Chapter 9

# Coral Reef Resilience Index for Novel Ecosystems: A Spatial Planning Tool for Managers and Decision Makers - A Case Study from Puerto Rico

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http://dx.doi.org/10.5772/intechopen.71605

**Abstract**

Timely information is critical for coral reef managers and decision-makers to implement sustainable management measures. A Coral Reef Resilience Index (CRRI) was developed with a GIS-coupled decision-making tool applicable for Caribbean coral reef ecosystems. The CRRI is based on a five-point scale parameterized from the quantitative characterization of benthic assemblages. Separate subindices such as the Coral Index, the Threatened Species Index, and the Algal Index also provide specific information regarding targeted benthic components. This case study was based on assessments conducted in 2014 on 11 reef sites located across 3 geographic zones and 3 depth zones along the southwestern shelf of the island of Puerto Rico, Caribbean Sea. There was a significant spatial and bathymetric gradient ($p < 0.05$) in the distribution of CRRI values indicating higher degradation of inshore reefs. Mean global CRRI ranged from 2.78 to 3.17 across the shelf, ranking them as "fair." The Coral Index ranged from 2.60 to 3.76, ranking reefs from "poor" to "good," showing a general cross-shelf trend of improving conditions with increasing distance from pollution sources. Turbidity and ammonia were significantly correlated to CRRI scores. Multiple recommendations are provided based on coral reef conditions according to observed CRRI rankings.

**Keywords:** benthic community structure, coral reefs, Coral Reef Resilience Index (CRRI), Caribbean Sea, Puerto Rico, ecosystem health, marine management, marine biodiversity, novel ecosystems, conservation, coral bleaching, tropical ecosystems

# 1. Introduction

## 1.1. The emergence of novel ecosystems

Coral reefs across regional to global scales are showing unequivocal signs of decline. The long-term combined impacts of local human-driven factors, such as land-based source pollution (LBSP), water quality decline and overfishing, as well as large-scale climate change-related factors, such as massive coral bleaching, coral disease outbreaks, and mass coral mortalities, have resulted in a large-scale alteration of coral reef community dynamics and in the irreversible demise of coral assemblages [1–4]. These have resulted in a net coral reef decline and in often irreversible benthic community regime shifts [5–9], with significant impacts on multiple coral and fish functional groups [10]. These alterations might impair considerable coral reef ecosystem functions. Three massive coral bleaching events occurred across the northeastern Caribbean region in 1987, 1998, and 2005. But the 2005 sea surface warming episode and massive coral reef bleaching event caused an unprecedented coral mortality episode across the northeastern Caribbean region, including P.R., that mostly impacted large reef-building taxa [11–14]. More than a decade later, there is still no net recovery among many of the impacted coral species, and reef communities have followed a significantly different trajectory resulting in the emergence of novel ecosystems largely dominated by ephemeral coral species [15] and macroalgal growth [16–18]. Although such impacts have been well documented, long-term impacts associated to the emergence of novel benthic assemblages on reef functions, values, and benefits still remain largely unknown. Such rapidly changing reefs have been deemed as unhealthy. However, there are still no clear definitions of what exactly is a healthy reef.

Large-scale declines in Caribbean coral reef fish communities have also been documented across fishery target species, mostly resulting from long-term fishing effects [19, 20], but also across multiple nontarget taxa resulting from large-scale, long-term coral reef habitat decline and flattening [21, 22]. Coral cover and topographic complexity are critical components of habitat structure for supporting diverse fish assemblages and must be managed accordingly [23–25]. Evidence from a multiplicity of fish assemblage data sets across the Caribbean suggests that specialist reef fish species have largely declined across very large spatial scales, implying the large-scale nature of reef decline and its negative consequences on multiple fish taxa [22, 25]. Highly altered novel ecosystems have emerged from largely declining benthic communities. Novel ecosystems can be defined as: "*ecosystems containing new combinations of species that arise through human action, environmental change, and the impacts of the deliberate and inadvertent introduction of species from other regions. Novel ecosystems (also termed 'emerging ecosystems') result when species occur in combinations and relative abundances that have not occurred previously within a given biome. Key characteristics are novelty, in the form of new species combinations and the potential for changes in ecosystem functioning, and human agency, in that these ecosystems are the result of deliberate or inadvertent human action*" [26]. Novel coral reef ecosystems have emerged out of the dramatic changes in benthic community trajectory that have followed long-term reef decline and slowly evolving regime shifts, favoring macroalgal and nonreef building taxa dominance [27]. Coral reefs across regional and global scales are showing unequivocal signs of distress, with the emergence of novel assemblages of multiple taxa, including corals, algae,

http://dx.doi.org/10.5772/intechopen.71605

sponges, fish, and seagrasses. Such significant regime shifts have pushed out many coral reefs beyond the point of recovery. Hobbs et al. [28] suggested that *these novel systems will require significant revision of conservation and restoration norms and practices away from the traditional place-based focus on existing or historical assemblages*. But how much have such changes impacted ecosystem functions, resilience, benefits, and values is still poorly understood due to the lack of appropriate indicators of reef condition. This information is essential for reef managers and decision-makers.

### 1.2. The concept of "coral reef health" in the context of novel ecosystems

One fundamental challenge is still the need to develop an operational/functional definition of "coral reef health," particularly in the context of novel ecosystems. According to McField and Kramer [29], a healthy reef would be "*the presence of indicator species,*" "*maintaining key processes like herbivory,*" "*having higher fishing catches/landings,*" or even "*just looking like it did in years past.*" These seem to be obvious indicators of reef health. But there is not an exact definition relying on a single indicator species, taxa, or group due to the highly variable nature of coral reefs. For instance, a coral reef with high fish species richness, abundance, or biomass may appear to be healthy, but if its living coral cover is very low, then it may not, depending on which indicator we use. Therefore, the definition of reef health must incorporate a suite of indicator variables and then combine and weight them in such a way that a more holistic index can be defined to rank a coral reef as healthy, fair, or unhealthy. A more holistic definition of a healthy reef was provided by McField and Kramer [29]: "*A reef is healthy if it maintains its structure and function and allows for the fulfillment of reasonable human needs.*" Alternatively, we suggest a broader definition: *A reef is healthy if it maintains its structure, function, and self-replenishing capacity, if it can naturally recover from disturbance, and if it can maintain its natural connectivity with other ecosystems and allows for the fulfillment of reasonable human needs*. In this sense, the interaction of six factors can influence reef health (**Figure 1**). These include (1) ecosystem structure, (2) ecosystem processes, (3) connectivity, (4) human well-being, (5) governance, and (6) drivers of change.

The interaction of multiple processes is fundamental for maintaining reef health, including maintaining biodiversity, community structure, habitat extent, and abiotic factors (e.g., low sediment inputs, water quality, and sea surface temperature). Also, coral condition, reproduction, and recruitment success, high reef accretion:bioerosion rates (a positive carbon budget balance), and herbivory are important. Maintaining functional terrestrial-marine, genetic, ecological, and energetic connectivity is vital to support high productivity. In addition, a healthy reef should contribute to support human health (e.g., through food protein), local economy and livelihoods (e.g., fisheries, tourism-based businesses, coastal protection, and pharmacological products), and culture (e.g., traditional artisanal fisheries and other uses). Governance is a critical factor for sustaining healthy reefs, particularly if appropriate and operational public policies are fully implemented and supported by a strong legal framework and enforcement. However, the lack of available human resources (e.g., natural resource managers, scientific staff, enforcement officers) is central for governance efficiency. Finally, a combination of local, regional, and global drivers of change will determine reef health, including

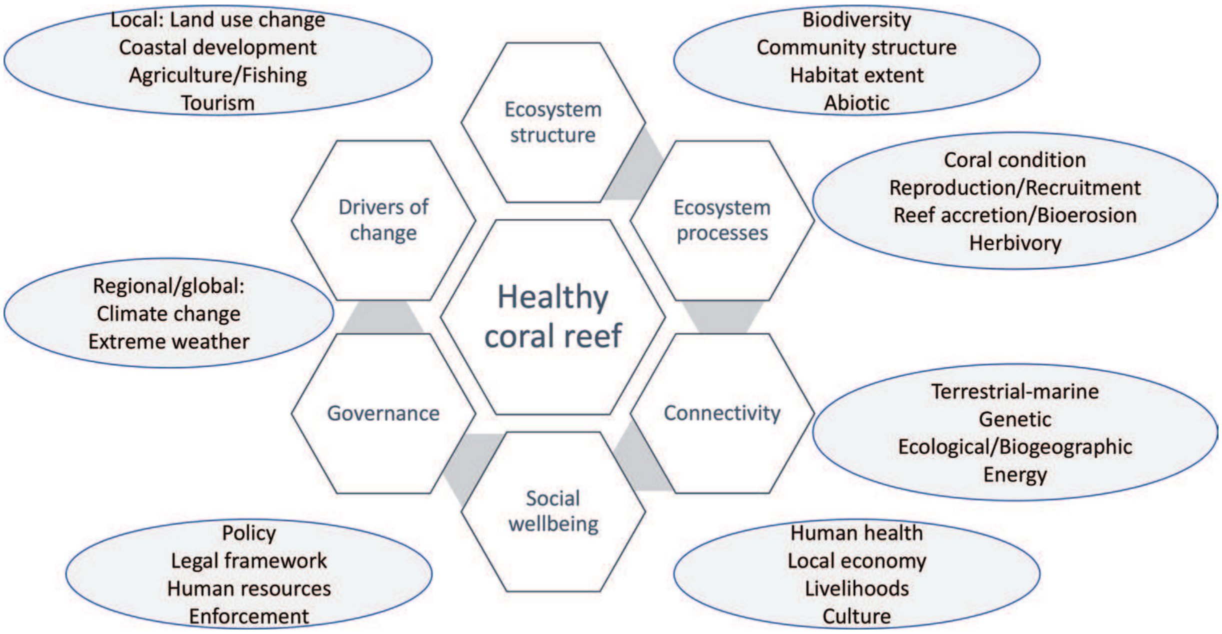


**Figure 1.** Conceptual model of factors affecting coral reef health.

factors that operate on different spatiotemporal scales. This may include local factors such as land use changes, tourism, agriculture and fishing, and regional/global factors such as climate change and extreme weather events.

As more of the Earth becomes transformed by human actions, novel ecosystems increase in importance, but these still remain barely studied. In the particular case of emergent novel coral reefs, their impact on fish assemblages or whether these new systems are persistent over large spatial and temporal scales still remains largely unknown. Also, how such alteration can affect ecosystem functions, resilience, benefits, and values remains poorly understood. There is also limited information with regard to novel reef ecosystem's health and how reef health responds to gradients of human pressure. It might be difficult or costly to return such systems to their previous state, and hence consideration needs to be given to developing appropriate *real-time* metrics applied to develop, modify, or adapt management goals and conservation approaches through the fine-tuning and implementation of coral reef health indices. This would provide rapid and effective tools for managers and decision-makers, information that would be critical to adapt management plans to face increasing climate change–related threats.

### 1.3. The development of coral reef health indices

There are multiple known attempts to implement indices to address reef health [30, 31]. Most classical examples of indicator parameters are based on single indicators such as percent live coral cover [32], the Mortality Index [33], the ratio between living and dead corals [34], or the size–frequency distribution of corals, with emphasis on estimating the proportion of small corals, which may indicate recruitment [35, 36]. There is also the Deterioration Index, which is based on the ratio between mortality and recruitment rates of branching corals [37]. Crosby and Reese [38] proposed an index for Pacific coral reefs using butterflyfish diversity as a bioindicator of reef condition. Edinger et al. [39] proposed the use of coral growth rates as indicators of eutrophication impacts. Holmes et al. [40] proposed the use of branching coral rubble bioerosion as indicators of reef trophic condition. Lirman et al. [41] suggested the use of percent recent mortality as indicators of reef adverse conditions. Edinger and Risk [42] also suggested the pattern of coral morphotypes as indicators of Pacific coral reef condition. Jameson et al. [43] developed a Coral Damage Index (CDI) based on the abundance of broken coral and coral rubble to address SCUBA diving impacts on reefs. Hawkins et al. [44] also developed a method to assess coral fragmentation and overall reef condition across reefs impacted by SCUBA diving. Swain et al. [45] developed a coral taxon–specific bleaching response index (taxon-BRI) by averaging taxon-specific response over all sites where a taxon was present. Nonetheless, the most significant limitation of methods based on a single or few bioindicators is that many of them can have significant variability due to factors that may not necessarily reflect changes in reef health. This suggests the need to use a combination of parameters to improve the accuracy of reef condition assessments.

Jokiel and Rodgers [46] used reef fish biomass, reef fish endemicity, total living coral cover, population of the endangered Hawaiian monk seal (*Monachus schauinslandi*), and the number of female green sea turtles (*Chelonia mydas*) nesting annually on each Hawaiian island as bioindicators, developing a simple integrated, composite scoring and ranking system. Rodgers et al. [47] further expanded this approach by integrating 46 different indicators, developing a reference site model and an ecological gradient model to assess impacts on coral reefs. Kaufman et al. [48] also developed the Coral Health Index aimed at assessing the condition of benthic fish and microbial communities. Lasagna et al. [49] developed the Coral Condition Index, which was based on the proportional abundance of coral colonies belonging to six categories: recently dead, bleached, smothered, upturned, broken, and healthy. This index ranges from 0 (100% of dead corals) to 1 (100% of healthy corals), with low values suggesting large scale disturbances (e.g., climate impacts) and high values suggesting disturbances acting on a small scale. Jameson et al. [50], Fore et al. [51], and Bradley et al. [52] suggested the development of a multiparameter Coral Reef Biocriteria Index for addressing coral reef ecological condition. Fabricius et al. [53] tested the use of 38 indicators, where 33 of them (including coral physiology, benthic composition, coral recruitment, macrobioeroder densities, and a foraminifera index) showed significant relationships with a composite index of 13 water quality variables. However, many of these methods based on multiple parameters, although scientifically robust, can be significantly complex and difficult to implement by non-academic personnel (e.g., managers, NGOs, and base communities). Thus, there is still a need to develop robust yet simple methods with multiple potential applications and which can be used by a wide range of users.

Risk et al. [54] suggested the use by coastal communities of simple techniques that have been shown to identify stress on reefs including coral mortality indices, benthic bioindicators (e.g., stomatopods, foraminifera, and amphipods), coral associate counts, and coral rubble bioerosion. McField and Kramer [29, 55] developed the Coral Reef Health Index (CRHI) in the Mesoamerican Barrier System based on assessing several parameters of benthic and fish assemblages. This method has been successfully used across the Caribbean [56–59]. McField and Kramer [60] summarized a set of multiple simple criteria to be used by coastal communities. In a comparative study between two reef health indices and different metrics of biological, ecological, and functional diversity of fish and corals, Díaz-Pérez et al. [61] found out that health indices should be complemented with classic community indices to improve the accuracy of the estimated health status of Caribbean coral reefs. This brings in the idea that coral reef health indices must be made more robust by complementing them with a suite of biological and water quality parameters often easily obtained from standard reef characterization and long-term monitoring data sets.

According to Ben-Tzvi et al. [37], any broad-based reef health index monitoring should *(1) enable reliable comparison between different reef types (e.g., reefs of different live cover); (2) be simple to apply, including by nonscientific personnel (e.g., recreational divers); (3) provide an indication of the trend in reef health rather than only the current state of the reef; (4) provide a quantitative, or at least semiquantitative, indication of the reef state, to enable comparisons between distinct reefs of different characters; and (5) not require repeated serial surveys, but be able to provide some indication of the state of the health of the reef from a single survey event*. An easy-to-implement rapid assessment method of novel coral reef assemblages was tested, in combination with a rapid diagnostic tool of reef condition useful for managers and decision-makers for both small- and large-scale assessments, which could also be implemented in standard long-term monitoring programs.

### 1.4. Goals and objectives

The goal of this chapter is to test an easy-to-implement rapid assessment, reef characterization, and decision-making tool for coral reef managers. Many countries, particularly, small island nations, with limited socioeconomic resources, lack appropriate governance infrastructure, human resources, and economic and technological tools to incorporate scientific information into decision-making regarding the management of coral reefs and fishery resources. The lack of appropriate management is a critical concern in the face of current and forecasted climate change–impacts. Coral reefs are often the first line of defense against storm swells and sea level rise, besides their importance as a source of food protein, for sustaining biodiversity, as a sinkhole of ATM $CO_2$, as a source of natural products of biomedical importance, and as a source of revenue for multiple local economies. Coral reef conservation becomes particularly important in novel coastal ecosystems adjacent to large urban centers, subjected to significant local sources of human stressors. We propose the application of a Coral Reef Resilience Index (CRRI) focused on scoring the ecological condition of coral reef benthic and fish communities, based on actual quantitative data obtained from ecological characterization surveys or from long-term monitoring efforts. Complex quantitative data, difficult to analyze and interpret, are changed into a five-point scale scoring system, similar to the one developed by McField and Kramer [29], and also converted into GIS-based format to produce a set of indicator maps. This will provide managers with easy-to-interpret tools for decision-making regarding conservation- and restoration-oriented management strategies. A step-by-step guide for the implementation of the tool is discussed. This chapter also provides a case study from coral reefs across a water quality stress gradient from the Southwestern Puerto Rico shelf and provides a basic guide for management recommendations based on different scores of the CRRI with application across multiple coral reef ecosystems on a global scale.

## 2. Methods

### 2.1. Study sites

Field data used to parameterize the CRRI were obtained from a study of coral reef condition across a water quality stress gradient through the southwestern Puerto Rico insular shelf during the month of July 2014 [62]. Sampling was conducted at 11 locations along a water quality stress gradient and a distance gradient from the coast (**Figure 2**). Coral reefs were subdivided into three different geographic zones: (1) inshore reefs [<4 km] (Punta Ostiones [OST], Punta Lamela [LAM], Punta Guaniquilla [GUA], Cayo Ratones [RAT], Bajo Enmedio [EME]), (2) mid-shelf reefs [4–8 km] (Arrecife Resuello [RES], Corona del Norte [CON], Arrecife El Ron [RON]), and (3) outer-shelf reefs [8–20 km] (Escollo El Negro [NEG], Arrecife Papa San [PPS], Arrecife Gallardo [GAL]). A total of 55% of the studied reefs were located within natural reserves managed by the Puerto Rico Department of Natural and Environmental Resources (DNER), including inshore location RAT (Isla Ratones Natural Reserve), OST (Finca Belvedere Natural Reserve Marine Extension), and GUA (Punta Guaniquilla Natural Reserve Marine Extension). Mid-shelf locations RON and CON, and outer-shelf location PPS

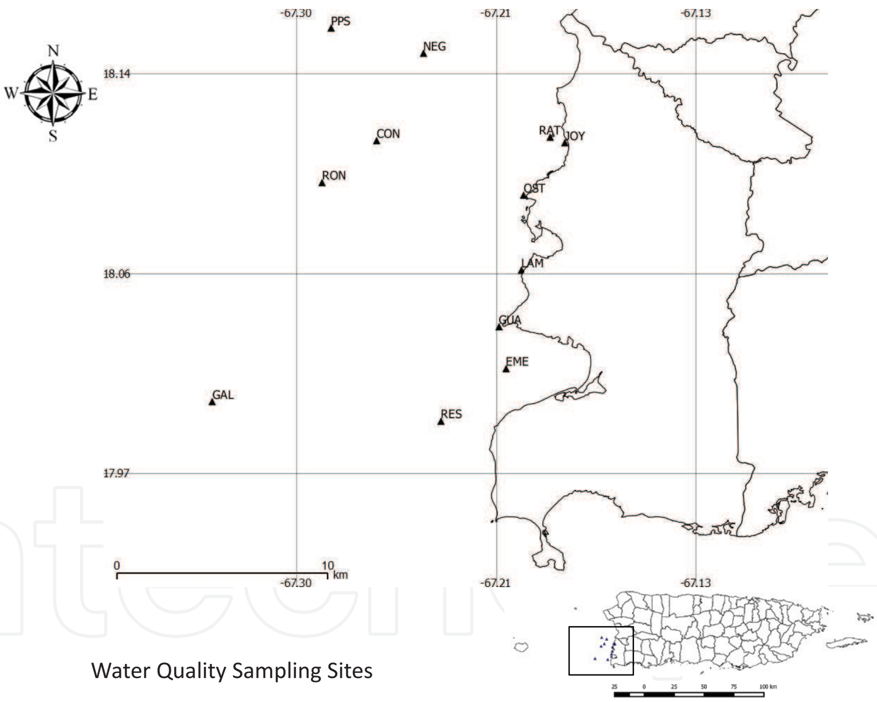


**Figure 2.** Locations of study sites through the southwestern Puerto Rico insular platform. These were divided into three geographic areas: inshore reefs (<4 km)—Cayo Ratones (RAT), Punta Ostiones (OST), Punta Lamela (LAM), Punta Guaniquilla (GUA), Bajo Enmedio (EME); mid-shelf reefs (4–8 km)—Arrecife Resuello (RES), Corona del Norte (CON), El Ron (RON); and outer-shelf reefs (8–20 km)—Escollo El Negro (NEG), Arrecife Papa San (PPS), Bajo Gallardo (GAL). Acronyms of protected areas: BEB = Bosque Estatal de Boquerón; CRNWR = Cabo Rojo National Wildlife Refuge; EMRNFB = Extensión Marina Reserva Natural Finca Belvedere; EXRNPG = Extensión Marina Reserva Natural Punta Guaniquilla; EMBEB = Extensión Marina Bosque Estatal Boquerón; RVSIAB = Refugio de Vida Silvestre y de Aves de Boquerón; RNAT = Reserva Natural Arrecifes Tourmaline; RNCR = Reserva Natural Cayo Ratones; RNFB = Reserva Natural Finca Belvedere; RNLJ = Reserva Natural Laguna Joyuda; RNPG = Reserva Natural Punta Guaniquilla. Gray-shaded areas in the left image represent coral reefs.

were located within Arrecife's Tourmaline Natural Reserve, which has a six-month seasonal fishing closure (December 1–May 31). Other studied reserve and nonreserve locations are open to fishing.

### 2.2. Sampling design

With the exception of inshore locations OST, LAM, GUA, and RAT, characterized only by shallow areas, each remaining locality was subdivided into three depth zones: depth 1 (<5 m), depth 2 (5–10 m), and depth 3 (10–20 m). Only depths 1 and 2 were studied in EME, and depth 3 and depth 4 (20–30 m) were studied in PPS. In each of these depths, from 5 to 15 random belt phototransects (10 × 1 m) were studied by taking 5 high-resolution, nonoverlapping, digital images of 1.0 × 0.7 m per transect at fixed intervals, obtaining a total of 25–75 images per depth zone from each location. A 48-point dot grid was digitally projected over each image and benthic components under each point were identified to the lowest taxon possible (e.g., Scleractinian corals, hydrocorals, octocorals, sponges, algal functional groups, cyanobacteria, and open substrate [sand, rubble, and pavement]). The relative number of points per category was counted and divided by the total number of points to obtain the percentage of coverage of the benthic components.

### 2.3. Coral Reef Resilience Index (CRRI)

A modification and expansion of McField and Kramer [60] and NEPA [63] was used to define CRRI's parameters. An average index score for each indicator listed in **Table 1** was calculated for each individual transect, depth zone, and location and compared to threshold value ranges listed in the table. CRRI rankings were similar to those defined by McField and Kramer [60], with a scale of 1–5 points as follows: 5 = very good, 4 = good, 3 = fair, 2 = poor, and 1 = critical. Four different indices were calculated: (1) Global Index = an average of all the parameters; (2) Coral Index = an average of all coral parameters; (3) Threatened Species Index = an average of all threatened coral parameters; and (4) Algal Index = an average of all algal parameters. Mean scores were calculated for all four indices, for each geographic zone and location and for each depth zone. The final mean value of each index is deemed as very good (4.2–5), good (3.4–4.2), fair (2.6–3.4), poor (1.8–2.6), and critical (1–1.8).

Fifteen indicators were selected to calculate the benthic index (**Table 1**). In the coral index, percentage of living tissue coverage, species richness, coral recruit density (diameter < 5 cm), and percentage of bleaching frequency were used. In the Threatened Species Index, based on the International Union for the Conservation of Nature (IUCN) Red List and on the U.S. Endangered Species Act listed coral species, the following species were used: Staghorn coral (*Acropora cervicornis*), Elkhorn coral (*A. palmata*), Columnar star columnar coral (*Orbicella annularis*), and Laminar star coral (*O. faveolata*). Of the seven threatened species in the Caribbean, these were the most common species throughout the study areas [62]. In the Algal Index, macroalgae, turf, crustose coralline algae (CCA), *Halimeda* spp., *Dictyota* spp., *Lobophora*

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| Indices | Very good(5) | Good(4) | Fair(3) | Poor(2) | Critical(1) |
|---|---|---|---|---|---|
| **Coral Index** | | | | | |
| % Coral cover | >40% | 20–39.9% | 10–19.9% | 5–9.9% | <5% |
| Species richness | >10 | 7–9.9 | 5–6.9 | 3–4.9 | <2.9 |
| Recruitment density (#/m$^2$) | >10 | 5–9.9 | 3–4.9 | 2–2.9 | <2 |
| % Bleaching | 0% | <2% | 2–9.9% | 10–50% | >50% |
| **Threatened Species Index** | | | | | |
| *Acropora cervicornis* | >20% | 10–19.9% | 5–9.9% | 2–4.9% | <2% |
| *Acropora palmata* | >20% | 10–19.9% | 5–9.9% | 2–4.9% | <2% |
| *Orbicella annularis* | >40% | 20–39.9% | 10–19.9% | 5–9.9% | <5% |
| *Orbicella faveolata* | >40% | 20–39.9% | 10–19.9% | 5–9.9% | <5% |
| **Algal Index** | | | | | |
| Macroalgae | <10% | 10–19.9% | 20–39.9% | 40–59.9% | >60% |
| Turf | <10% | 10–19.9% | 20–39.9% | 40–59.9% | >60% |
| Crustose coralline algae | >30% | 20–29.9% | 10–19.9% | 5–9.9% | <5% |
| *Halimeda* spp. | <5% | 5–9.9% | 10–19.9% | 20–29.9% | >30% |
| *Dictyota* spp. | <5% | 5–9.9% | 10–19.9% | 20–29.9% | >30% |
| *Lobophora variegata* | <5% | 5–9.9% | 10–19.9% | 20–29.9% | >30% |
| *Ramicrusta/Peyssonnelia* | <5% | 5–9.9% | 10–19.9% | 20–29.9% | >30% |

**Table 1.** Benthic community indicators, with their corresponding CRRI scores.

*variegata*, and red encrusting algae *Ramicrusta* spp./*Peyssonnelia* spp. (species that can overgrow living corals) were used.

### 2.4. Statistical testing

A three-way permutational analysis of variance (PERMANOVA) was used to test the null hypothesis of no significant difference in CRRI scores among geographic zones, locations, and depth zones [64]. Multivariate tests were carried out in statistical package.

PRIMER v7 + PERMANOVA 1.06 (PRIMER-e, Auckland, New Zealand). Scores were $\log_{10}$-transformed and Bay-Curtis similarity resemblance matrices were calculated for each individual index. Nonmetric multidimensional scaling (nMDS) was used to illustrate spatial pattern of mean scores of each index [65]. A 'linkage tree' of coral reef benthic community structure based on the BIOENV routine to environmental variables was also carried out to determine the influence of environmental variables on the spatial patterns of benthic community structure and thus on the CRRI.

## 3. Results

### 3.1. Water quality stress gradients

Water turbidity showed a highly significant decline with increasing distance from the shoreline ($r^2 = 0.7119$; $p = 0.0006$), suggesting a strong cross-shelf spatial gradient. Turbidity was significantly different among geographic zones ($p < 0.0001$) and among locations ($p < 0.0001$). The zone × location interactions were also significant ($p < 0.0001$). Higher mean values across inshore locations showed a range from 1.0 to 3.8 NTU (**Figure 3**). Mid-shelf locations averaged 0.9–1.0 NTU, and outer-shelf locations averaged 0.4–0.9 NTU. Turbidity patterns show often complex spatial and temporal variability across the western shelf due to complex circulation patterns.

There was also a highly significant ($r^2 = 0.4961$; $p = 0.0458$) nonlinear decline in ammonia ($NH_3^+$) and increasing distance from the shore (**Figure 4**), suggesting a similar strong cross-shelf spatial

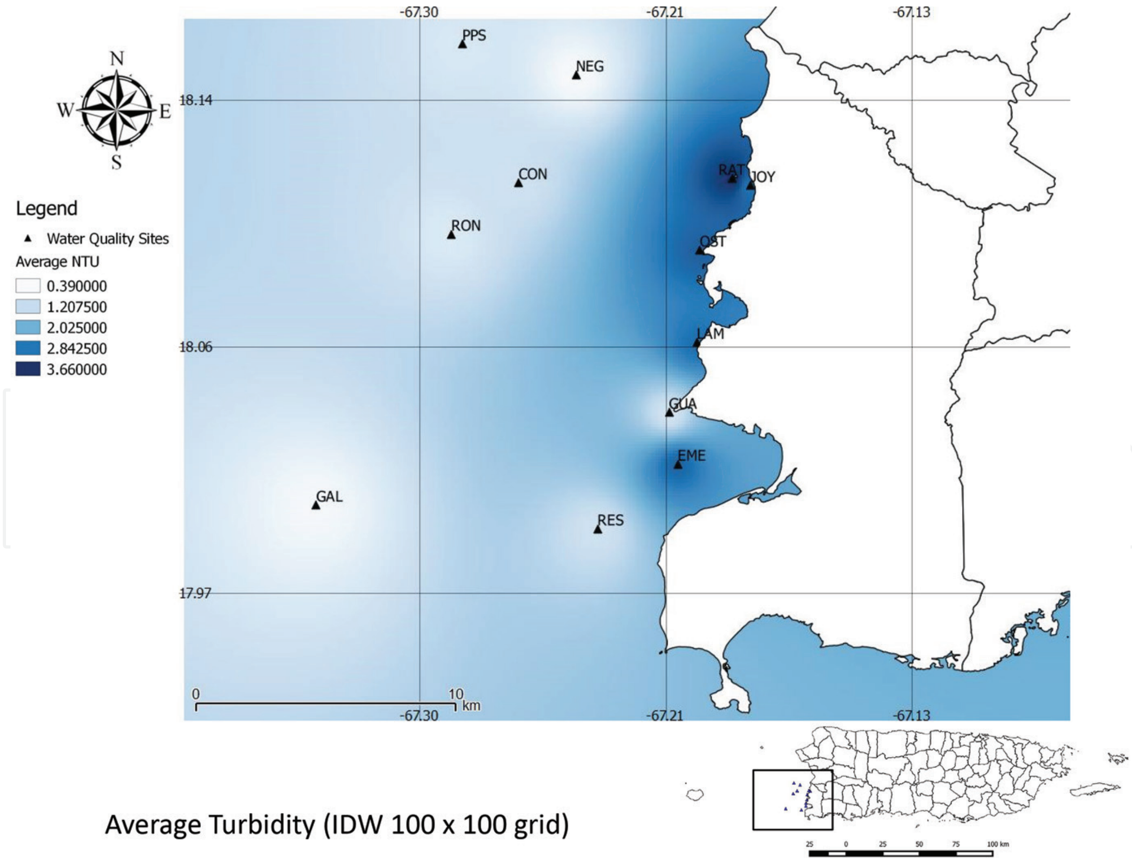


**Figure 3.** GIS-based inverse distance weighting (IDW) interpolation showing water turbidity spatial patterns. For location acronyms refer to **Figure 2**.

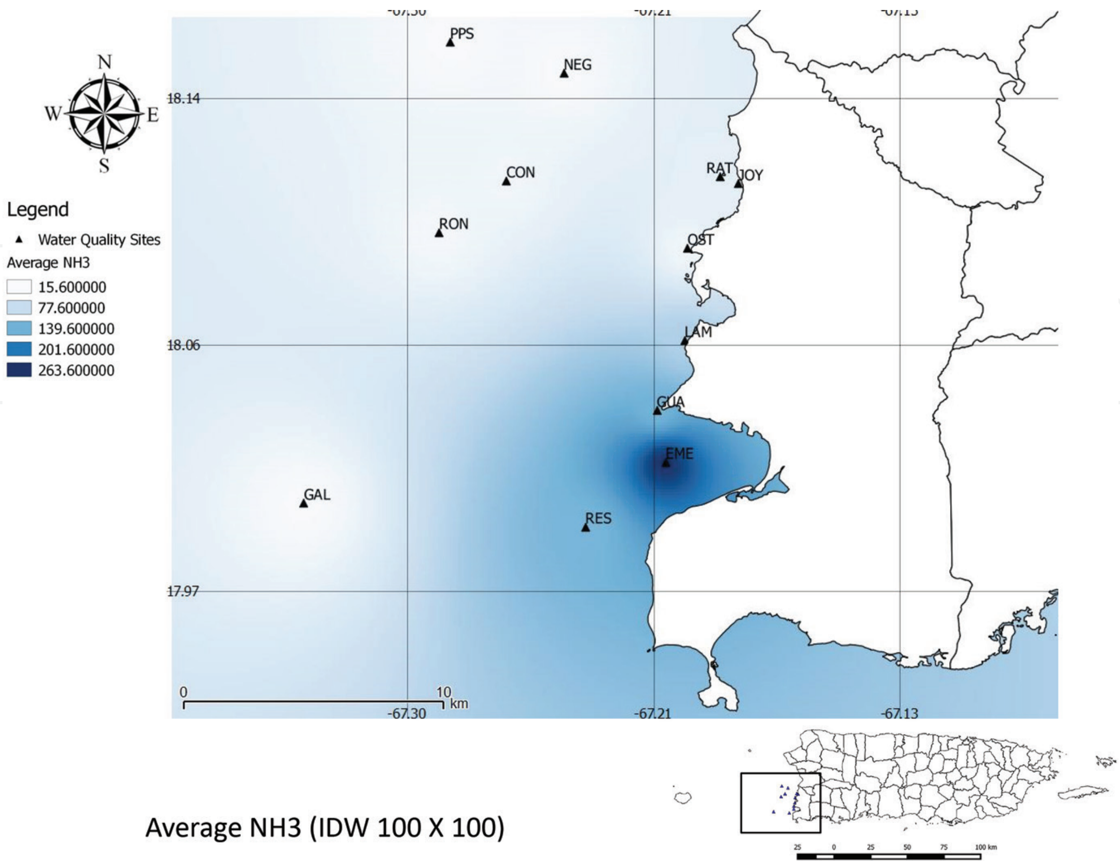


**Figure 4.** GIS-based inverse distance weighting (IDW) interpolation showing ammonia ($NH_3^+$) concentration spatial patterns. For site acronyms refer to **Figure 2**.

gradient. $NH_3^+$ was significantly different among geographic zones ($p < 0.0001$) and among locations ($p < 0.0001$). The geographic zone × location interaction was also significant ($p < 0.0001$). $NH_3^+$ concentrations showed large spatial variability, with inshore locations ranging from 25 to 264 μM. Mid-shelf locations ranged from 22 to 133 μM, and outer-shelf sites ranged from 15 to 16 μM. EME (264 μM), GUA (136 μM), and RES (133 μM), which are located just off Boquerón Bay and are known to receive recurrent raw sewage illegal discharges and poorly treated sewage effluents from a malfunctioning treatment facility from Boquerón Bay, showed the highest $NH_3^+$ concentrations. $NH_3^+$ concentration at nearby, sewage-polluted LAM, located just off Puerto Real, showed a concentration of 94 μM, which is also considered very high.

### 3.2. Global Coral Reef Resilience Index (CRRI)

A significant cross-shelf increase ($p < 0.0001$) was observed in the mean global CRRI score in coral reefs (**Figure 5a**, **Table 2**). Mean global CRRI across inshore sites was 2.83, with a range of 2.79–2.90 (**Table 3**). The average on the mid-shelf reefs was 3.04 with a range of 2.88–3.20. Meanwhile, the average reef at the outer shelf was 3.12, with a range of 3.00–3.26. The global CRRI spatial gradient was evident (**Figure 6**). Differences among geographic zones, locations, and depth zones were highly significant ($p < 0.0001$). All possible interaction combinations were also significant. However, cross-shelf mean values of global CRRI ranked all locations as “fair.”

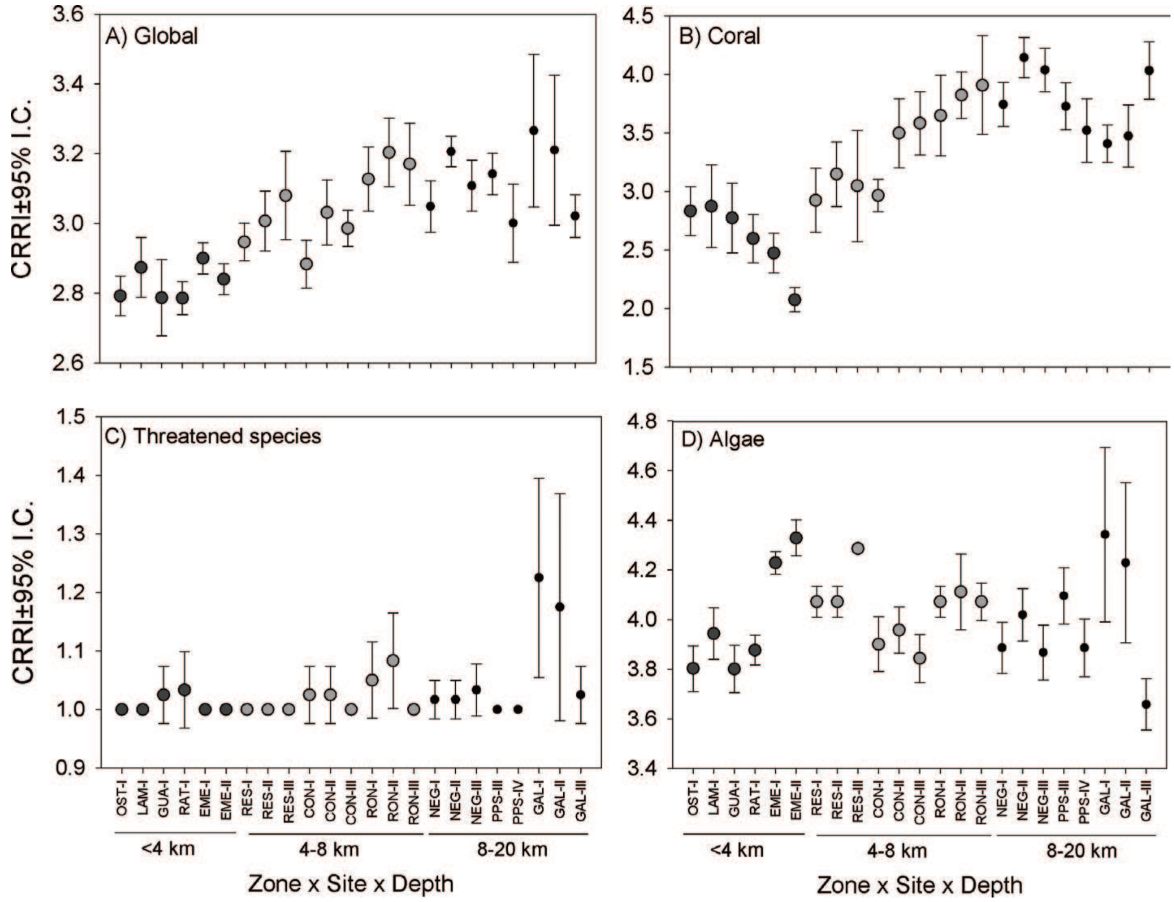


**Figure 5.** Coral Reef Resilience Index: (A) Global Index; (B) Coral Index; (C) Threatened Coral Species Index; and (D) Algal Index. Mean ± 95% confidence intervals. For site acronyms refer to **Figure 2**.

| Variable | d.f. | Global CRRI | Coral Index | Threatened Species Index | Algal Index |
|---|---|---|---|---|---|
| Geographic zone (Z) | 2254 | 41.85<0.0001 | 115.5<0.0001 | 2.980.0469 | 1.010.3651 |
| Location (L) | 10,246 | 10.96<0.0001 | 35.31<0.0001 | 4.290.0006 | 7.01<0.0001 |
| Depth (D) | 3253 | 9.73<0.0001 | 22.30<0.0001 | 1.530.1910 | 5.690.0014 |
| Z × L | 10,246 | 10.96<0.0001 | 35.31<0.0001 | 4.290.0009 | 7.01<0.0001 |
| Z × D | 8248 | 13.49<0.0001 | 36.53<0.0001 | 2.660.0124 | 4.75<0.0001 |
| L × D | 22,234 | 7.42<0.0001 | 19.97<0.0001 | 3.160.0003 | 7.00<0.0001 |
| Z × L × D | 22,234 | 7.42<0.0001 | 19.97<0.0001 | 3.160.0005 | 7.00<0.0001 |

**Table 2.** Summary of a three-way PERMANOVA on global CRRI. Pseudo-F value and statistical probability.

The nMDS analysis showed a spatial pattern confirming a significant cross-shelf gradient of global CRRI (stress = 0.01) (**Figure 7**). Three clustering patterns were observed. The first cluster was dominated by locations across the inshore geographic zone. The second cluster was a mixed group of some inshore and mid-shelf reefs. The third mixed group was composed of some mid-shelf and outer-shelf reefs. The location with the highest global CRRI value was GAL (depth I)

| Zone | Global CRRI | Coral Index | Threatened Species Index | Algal Index |
|---|---|---|---|---|
| Entire shelf | 3.02 (fair) | 3.32 (fair) | 1.03 (critical) | 4.01 (good) |
| Inshore | 2.83 (fair) | 2.60 (poor) | 1.01 (critical) | 4.00 (good) |
| Mid-shelf | 3.05 (fair) | 3.40 (fair) | 1.02 (critical) | 4.04 (good) |
| Outer shelf | 3.13 (fair) | 3.76 (good) | 1.06 (critical) | 4.00 (good) |

**Table 3.** Mean CRRI values across the western Puerto Rican shelf.

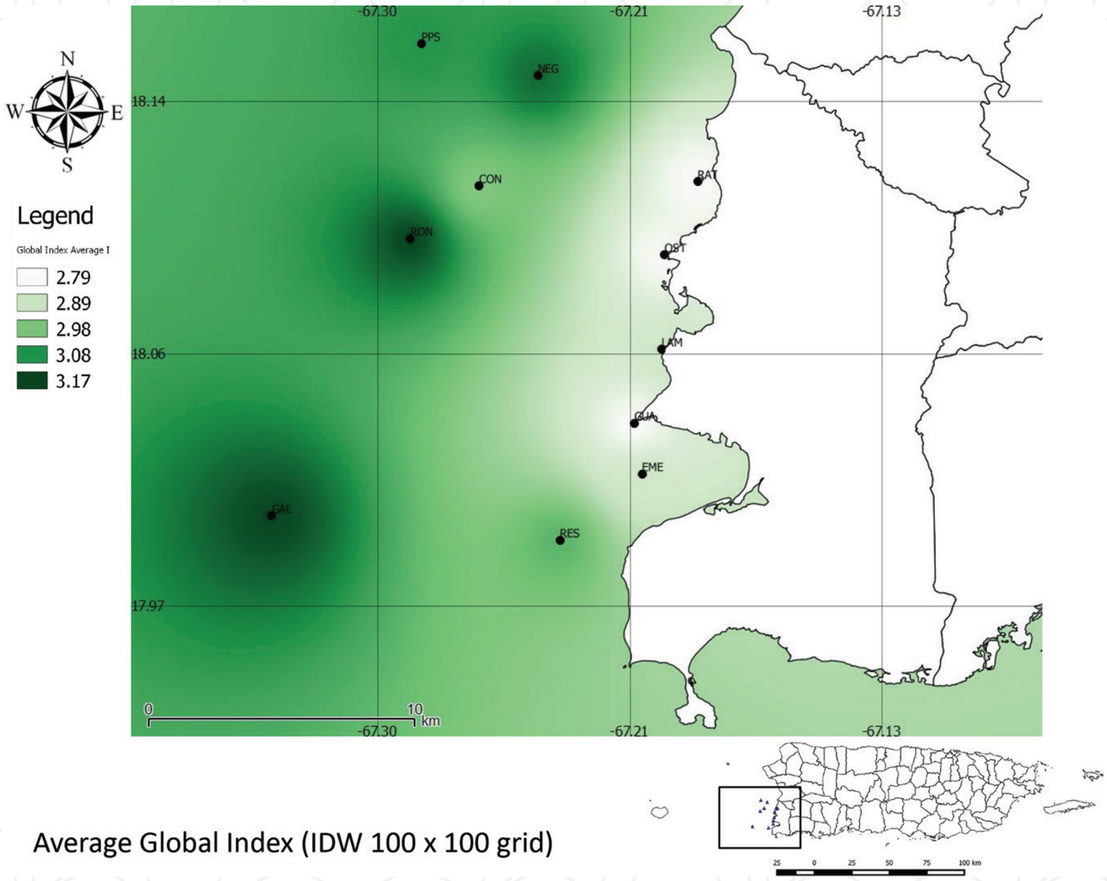


**Figure 6.** GIS-based inverse distance weighting (IDW) interpolation showing mean global CRRI spatial patterns. For site acronyms refer to **Figure 2**.

with 3.27. The locality with the lowest overall CRRI value was RAT (depth I) with 2.79. In general, depth zones II and III showed global CRRI values greater than those documented in zone I. Variation in depth was related to geographic patterns of variation.

### 3.3. Coral Index

A significant cross-shelf increase ($p < 0.0001$) was also observed in the mean Coral Index score in coral reefs (**Figure 5b**, **Table 2**). Mean Coral Index across inshore sites was 2.60, with a range of 2.07–2.87 (**Table 3**). On average, inshore coral reefs were classified as "poor," although three of them were classified as "fair." Mid-shelf reef Coral Index averaged 3.40, with a range

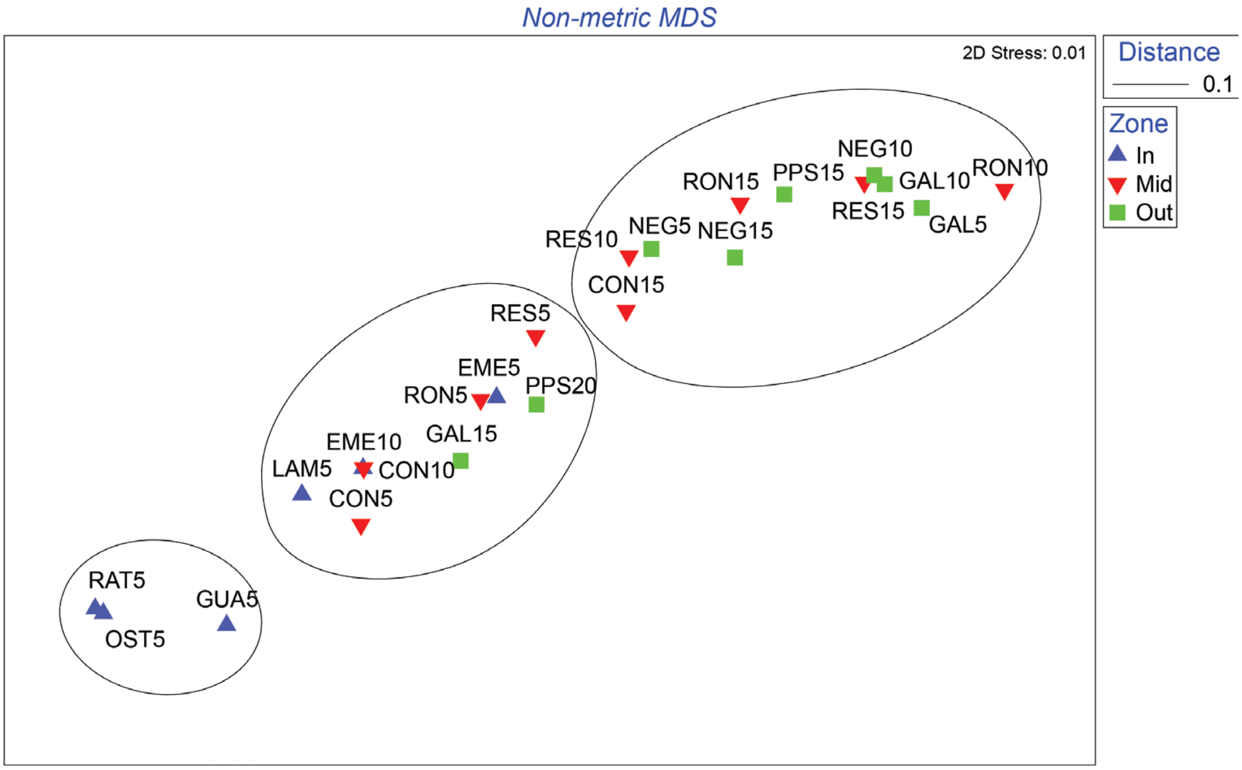


**Figure 7.** Nonmetric multidimensional scaling plot (nMDS) based on global CRRI scores across geographic zones × location × depth.

of 2.92–3.90. Of these, all depth areas of RES were classified as "fair," the flat area of CON was classified as "fair," but its deeper zones were classified as "good." RON reef was categorized as "good." Coral Index mean values averaged 3.76 across outer-shelf locations, ranging from 3.41 to 4.14, which classified reefs as "good." The Coral Index spatial gradient was evident (**Figure 8**). Differences among geographic zones, locations, and depth zones were highly significant ($p < 0.0001$). All possible interaction combinations were also significant.

The nMDS analysis showed a nearly similar spatial pattern confirming a significant cross-shelf gradient of the Coral Index (stress = 0.01) (**Figure 9**). Clustering patterns were nearly similar as those documented for global CRRI. The first cluster was dominated by locations across the inshore geographic zone. The second cluster was a mixed group of some inshore and mid-shelf reefs. The third mixed group was composed of some mid-shelf and outer-shelf reefs. The location with the highest Coral Index value was NEG (depth II) with 4.14. The locality with the lowest overall Coral Index value was EME (depth II) with 2.08. In general, depth zones II and III showed Coral Index values greater than those documented in zone I. Variation in depth was related to geographic patterns of variation.

### 3.4. Threatened Coral Index

A significant cross-shelf increase ($p = 0.0469$) was also observed in the mean Threatened Coral Index score in coral reefs (**Figure 5c**, **Table 2**). Mean Threatened Coral Index across inshore sites was 1.00, with a range of 1.00–1.03 (**Table 3**). On average, inshore coral reefs were classified as

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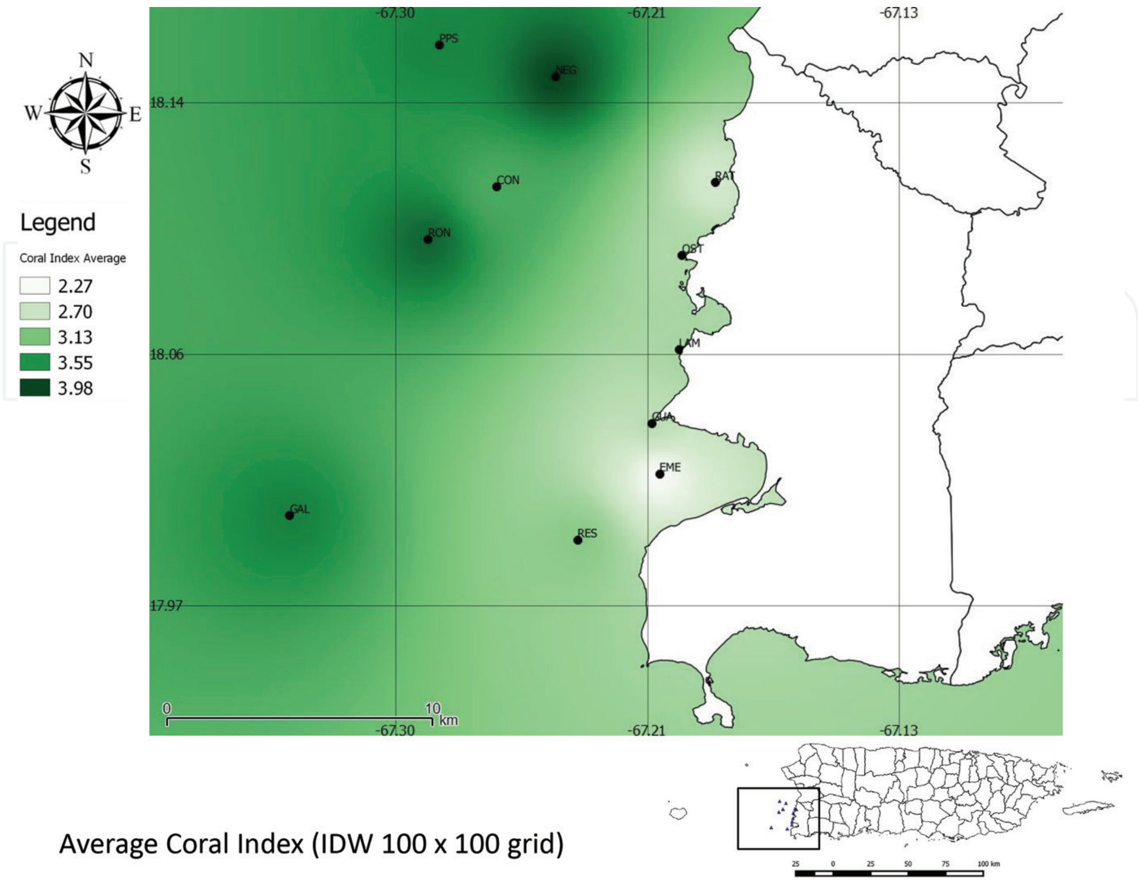


**Figure 8.** GIS-based inverse distance weighting (IDW) interpolation showing mean Coral Index spatial patterns. For site acronyms refer to **Figure 2**.

"critical." Mid-shelf reef Coral Index averaged 1.02, with a range of 1.00–1.08. Mid-shelf reefs were also classified as "critical." Threatened Coral Index mean values averaged 1.06 across outer-shelf locations, ranging from 1.00 to 1.22, which also classified outer-shelf reefs as "critical." However, the Threatened Coral Index spatial gradient was also evident (**Figure 10**). Differences among geographic zones ($p = 0.0469$) and locations ($p = 0.0006$) were significant, but not among depth zones ($p = 0.1910$). All possible interaction combinations were also significant.

The nMDS analysis confirmed a significant cross-shelf gradient of the Threatened Coral Index (stress <0.01) (**Figure 11**). The first cluster was dominated by two depth zones of outer-shelf GAL location. The second cluster was a mixed group of some inshore and mid-shelf reefs, which had sporadic colonies of threatened species. The third mixed group was composed of some inshore and mid-shelf reefs, which lacked threatened species. The location with the highest Threatened Coral Index value was GAL (depth I) with 1.23. Multiple locations shared the lowest overall Threatened Coral Index value, with 1.00.

### 3.5. Algal Index

A significant cross-shelf increase was observed in the mean Algal Index score among locations ($p < 0.0001$) and among depth zones ($p = 0.0014$), but not among geographic zones (**Figure 5d**,

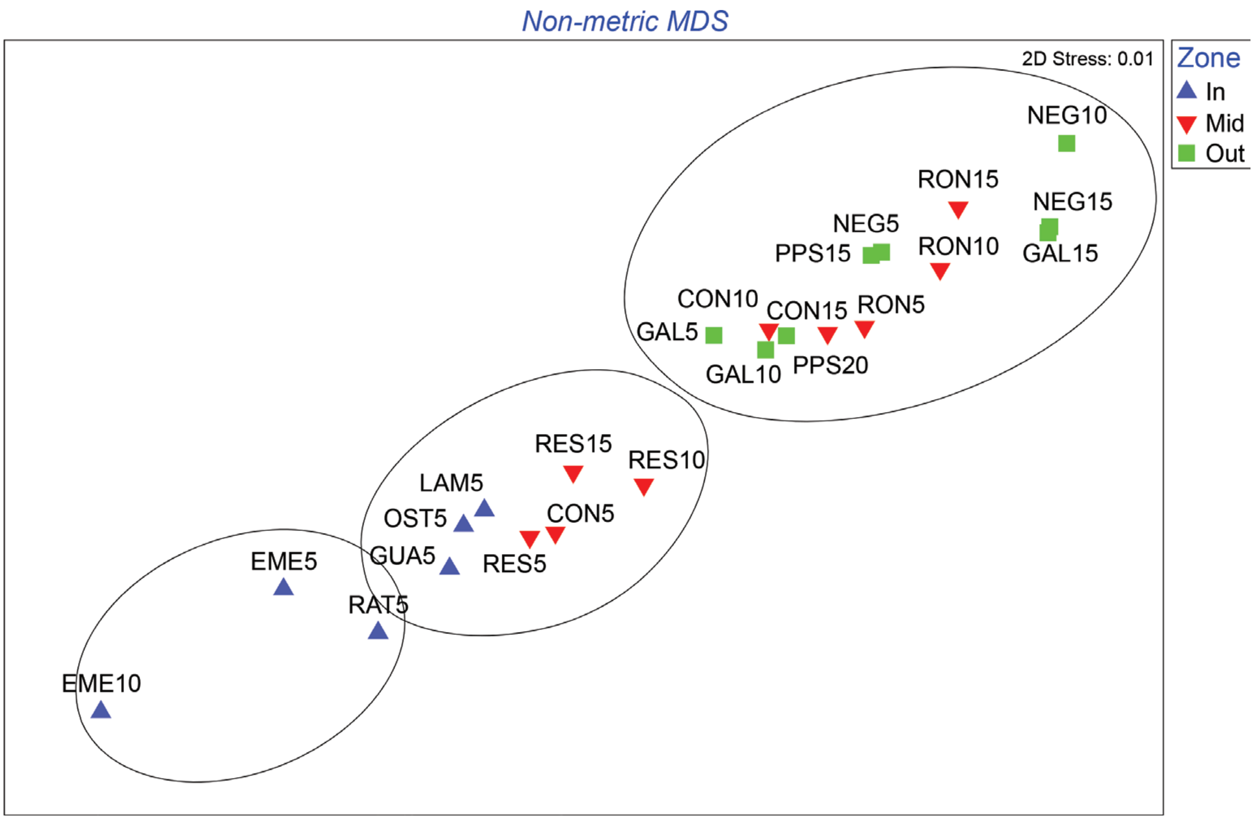


**Figure 9.** Nonmetric multidimensional scaling plot (nMDS) based on Coral Index scores across geographic zones × location × depth.

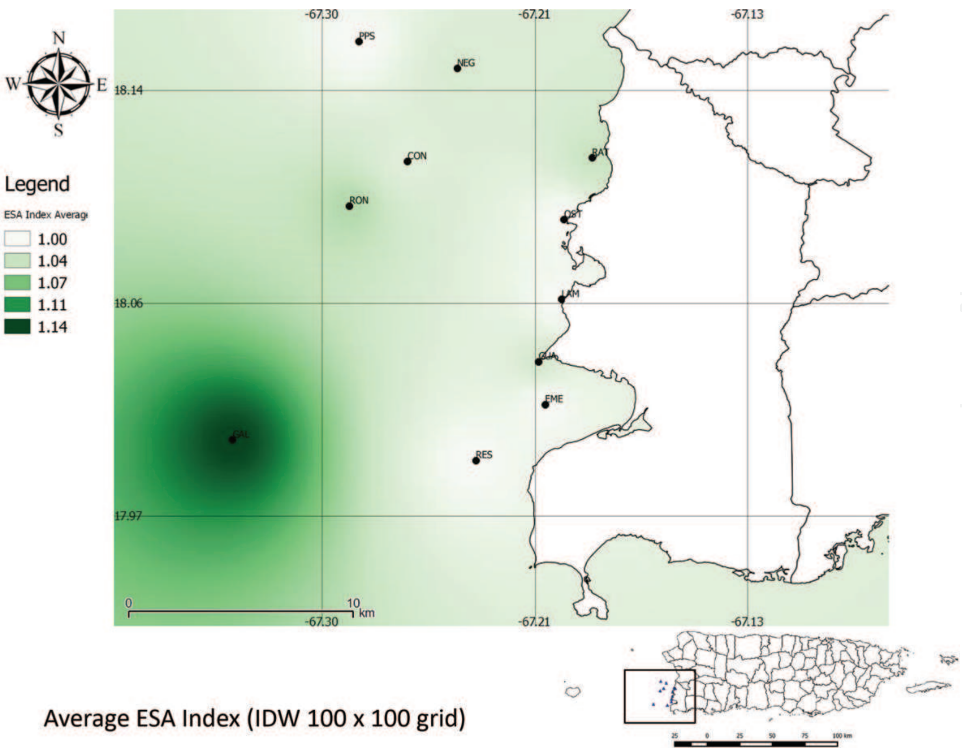


**Figure 10.** GIS-based inverse distance weighting (IDW) interpolation showing average Threatened Coral Index spatial patterns. For site acronyms refer to **Figure 2**.

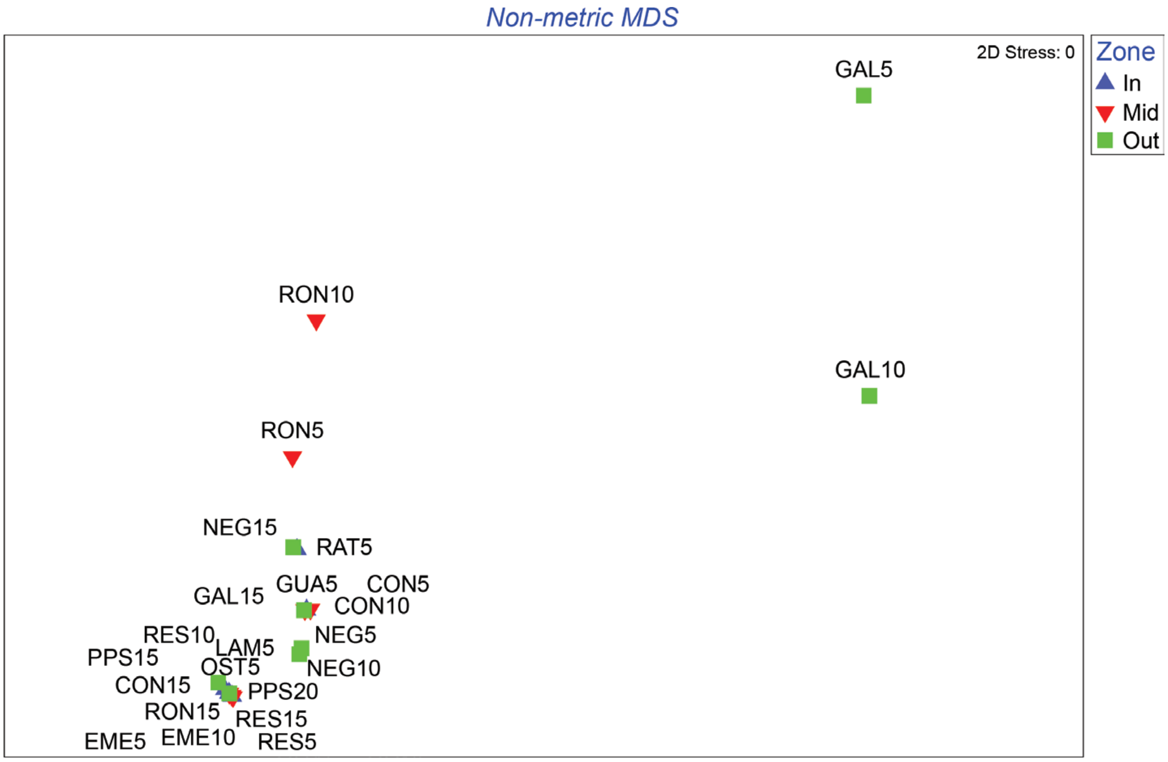


**Figure 11.** Nonmetric multidimensional scaling plot (nMDS) based on Threatened Coral Index scores across geographic zones × location × depth.

**Table 2**). All possible interaction combinations were also significant. Mean Algal Index across inshore sites was 4.00, with a range of 3.80 to 4.33 (**Table 3**). On average, inshore coral reefs were classified as "good." Mid-shelf reef Algal Index averaged 4.04, with a range of 3.84 to 4.11. Mid-shelf reefs were also classified as "good." Algal Index mean values averaged 4.00 across outer-shelf locations, ranging from 3.87 to 4.34, which also classified outer-shelf reefs as "good." The Algal Index spatial gradient was also evident (**Figure 12**).

The nMDS analysis confirmed a significant cross-shelf gradient of the Algal Index (stress = 0.01) (**Figure 13**). The first cluster was dominated by two depth zones of outer shelf GAL location. The second cluster was a mixed group of some inshore and mid-shelf reefs. The third mixed group was composed of some inshore and mid-shelf reefs. Spatial patterns of algal assemblages varied depending on the location and reef's trophic state, as well as on the cross-shelf complex water circulation pattern. The locality with the highest Algal Index value was GAL (depth I) with 4.34, and it was classified as "very good." The locality with a lower Algal Index was found on the same reef (GAL) but at depth III, with 3.66, with a category of "good."

### 3.6. Impacts of water quality stress gradient on CRRI

A 'linkage tree' of coral reef benthic community structure based on the BIOENV routine to environmental variables was carried out and a binary split on the basis of the best single environmental variable was thresholded to maximize the analysis of similitude (ANOSIM) R statistic for the two groups formed. This observed ANOSIM of R = 0.57 and B = 85.9%, which suggests that most of the observed variation can be explained by this solution (**Figure 14**). The

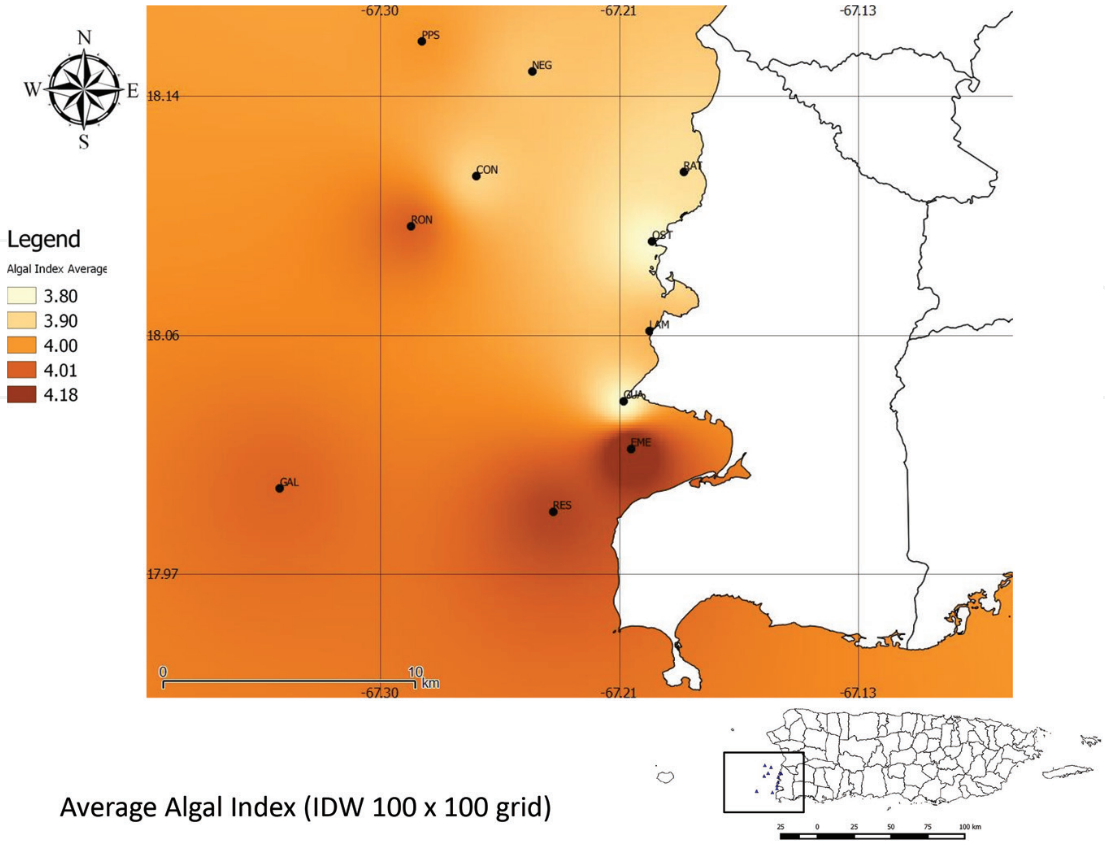


**Figure 12.** GIS-based inverse distance weighting (IDW) interpolation showing average Algal Index spatial patterns. For site acronyms refer to **Figure 2**.

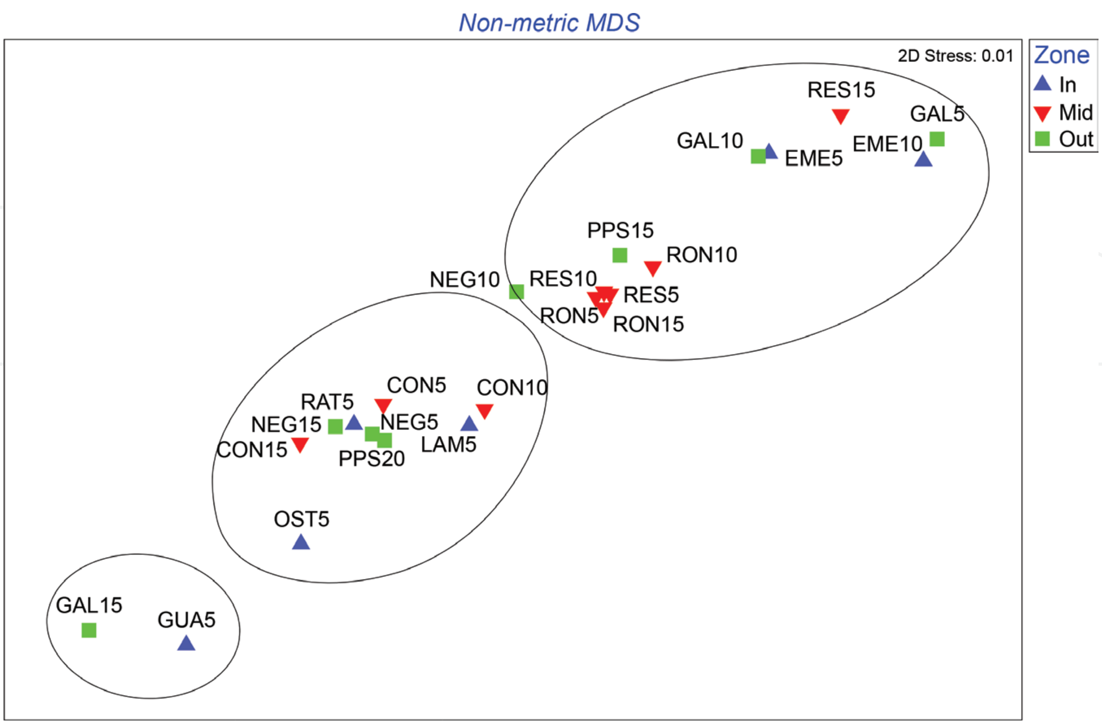


**Figure 13.** Nonmetric multidimensional scaling plot (nMDS) based on the Algal Index scores across geographic zones × location × depth.

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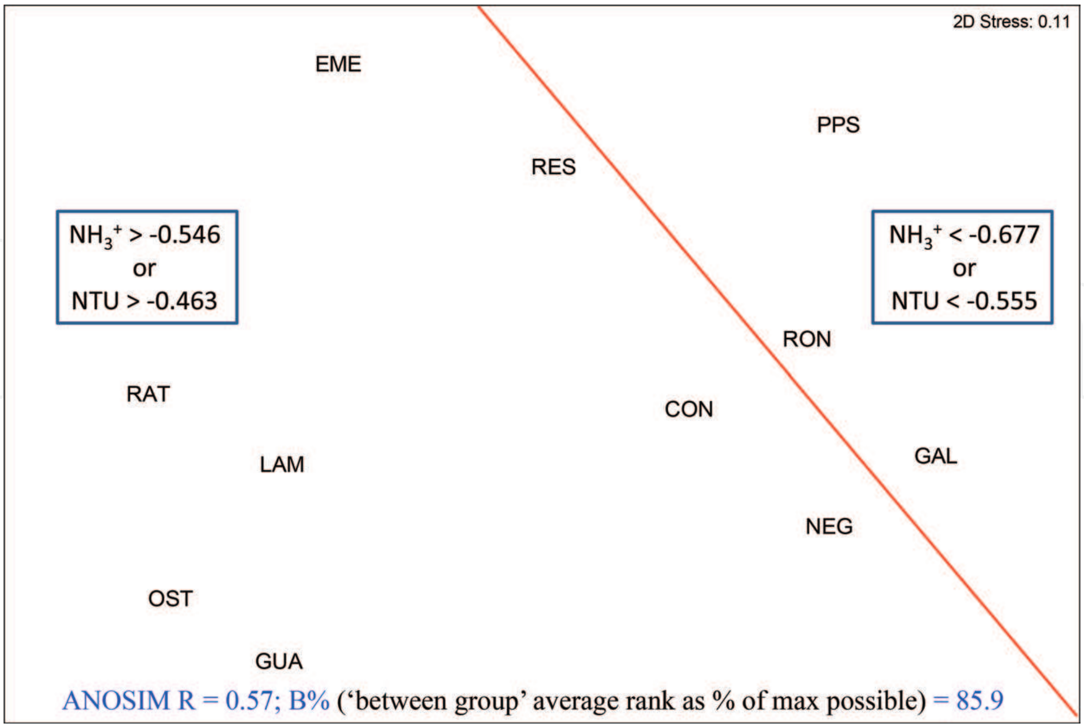


**Figure 14.** Multidimensional scaling (MDS) plot of the first stage in a 'linkage tree' of coral reef benthic community structure to environmental variables. Binary split on the basis of the best single environmental variable, thresholded to maximize the analysis of similitude (ANOSIM) R statistic for the two groups formed.

pattern was characterized by lower $NH_3^+$ to the right side of the plot ($NH_3^+$ Euclidean distance < −0.677) at outer-shelf sites PPS and GAL and at mid-shelf site RON and by higher values ($NH_3^+$ Euclidean distance > −0.546) to the left side of the plot across the remaining inshore and mid-shelf sites. Alternatively, the same split of sites was obtained by choosing lower turbidity to the right side of the plot (Turbidity Euclidean distance < −0.555) at outer-shelf sites PPS and GAL and at mid-shelf site RON and high turbidity (Turbidity Euclidean distance > −0.463) to the right side of the plot. ANOSIM R was the same whichever of the two variables was used as they gave the same split of biotic data. LINKTREE analysis showed that variation in $NH_3^+$ and turbidity explained most of the spatial variation observed in coral reef benthic community structure, therefore, in the CRRI spatial distribution.

## 4. Discussion

### 4.1. Spatial variation patterns of water quality conditions

This study showed important evidence of an LBSP gradient across the western Puerto Rico shelf and that chronic water quality decline has significantly affected the face of coral reef benthic communities, which was reflected on the mean CRRI scores. A snapshot view of LBSP showed that particularly turbidity and $NH_3^+$ concentrations increased along inshore locations. It is particularly concerning that EME reef site and to some extent GUA, LAM, and OST are being exposed to recurrent pulses of sewage effluents from malfunctioning sewage treatment facilities at Boquerón Bay and from multiple nonpoint sewage sources. Elevated $NH_3^+$ concentrations at EME suggest that tidal cycles may continuously expose coral reefs adjacent to Boquerón Bay to recurrent sewage pollution and eutrophication impacts. Turbidity was also higher at inshore locations such as JOY, RAT, and OST. Their proximity to Joyuda Bay and Puerto Real Bay continuously expose these sampling sites to recurrent polluted, turbid runoff pulses. A particular concern was degraded water quality pulses even across outer-shelf sites, where $NH_3^+$ concentrations exceeded recommended levels for healthy coral reefs. Pollution across outer-shelf sites may come from other significant sources such as the Río Guanajibo, Río Yagüez, and the Mayagüez Bay.

Documented turbidity spatial patterns were highly consistent with findings of cross-shelf scale pollution patterns documented by Bonkosky et al. [66]. Turbidity patterns were also consistent with previous unpublished observations from year 2000 (Hernández-Delgado, unpub. Data). Therefore, it is reasonable to assume that observed spatial patterns of water quality conditions in this study were highly consistent with chronic large-scale degradation at least over the last two decades and that the observed LBSP stress gradient in the form of chronic turbidity and eutrophication, mostly associated to sewage pollution, represent a nearly permanent state. Observed $NH_3^+$ concentrations in this study also reflected an evident cross-shelf gradient with increasing distance from known sewage pollution sources. Lapointe and Clark [67] suggested that $NH_3^+$ concentrations for coral reefs should not exceed 0.1 μM and that any concentration above 24 μM were deemed as too high. Our findings are highly concerning as observed $NH_3^+$ concentrations were from 150 to 2600 times higher than recommended limits for healthy coral reefs. Eight out the twelve sampled sites (75%) showed $NH_3^+$ concentrations exceeding dangerous concentrations for coral reefs as much as 10.8 times.

Regression analyses have previously shown that several water quality indicator parameters reflected significant gradients with increasing distance from LBSP [62]. These authors found a significant relationship among turbidity, phosphate ($PO_4$), chlorophyll-a, and dissolved oxygen concentration, implying that increasing chronic water quality degradation can significantly affect multiple parameters, adversely impacting coral reefs. Although this study just provided a snapshot view of water quality across the western Puerto Rico shelf, results were concerning as critical water quality parameters resulted significantly higher than recommended limits for sustaining coral reef health. These results suggest that human-driven LBSP across the western Puerto Rico shelf is highly significant; it is a large-scale, chronic phenomenon and deserves full long-term monitoring across large spatial and temporal scales. It also suggests the need to rapidly implement best management practices (BMPs) to reduce LBSP impacts across the shelf.

### 4.2. Spatial variation patterns of the benthic CRRI

The observed spatial pattern in CRRI values was significantly influenced by an LBSP stress gradient across the entire western Puerto Rican shelf. Overall, the global CRRI averaged 3.02 ("fair") across the entire shelf, the Coral Index averaged 3.32 ("fair"), the Threatened Species Index 1.03 ("critical"), and the Algal Index 4.01 ("good"). Based on the spatial distribution of the global CRRI mean values, coral reefs across the western Puerto Rican shelf can be classified as "fair." But based on the spatial patterns of the Coral Index, reefs showed a more consistent cross-shelf gradient of conditions, ranging from "poor" to "fair" across inshore locations, from "fair" to "good" along mid-shelf locations, and "good" across outer-shelf locations. There was also an evident depth-related gradient, with deeper reef zones showing higher CRRI and higher Coral Index values, in comparison to shallower zones. Based on the global CRRI, 100% of the surveyed reefs in this study were classified as "fair." But based on the Coral Index, 45% of the surveyed reefs across the western Puerto Rican shelf were classified as "good," 36% as "fair," and 19% as "poor," reflecting a strong inshore-offshore environmental stress gradient. This implies that a potential combination of human and natural factors can be influencing reef condition and CRRI values in Puerto Rico. The cross-shelf spatial gradient can be the result of chronic water quality degradation along inshore zones, which are located adjacent to known pollution sources. But the bathymetric gradient in reef conditions and CRRI values can be the potential combined result of variation in water turbidity, and the combined long-term impacts of postbleaching coral mortality, coral disease outbreaks, and impacts from hurricanes and north-western winter swells.

In comparison, previous studies using a nearly similar Coral Reef Health Index in Jamaica showed a mean value of 2.1 ("poor"), with ranges from 1.6 to 2.6 [63]. A similar study from 326 locations across four countries of the Mesoamerican Barrier Reef System (Belize, Guatemala, Honduras, and México) showed that 47% of the reefs were in "poor" condition in 2008, 6% were "critical," 41% "fair," 6% "good," and none were classified as "very good" [57]. A survey of 130 locations across the same region in 2010 showed that 40% of the reefs were in "poor" condition, 30% were "critical," 21% "fair," 8% "good," and only 1% "very good" [57]. A similar study from 193 locations across the same region in 2012 showed that 40% of the reefs were in "poor" condition, 24% were "critical," 25% "fair," 9% "good," and only 2% "very good" [58]. A similar study from 149 locations across the same region in 2015 showed that 40% of the reefs were still in "poor" condition, 17% were "critical," 34% "fair," 8% "good," and only 1% "very good" [59]. From this comparison, it is evident that multiple reef locations across the wider Caribbean region are significantly degraded by a multiplicity of factors, including a combination of overfishing [19, 21, 68], LBSP [7], and climate change [11]. Many of these locations are not showing signs of recovery [16, 17, 68].

Findings in this study of a strong cross-shelf stress gradient on coral reefs is also consistent with the literature that suggests significant impacts of LBSP [69], eutrophication [70, 71], sewage pollution [72], turbidity [73, 74], sedimentation [75–77], and bioerosion [78] on coral reefs adjacent to sources of stress.

### 4.3. Implications for coral reef conservation

Coral reef benthic assemblages in this study were showing signs of a cross-shelf environmental stress (e.g., turbidity, sewage pollution, eutrophication, sedimentation, and sediment bedload), therefore potentially compromising coral reefs' long-term reef accretion sustainability and ecosystem resilience. Coral reefs across the southwestern shelf of Puerto Rico have shown evidence of significant environmental degradation over the last four decades. Loya [79] and Goenaga and Cintrón [80] documented signs of degradation across inshore and mid-shelf reefs from chronic sedimentation. Many of these have suffered damage over time due to high terrigenous sediment loads [81, 82] and massive coral bleaching [83]. Schärer et al. (2010). High percent cover of threatened Elkhorn coral, *Acropora palmata*, were documented across offshore western mid-shelf reefs, but populations were largely declining in reefs adjacent to the coast due to water quality degradation [72]. Other studies have shown further reef degradation associated to LBSP, including the combination of sedimentation and turbidity [84, 85] and sewage and eutrophication [66, 72, 86]. Declining environmental conditions across the shelf have resulted in declining coral growth rates [81] and in significant declines of *A. palmata* populations across inshore reefs adjacent to areas impacted by LBSP [72, 84, 87–90]. Chronic decline in water quality could also have significant negative impacts on fish assemblages as several fish taxa can be sensitive to environmental degradation [91].

Findings in this study imply potential LBSP impacts across very large temporal and spatial scales, with very wide and persistent implications on coral reef benthic communities and on reef-associated fauna. LBSP impacts (i.e., sewage pollution from human and animal sources) were documented across the entire southwestern shelf in Puerto Rico, even in waters complying with existing microbiological quality standards [66]. This points out at the increasing spatial scale of chronic LBSP impacts across multiple coral reef systems and at the potentially increasing turnover rates of reef communities. The lack of adequate controls of LBSP across the region constitutes one of the most significant concerns regarding the conservation and recovery of declining coral reef ecosystems.

Efforts are being currently developed to implement erosion and sedimentation controls across watershed scales in southwestern Puerto Rico. But so far, these efforts have completely missed a long-term ecological monitoring component to determine if current land-based efforts have had any meaningful impacts on improving adjacent coral reef ecosystems. Therefore, the use of rapid assessment approaches, such as the one implemented in this study, could provide a meaningful approach to address the spatial patterns of coral reef conditions, understand its potential causes of stress, and identify alternative strategies to implement BMPs to reduce stressors.

### 4.4. Management recommendations for decision-making

A summary of management recommendations for decision-making has been included in **Table 4**. These are based on the CRRI score rankings. Suggested actions were subdivided by sector following the suggestions of HRI [56] into government, NGOs, private sector, and the academia. Recommendations included a combination of broad and targeted management actions aimed at improving governance by regulatory agencies, including improving enforcement capacity of water quality regulations and land use plan and fostering the implementation of BMPs of erosion control. They are also aimed at supporting NGOs and academic research to strengthen ecosystem-based management of coral reefs and other coastal resources. The government should also provide economic incentives for conservation and sustainable business, implement a green tax system to support these initiatives, and establish a functional network of no-take marine protected areas (MPAs).

Recommendations are also aimed to empower base communities to undertake management actions and engage into citizen science programs, including coral farming and reef rehabilitation through community-based NGO efforts. Also, base communities should strengthen their advocacy for coral reef conservation and fully support government initiatives, which promote community-based participation in management. The private sector should also become more active in supporting government efforts to manage MPAs, as well supporting coral farming and reef restoration efforts led by government, NGOs, or other sectors. The academia needs also to develop management-oriented research aimed at responding to multiple questions by natural resource and MPA managers. Applied research should also aim to understand the long-term dynamics of change of novel coral reef ecosystems. Multidisciplinary research should also be implemented to address the impacts of potential sources of stress on coral reefs. Communications and outreach need also to be improved between the academia and other sectors.

Based on the observed global CRRI and on the Coral Index scores in this study, the government should focus their efforts on implementing many of the above-mentioned suggestions, but in particular, strengthening the implementation of BMPs for erosion and runoff control, and support the ecological restoration of depleted coral reefs. NGOs should also strengthen community-based coral farming and reef restoration efforts. The private sector should also implement/support "adopt a reef" programs to promote reef conservation and restoration, and/or fully support NGO efforts. The academia should also strengthen long-term ecological monitoring programs to address sources of stress and should engage in research to understand the dynamics of emergent, novel coral reef ecosystems.

Nevertheless, the successful implementation of coral reef conservation will largely depend on the effective implementation of a coastal zone management plan, in the successful networking and effective communication among multiple stakeholders, in the implementation of effective communication among and in translating scientific information to managers, decision-makers, government leaders, and base communities, and in building trust and transparency among different sectors of society. It would also be critical to reduce pollution sources across watersheds (e.g., raw sewage discharges, agricultural, livestock, urban, and industrial runoff) through the implementation of sustainable BMPs and strict enforcement of existing regulations. Effective enforcement of fishery regulations and improved no-take MPA governance are also fundamental for achieving sustainable coral reef resilience. Further, there is a need to comply with internationally recommended protection of 20% of territorial sea as no-take MPAs. There are Caribbean islands that comply with that recommended goal, such as the U.S. Virgin Islands, where 15% of the area within their MPA boundaries had no-take regulations, in contrast to Puerto Rico, which only had 3% [92].

It would also be critical to implement sustainable development practices, particularly for small tropical island nations [88], including establishing setbacks from vulnerable areas along the shoreline and measures to protect local community livelihoods. A climate change adaptation program must also be implemented focused on the sustainable adaptability of coupled social-ecological systems, on the sustainability of the ecosystem services provided by the first line of defense against storm swells (e.g., coral reefs and mangroves) and on fishery sustainable adaptability [93]. The implementation of alternative livelihood programs for displaced fishers and an improved effectiveness in the management of no-take MPAs through consistent enforcement, sustainable funding, and technical capacity building is also paramount.

| Category | Sectors | | | |
|---|---|---|---|---|
| | **Government** | **NGOs** | **Private sector** | **Academic researchers** |
| Very good | Provide economic incentives for conservation and sustainable businessDesignate no-take MPAs to maintain resilient reef fish assemblagesFully support citizen science programsFully support long-term ecological monitoring led by NGOs and academiaEnforce existing water quality regulations | Support efforts to fully protect more reefs (MPAs)Increase public participation in managementDevelop management-oriented citizen science programs | Sustain local MPAs through financial, staff, or technical assistanceCollaborate and support government, academic, and NGO efforts for reef conservation and restorationImprove the implementation of BMPs, sustainable codes of conduct, and other strategies to reduce environmental impacts | Engage in research to respond questions by natural resource and MPA managersDevelop long-term ecological monitoring programs to address ecological change and climate change impactsPromote integration of citizen science programsEstablish communication and outreach programs with other sectors |
| Good | As in "very good" +Implement coral farming and reef restoration to maintain healthy coral populationsImplement a green tax system to support coral reef conservation and restoration initiative | As in "very good" +Implement community-based coral farming and reef restoration | As in "very good" +Promote partnerships with other sectors to support coral farming and reef restoration | As in "very good" +Promote partnerships with other sectors to support coral farming and reef restorationDevelop multidisciplinary research integrating social sciences and economy |
| Fair | As in "good" +Implement BMPs for erosion and runoff controlRestore depleted coral reef | As in "good" +Strengthen community-based coral farming and reef restoration | As in "good" +Implement/support "adopt a reef" programs to promote reef conservation and restoration | As in "good" +Strengthen long-term ecological monitoring programs to address sources of stress |
| Poor | As in "fair" +Strengthen the implementation of the coastal zone management plan and the land use planAggressive implementation of BMPs for erosion and runoff controlStrengthen enforcement of fisheries regulations to enhance herbivorous fish populationsImprove land use, management of soil erosion, wastewater, and urban runoffImplement local moratoriums on coastal development projects | As in "fair" +Strengthen community-based advocacy in coral reef conservationStrengthen community-based coral farming and reef restoration | As in "fair" +Strengthen partnerships and support of coral reef management efforts by governmentStrengthen partnerships and support of coral farming and reef restoration | As in "fair" +Strengthen collaborations and communication with natural resource and MPA managersConduct management-oriented research on novel reef ecosystemsAssist government and other sectors in developing or strengthening management plans |

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| Category | Sectors | | | |
|---|---|---|---|---|
| | Government | NGOs | Private sector | Academic researchers |
| Critical | As in "poor" +Establish emergency measures to reduce environmental stressors to reefsEstablish priority mechanisms to implement BMPs to reduce sediment delivery to coastal waters and to improve efficiency of wastewater and urban runoff management | As in "poor" +Promote effective enforcement of fishery regulations to enhance herbivorous fish populationsImplement community-based reef restoration | As in "poor" +Strengthen partnerships and fully support efforts led by government, NGOs, and the academia for coping critical declining coral reefs | As in "poor" +Strengthen multidisciplinary approaches to reef management to understand the role of human uses of reef ecosystems |

**Table 4.** Summary of recommended management actions.

Government agencies also need to establish effective partnerships with the academia, NGOs, and the private sector to promote applied research aimed at responding to management-oriented research questions regarding emergent novel coral reef ecosystems, which are characterized by altered benthic and fish assemblages as a result of multiple human impacts. Also, in a moment of complex and profound socioeconomic crisis, it is pivotal that governments need to promote and adopt sustainable consumption guidelines for marine resources; protect vulnerable coastal habitats, watersheds, and water sources; and secure food security and sovereignty [93]. Local governments should establish effective mechanisms, such as green taxes, to enhance available funding to support MPA management, coral farming, reef rehabilitation, and sustainable natural resource-based recreation. The private sector should contribute significantly to MPA and coral reef conservation and restoration through financial assistance and through supporting human and technical resources. Moreover, there is a critical need to reduce impacts by massive tourism activities [88], to reduce carbon emissions [94], and to adopt and expand a reward system for carbon sequestration, with the reduction of hydrocarbon dependency [56]. Approximately 85% of the energy produced in Puerto Rico is derived from hydrocarbon burning. There is a need to promote the use of alternative renewable energy sources.

### 4.5. Other potential applications of the modified CRRI

Multiple coral reef health indices have been successfully implemented across the globe to address a multiplicity of management-oriented questions. Some of them are very specific, while others can be applied to a variety of questions. The proposed CRRI is a very useful method to address coral reef conditions under a variety of scenarios. With the proper sampling design, the method can provide rapid, robust data to address spatial and temporal variability in coral reef conditions across multiple environmental conditions and across a variety of reef morphotypes and depth zones. It can also be implemented across leeward (protected) habitats, as well as across windward (exposed) sites. The CRRI can be used to address the long-term environmental impacts of any coastal development project, such as dredging, the construction of seawalls, marinas, beach renourishment, and other activities. With the proper sampling design, it can even be used following a before-after-control-impact (BACI) approach to simultaneously address multiple research questions. The proposed CRRI can also be implemented to address impacts by acute factors such as vessel groundings. In addition, it can address impacts of large-scale phenomena such as hurricanes, winter swells, coral mortality events, and massive bleaching. The CRRI can even be applied during assessments of the effectiveness of coral outplanting and reef restoration.

With minimal training, the CRRI can be fully adapted and implemented through a combination of academic, government, or community-based NGO and private-led citizen science programs. It can further be easily combined with other standard long-term monitoring efforts (e.g., Atlantic and Gulf Rapid Reef Assessment [AGRRA]). Therefore, its implementation can become a paramount tool to facilitate the interpretation of large data sets by the scientific community, politicians, government decision-makers, natural resource managers, economists, private stakeholders, base communities, fishermen, and other interested sectors. This element of cross-participation, integration, and understanding of science is fundamental for helping planning and decision-making processes.

## 5. Conclusions

Coral reefs across the western Puerto Rican platform are showing signs of environmental stress. This was reflected on a cross-shelf spatial gradient of water turbidity and $NH_3^+$ that is affecting coral reef ecosystems across the entire shelf. CRRI mean values reflected this trend and pointed out at a gradient of reef conditions from inshore, highly degraded locations, to mid-shelf moderately degraded reefs, to less degraded outer-shelf locations. This suggests the need to implement a suite of management strategies by multiple societal sectors, from government, to NGOs, the private sector, and the academia. When coupled with a long-term permanent monitoring program or any reef rapid assessment method, the proposed CRRI can become a useful tool for all sectors, in particular for natural resource and MPA managers, and for community-based, NGO-led citizen science programs in support of government management efforts and of academic research. The successful implementation of the CRRI would provide the basic framework for wide participation of stakeholder networks, which would provide baseline information for improving coral reef management. However, successful and effective coral reef conservation can be achieved only if such efforts are multidisciplinary and are broadly participatory (fair and meaningful engagement of multiple sectors) and if science is translated into easy-to-understand information for all sectors of society, including decision-makers. A key benefit of the proposed CRRI method is that, with proper training, it can be implemented by any members of any sector and that complex quantitative information generated can be rapidly translated into easy-to-interpret formats. This is critical for the timely implementation of adaptive management actions, particularly in the context of rapidly shifting ecosystems by climate change–related impacts and by other ecological surprises.

Coastal ecosystem resilience and sustainability are fundamental goals for many small island nations. The implementation of long-term ecological monitoring programs is important to address management effectiveness. However, it could be difficult for many small islands and developing countries to implement such programs due to economic constraints and/or lack of trained personnel or appropriate resources. Therefore, easy-to-implement, economic, reliable, rapid assessment methods such as the CRRI can become valuable tools for achieving such goals, particularly in a time of socioeconomic crisis and accelerating climate change.

Nevertheless, Sammarco et al. [95] found that a key problem regarding coral reef assessment and monitoring strategies was that differences in objectives can create communication and information gaps. These may even prevent direct comparisons among studies. There is a need to improve communications among government agencies, managers, academia, and groups engaged in reef assessment and monitoring activities and to promote community-based participation through fully supported citizen science programs. Only improved science and communication will lead to improved decision-making on both local and Caribbean-wide regional scales [96]. It is also important to understand the ultimate requirements of local, state, and national governments and understand their staff and funding limitations and management needs. These will help identify clear management questions and goals and design hypothesis-driven research, which will ultimately determine which specific indicators would be required. As a final thought, given the continuously declining conditions of multiple coral reefs around the Caribbean region, promoting community-based efforts of coral farming and reef restoration, coupled with continuous monitoring, must become a top priority. There are important published success stories of community-based coral reef restoration in Puerto Rico (e.g., [97, 98]). The take-home message is that planning and selection of bioindicators for coral reef assessment and monitoring need to start from the end in mind in order to achieve the common ultimate goal of coral reef conservation and the sustainability of ecosystem productivity, resilience, functions, benefits, and services. This will require strengthening networking among different stakeholders and promoting stronger community-based participation in planning, decision-making, and management-oriented science.

## Acknowledgements

This study was possible thanks to funding provided by NGOs Protectores de Cuencas, Inc. and Ridge to Reefs, Inc. to Sociedad Ambiente Marino under a Coral Reef Conservation grant from the National Fish and Wildlife Foundation (NFWF). Partial support was also provided by the National Science Foundation (HRD #0734826) through the Center for Applied Tropical Ecology and Conservation (CATEC) and the University of Puerto Rico's Vice-Presidency of Research and Technology to E.A. Hernández-Delgado. Our appreciation goes to the logistical field support provided by the crew of M/V *Tourmarine* and Capt. Elick Hernández. This publication is a contribution from CATEC's Coral Reef Research Group and SAM's collaborative *Coral Reefs Conservation and Rehabilitation Project*.

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