* (Perm)	ECV (%)	Perms
"Reef Promoter"	Site	19.823	**0.001**	20.6	9898
	Year	6.8869	**0.007**	5.8	9895
	Site X Year	5.7694	**0.001**	14.7	9898
"Reef Detractors"	Site	32.192	**0.001**	19.6	9897
	Year	131.91	**0.001**	20.1	9896
	Site X Year	12.283	**0.001**	16.7	9899
Coral Species Composition	Site	19.823	**0.001**	22.1	9851
	Year	6.8869	**0.001**	14.8	9935
	Site X Year	5.7694	**0.001**	20.0	9871

"Reef promoter" median was higher in 2019, while "reef detractors" median was lower in 2019 (Figure 6A,B). The first case was influenced by the higher mean values of living coral cover founded in Radio Pirata, Jardines, and La Pared. The second case was influenced by the lower values of fleshy algae cover founded in La Bocana, and by the lower values of turf cover in all sites (See metrics values of the 2016 study in Supplementary Table S7).

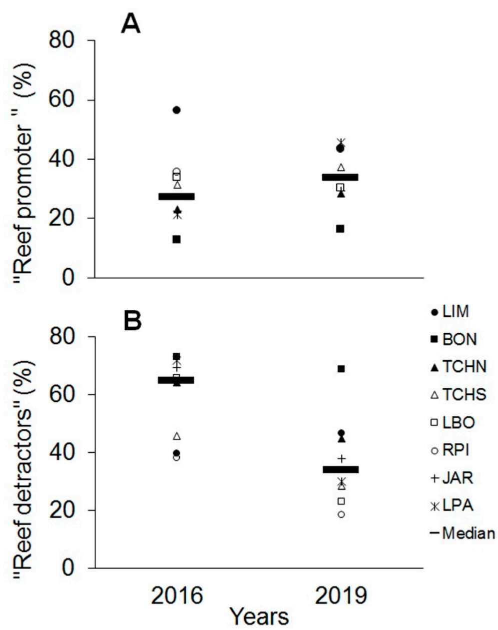

Figure 6. Comparison between the studies conducted in APMNP in 2016 and 2019. Bars represent the median value for the reef, and shapes represent means values of each site. (**A**) "reef promoter" (% living coral cover + % crustose coralline algae cover + % pavement), (**B**) "reef detractors" (% fleshy algae cover + % articulated calcareous algae cover + % turf cover + % cyanobacteria cover + % aggressive invertebrates cover). LIM: Limones, BON: Bonanza, TCHN: Tanchacté Norte, TCHS: Tanchacté Sur, LBO: La Bocana, RPI: Radio Pirata, JAR: Jardines, LPA: La Pared.

The nMDS results showed spatial and temporal dissimilarity between sites (Figure 7A). In Radio Pirata and La Bocana, *A. palmata* was not observed in 2016, however, it was abundant in the 2019 study. Tanchacté Norte showed great differences with respect to *Pseudodiploria strigosa* predominance across time. In Tachanté Sur, *O. annularis* species complex was more abundant in 2016, while *A. tenuifolia*, was more abundant in 2019 (See values of species predominance of 2016 and 2019 studies in Supplementary Table S3).

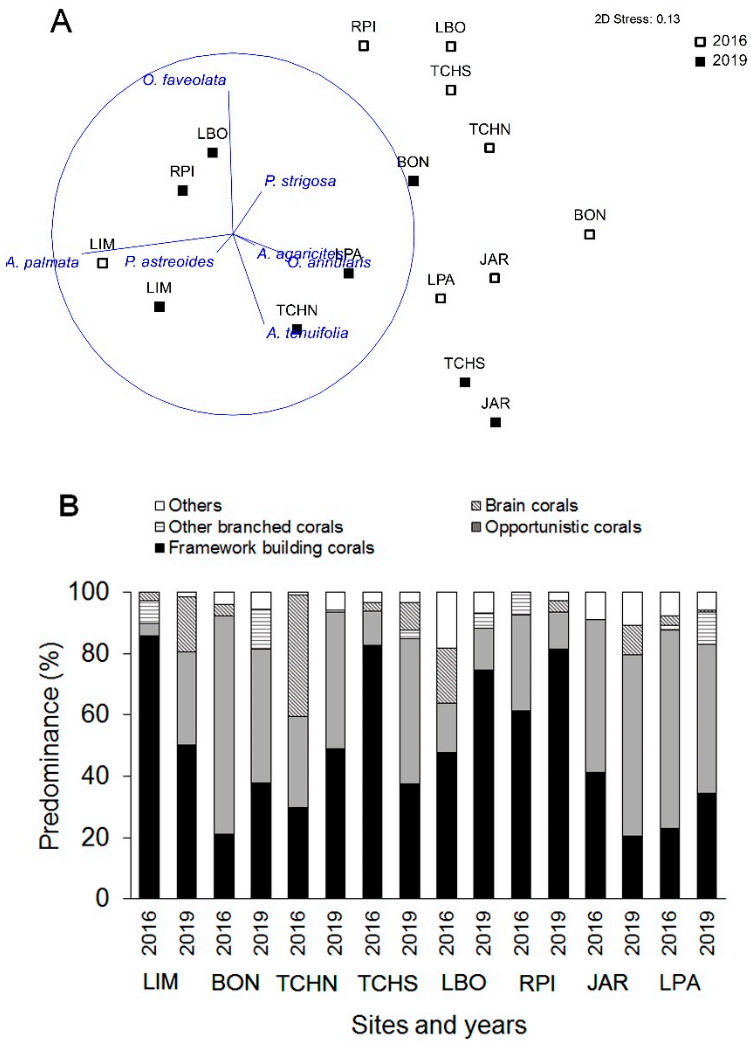

Figure 7. Comparison between the studies conducted in APMNP at 2016 and 2019. (**A**) Multidimensional scaling ordination (nMDS) of sites based on coral species composition according to their living cover, (**B**) Coral species predominance grouped according to their characteristics. LIM: Limones, BON: Bonanza, TCHN: Tanchacté Norte, TCHS: Tanchacté Sur, LBO: La Bocana, RPI: Radio Pirata, JAR: Jardines, LPA: La Pared.

In the 2016 study, the APMNP was composed of 49% framework building coral species, 35% opportunistic species, 2% other branching coral species, 9% brain coral species, and 5% of "other" species. Limones and Tanchacté Sur had higher prevalence of framework building coral species, while La Pared had the highest percentage of opportunistic species. In 2019 study, the APMNP was composed of 48% framework building coral species, 37% opportunistic species, 5% other branching coral species, 4% brain coral species, and 6% of "other" species. Radio Pirata and La Bocana had higher prevalence of framework building coral species, while Jardines had the highest percentage of opportunistic species (Figure 7B).

4. Discussion

Scoring system for the integral evaluation of the coral reef is a complementary tool to the application by Kramer and Lang [38] of regional bioindicators averages as reference parameters for the benthos and the ichthyofauna condition in the reef [32]. Through choices regarding separating or combining the various bioindicators, the aim is to assist decision makers in deciding relevant interventions and inform the general public in broad terms about the status and directions of change in key, easily understood indicators [39].

The scoring system used in this study, based on seven main benthic and fish indexes, classifies the overall condition of the APMNP coral reefs as "regular". This classification was mainly influenced by the low ranking of coral recruitment, and key commercial fish biomass. Within the eight studied sites, coral recruitment was "critical" in three, and key commercial fish biomass was "critical" in five. The general condition of APMNP coral reef (2.7) was similar to the one obtained for the Mesoamerican Reef (2.5) according to studies of 2018–2019, where, the fish communities also showed the lowest condition scoring [40].

Coral recruitment processes at the regional level (Caribbean) display a decreasing tendency [2,41]. Studies of the Mesoamerican Reef from the beginning of the century [38] already showed low averages of coral recruits (2 colonies m^{-2}), and the observed recruits were mainly brooder species (*Agaricia sp.* and *P. astreoides*). A similar situation of low recruit density and recruit species was observed in 41 recently studied reef crests in Cuba [42]. So, our results are in line with regional trends.

Recruitment rates depend on quantity, distribution, and status of the adults of coral species, survival of larvae during their life cycle, and the status of the habitat [43]. Corals in the Mexican Caribbean have been suffering a deadly disease since 2018 [25]. The above, together with the high frequency of bleaching events during summers (months of reproductive stage of many species), could be some of the causes of low corals reproduction [7,44]. Poor levels of coral recruitment in APMNP could also be related to the low crustose coralline algae cover observed in 2016 and 2019. Coral recruits prefer substrates covered by crustose coralline algae [45,46]. Chemical and biological properties of these algae, in addition to the films formed by diatoms and associated bacteria, influence the settlement and survival rates of corals [47]. Crustose coralline algae are known to be slow-growing organisms that establish in bare substrates, which they cover due to the fusion of their encrusting thalli [48]. In the majority of the APMNP's sites, the possible substrate areas available for coral recruitment were mainly occupied by turf, and to a lesser degree, by macroalgae.

D. antillarum black sea urchin is a great consumer of turf and macroalgae [43], which favors crustose coralline algae cover. Recovery in the Caribbean Sea of the black sea urchin after the 1982 epidemic [49] has been slow and not uniform, with the species currently having low densities in many of the reefs of the Caribbean [50–52]. The limited recruitment processes and post-settlement mortality of the black sea urchin seem to regulate the demographic recovery of the species [53]. The density of black sea urchin observed in APMNP was low. However, the highest densities of black sea urchins have been observed during the night [54], which suggests that they hide in the deepest part of the reef's structure during the day, so their study could easily be underestimated during diurnal samplings, as would be the case in the structurally complex habitats in the shallow reefs of the APMNP.

Coral communities of APMNP had better condition according to their values of living coral cover, coral density, coral colonies sizes, and coral species composition. Statistical variability founded among sites could respond to natural variability due to physical drivers of each site (shelter to waves, sedimentation, among others); or, historical variability between sites related to the occurrence of disturbing events (diseases, bleaching, among others). Our study cannot show evidence of direct anthropogenic disturbances causing variability in the structure and condition of the park's coral communities.

Mean living coral cover of APMNP, was similar to the one recently observed in Cuban shallow reefs (22%) [42], although in many sites of Cuban reefs, the species that most contributed to the average coverage value were *P. astreoides*, and *Millepora complanata*; and to a lesser degree *A. palmata* [55]. Mean living coral cover reported in the last Mesoamerican Reef report was 19%. This same study documented a 16% mean for Mexico; 17%, for Belize; 22%, for Guatemala and 27%, for Honduras [40]. Limones and Radio Pirata sites, maintain the best status of *A. palmata*, which favors average values of coral coverage and support Rodríguez-Martínez et al. [22], and Banaszak and Álvarez-Filip's findings [56].

Significant differences regarding the percentage of the "reef promoter" index, were found between 2016 and 2019, and an improvement was observed in some sites despite the occurrence of coral mortalities due to the SCTLD disease outbreak in 2018. We consider that some differences are given because the samplings carried out in 2019, were not done exactly in the same places of 2016 samples. For example, is possible that in Limones 2016 sample, were included more healthy colonies of *A. palmata* that in 2019, and is evident that in Radio Pirata 2016 sample, the researchers did not sample above *A. palmata* colonies, that were found in 2019. This probably influenced the living coral cover average per site, and may have also occurred in the rest of the sites. This sampling problem could also explain the differences observed in the nMDS analysis with respect to coral species composition.

Despite the stated above, in both studies (2016 and 2019), a higher proportion of framework building coral species was found. The shift to an ecological state dominated by non-framework building taxa has important ecological implications, such as lower general production of carbonates, lower reef structural complexity, and the loss of resilience [36,57]. Jardines and Tanchacté Sur presented the highest dominance of *A. tenuifolia* (>40%) in 2019 study, an opportunistic species according to Cote and Darling [58] and Darling et al. [59], which, nevertheless, is able to form colonies with diameters greater than one meter, that contribute to the three-dimensional structural complexity of the reef (Supplementary Figure S3). *P. astreoides*, also considered to be an opportunistic species [60], was most abundant at Tanchacté Sur, where it forms small encrusting colonies, generating less shelter for the rest of the reef inhabitants.

Percentages of affected colonies by SCTLD were not high within our sampling, partly because the two most abundant species (*A. palmata* and *A. teunifolia*), practically are not affected by the disease. Apparently, the disease outbreak has already declined, with its highest peak was observed during 2018 [25]. However, visual observations around the reef showed that, in spite of the low percentage within the sampling, this white syndrome has caused substantial damage to *Pseudodiploria*, and to a lesser degree, to *Orbicella*. The lower prevalence of these species observed in some sites of the 2019 study, compared to those of the 2016 study, could be due to the mortality of corals and this disease.

Differences respect to algae cover between 2016 and 2019, may be due to the fact that studies were carried out at different times of the year, and seasonality is a factor that influences algal communities [60]; although according to last HRI report, has been a decrease in the fleshy algae cover in the region of 23 to 20% [40]. In our study, an abundance of *Dictyota, Hallimeda*, and *Galaxaura* varied among sites, but a predominance of *Lobophora* sp., the most harmful to the coral reef species [60], was not observed. The low "reef detractor" proportion in the reef, was an indicator of good water quality in reef zone (despite decomposition of *Sargassum* at the shoreline) and herbivorous presence. We also observed a low abundance of Clionaidae sponges, which are typical of eutrophicated environments and capable of piercing the reefs thus weakening and destroying their structure [61].

General fish species richness and densities of some species were relatively high. According to HRI 2018 report, herbivorous fish biomass varies reef to reef, yet has remained stable in the last decade, and Mesoamerican reef wide average shows a slow, but positive increase likely due to management actions implemented in the region [34]. Our report shows a high relative average of herbivorous biomass (60 gm^{-2}), in comparison to the media reported for New Caledonia (40), other Bahamas sites (40), and Caribbean (>30) [62]. However, the fish biomass values observed in the APMNP were highly influenced by the schools of surgeon fish observed. The average size of Scaridae fishes was under 30 cm and, the *Scarus guacamaia* species was not recorded, and *S. coelestinus* species was not abundant.

Biomass of commercial fish was low, we observed almost no specimens of Serranidae and the species of Lutjanidae presented lengths below 30 cm. The lack of top predators we recorded might influence the reef's trophic cascade. Biomass of commercial fish values and general predominance of small species suggest a possible effect of overfishing [60]. However, the natural variability and seasonality of the fish must be considered. Many commercial species live in wider areas and have high mobility, so sampling has to be done at a higher frequency in order to obtain results that are representative of the actual status of this indicator [43].

The APMNP has made a significant effort in fisheries management with the community of Puerto Morelos. Fishing permits are granted in the MPA resulting from a strong negotiation with the Puerto Morelos fishing cooperative, which is the only one authorized to fish in the MPA areas. The APMNP administration is in charge of enforcing to ensure that the fishing zones and the regulations established in the zoning regarding the closures, catch quotas, and fishing gear are respected [28].

5. Conclusions

The general state of the APMNP reefs could be classified as regular based on the integral analysis of the condition indicators for benthos and fish. The average of the living coral cover was above 20%, higher than the current average observed in the Caribbean Sea, and the framework building coral species were dominant. However, coral recruitment was low, with a predominance of brooders and opportunistic species, and we found a low crustose coralline algae cover, which is the best substrate for the settlement of coral recruits. Fleshy algae cover was not high, in spite of the scarcity of black sea urchins and large herbivorous fish, which constitutes an indicator of low eutrophication of water in the reef area. Commercial fish biomass was also low, which is a reflection of the effects of regional overfishing. We found a better proportion of reef promoter elements than detractors, compared to the 2016 study. However, as not exactly the same areas of reef substrate within each site were compared (with non-fixed sampling transects), statistics results from this comparison may show some bias. Despite this fact, we consider that from December 2016 to June 2019, the coral communities studied do not appear to have suffered much deterioration in general.

Supplementary Materials: The following are available online at http://www.mdpi.com/1424-2818/12/7/272/s1, Figure S1: Puerto Morelos coral reefs. A: *Acropora palmata* colonies. B: *Orbicella annularis* colonies. C: Soft corals colonies. Photo H. Caballero-Aragón, Figure S2: *Orbicella annularis* colony affected by "stony coral tissue loss disease". Photo H. Caballero-Aragón, Figure S3: Colonies of *Agaricia tenuifolia*. Photo H. Caballero-Aragón, Table S1: Table S1: Sampled sites in the Arrecife de Puerto Morelos National Park. Geographic coordinates, site names, acronyms, depths, and distance from reefs to the coast, Table S2: Biological indicators for benthos and ichthyofauna (2019 study). SD= Standard deviations, Table S3: Corals predominance (%) according their living cover. Species number per sites (colonies ≥5 cm), Table S4 A: List of diseases, and percentage of diseased colonies by species, for each site and for the APMNP (2019 study), Table S4 B: List of diseases, and percentage of diseased colonies by site and for the APMNP (2019 study), Table S5: Coral recruits relative abundance (%), and species number per sites (colonies <5 cm). 2019 study, Table S6: Key fish species predominance (%) according to their biomass (g m^{-2}). 2019 study, Table S7: Bottom cover variables obtained from 2016 study. Table S8: Pair wise tests.

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