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A New Long-Term Marine Biodiversity Monitoring Program for the Knowledge and Management in Marine Protected Areas of the Mexican Caribbean

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Abstract: In the Mexican Caribbean, 15 marine protected areas (MPAs) have been established for managing and protecting marine ecosystems. These MPAs receive high anthropogenic pressure from coastal development, tourism, and fishing, all in synergy with climate change. To contribute to the MPAs' effectiveness, it is necessary to provide a long-term observation system of the condition of marine ecosystems and species. Our study proposes the establishment of a new marine biodiversity monitoring program (MBMP) focusing on three MPAs of the Mexican Caribbean. Five conservation objects (COs) were defined (coral reefs, seagrass beds, mangroves, marine turtles, and sharks-rays) for their ecological relevance and the pressures they are facing. Coral reef, seagrass and mangroves have multiple biological, biogeochemical and physical interactions. Marine turtles are listed as endangered species, and the status of their populations is unknown in the marine area of the MPAs. Elasmobranchs play a key role as top and medium predators, and their populations have been poorly studied. Indicators were proposed for monitoring each CO. As a technological innovation, all information obtained from the MBMP will be uploaded to the Coastal Marine Information and Analysis System (SIMAR), a public, user-friendly and interactive web platform that allows for automatic data management and processing.

Keywords: marine ecosystems; monitoring protocols; indicators; web data management

1. Introduction

Marine ecosystems provide essential goods and services to humans: food source, coastal protection and climate regulation, among others [1]. However, these contributions are currently declining, and their future sustainability is being threatened by human exploitation, which endanger the functionality of ecosystems and their resilience [2]. Ecosystem services such as fish catch have decreased dramatically due to overfishing, habitat destruction, pollution, among others [3]. New and reemerging diseases have also appeared in marine organisms, and invasive species have successfully colonized new areas [4]. The oceans are warming and becoming more acidic due to human-induced activities [5]. In many places, the combination of anthropogenic and natural impacts has caused dramatic changes in species composition and abundance, known as phase shifts, often long-lasting and difficult to reverse, which in turn compromise the integrity of ecosystems and affect their resilience [6–10]. Marine protected

areas (MPAs) have been established as essential components for managing and protecting marine ecosystems to mitigate natural and anthropogenic stressors [11].

The current understanding of the resilience of marine ecosystems in Mexico is limited, since it has been difficult to carry out monitoring and relevant assessment over time scales [12]. This is mainly due to the large extent of Mexico's marine ecosystems, their complexity, and because of multiple pressures they face [13]. In this context, there is an urgent need to coordinate and promote existing coastal and ocean monitoring capabilities of the country, in order to standardize data and fusion methodologies to face national, regional and global challenges [14]. Likewise, it is necessary to avoid duplication developing on various observation platforms and networks, and by adopting common standards for data collection and dissemination to maximize the use of data [15].

Among the most important marine regions of the country is the Mexican Caribbean, which stands out as the northern and most extensive portion of the Mesoamerican Barrier Reef System. Better known as the Mesoamerican Reef, this coral reef barrier stretches out over approximately 1000 km, along the Caribbean coast of Mexico, Belize, Guatemala, and Honduras [16]. In the Mexican Caribbean, there are 15 federal marine protected areas (Table 1; Figure 1), which provide critical habitats for feeding, nesting and raising a large number of commercially important, threatened or endangered species [17]. These MPAs include extensive regions of coral reefs, seagrass beds, coastal dunes and mangroves that maintain high ecological connectivity with each other. This existing natural ecological connectivity within and between these ecosystems allows them to remain resilient [18–21]. The conservation and management of interconnected ecosystems can enhance the resilience of individual ecosystems and species [22].

Table 1. Marine Protected areas (MPAs) of the Mexican Caribbean [23]. In Bold, the Three Studied MPAs.

Marine Protected Areas of the Mexican Caribbean	Marine Extension (ha)	Terrestrial Extension (ha)	Total Extension (ha)
Costa Occidental de Isla Mujeres, Punta Cancún y Punta Nizuc National Park	8672.45	0.61	8673.06
Manglares de Nichupté Flora and Fauna Protection Area	0.00	4257.49	4257.49
Arrecife de Puerto Morelos National Park	9028.89	37.74	9066.63
Isla Contoy National Park	4896.25	230.00	5126.25
Porción Norte y Franja Costera Oriental terrestres y marinas de la Isla de Cozumel Flora and Fauna Protection Area	32,095.96	5733.21	37,829.17
Arrecifes de Cozumel National Park	11,905.60	82.27	11,987.87
Tulum National Park	0.00	664.32	664.32
Sian Ka'an Biosphere Reserve	153,135.79	375,011.87	528,147.66
Arrecifes de Sian Ka'an Biosphere Reserve	33,566.15	1361.00	34,927.15
Banco Chinchorro Biosphere Reserve	143,774.21	585.79	144,360.00
Arrecifes de Xcalak National Park	13,427.61	4521.84	17,949.45
Tiburón Ballena Biosphere Reserve	145,988.13	0.00	145,988.13
Yum Balam Flora and Fauna Protection Area	101,744.63	52,307.62	154,052.25
Playa de Isla Contoy Sanctuary	10.21	0.00	10.21
Caribe mexicano Biosphere Reserve	5,725,465.86	28,589.49	5,754,055.35
Total extension of MPAs in the Mexican Caribbean	6,383,711.74	473,383.25	6,857,094.99

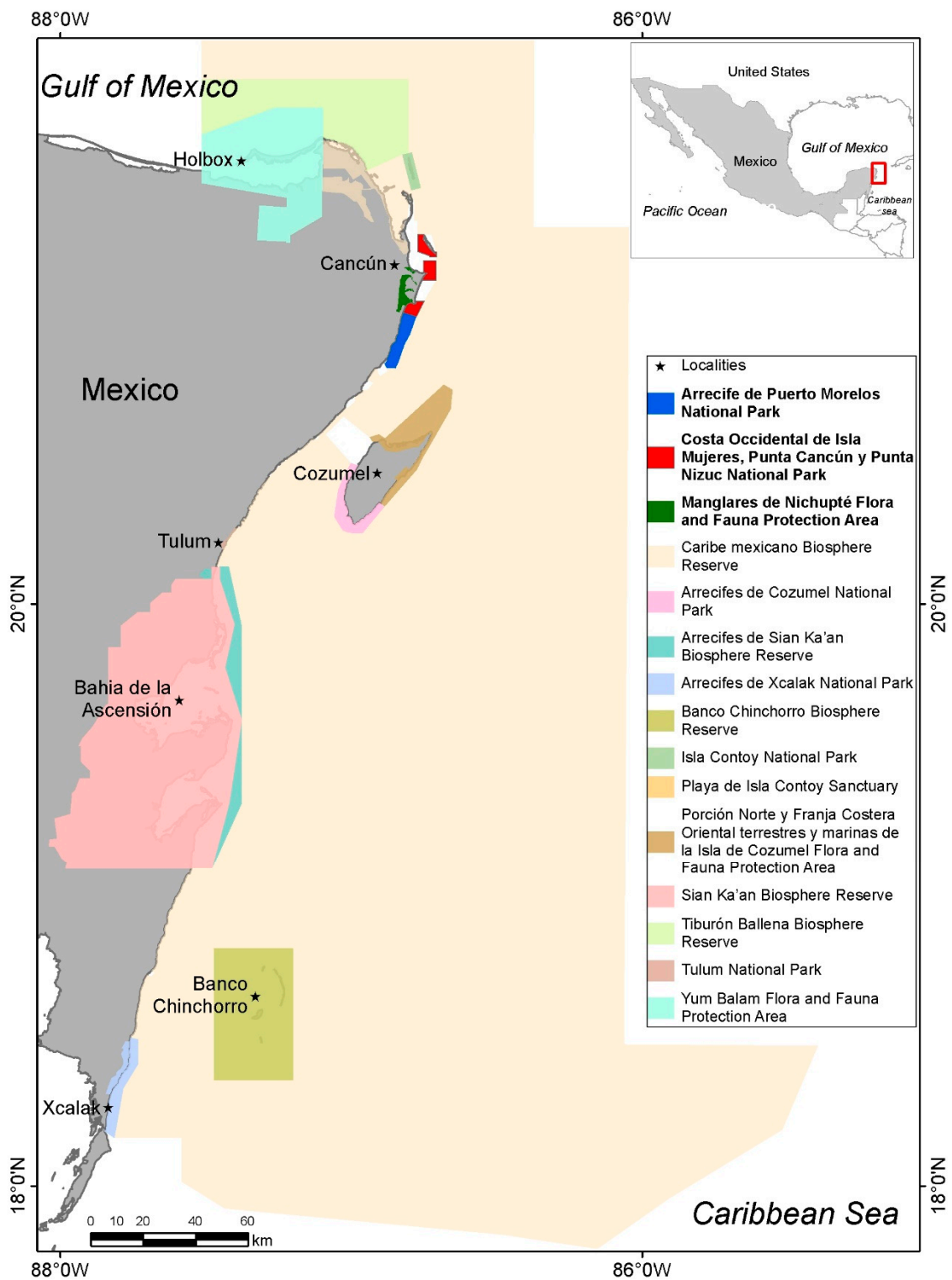


Figure 1. MPAs of the Mexican Caribbean. The three MPAs in Bold (Legend) Correspond to The Study Area.

A key challenge in conserving biodiversity, designing strategic biodiversity conservation plans and reporting on their success, is the establishment of reliable and constant monitoring systems [24]. The correct evaluation of monitoring indicators properly included in monitoring systems allows to provide an early warning system of stressors to ecosystems and the species that inhabit them [25]. This helps diagnose the possible causes of ecosystem degradation and determine the appropriate

management policies to combat them [26]. In addition, this allows to assess whether the implemented policies, such as MPAs, restrictions on tourist activities, fishing regulations, among others, are being effective [25].

Given the relevance of the Mexican Caribbean, forming part of the largest coral reef in the western hemisphere [27], numerous monitoring initiatives have been implemented and developed, mainly in the last 20 years, promoted by government organizations, the civil society and academia. However, this has led to an increasing number of databases produced using different monitoring methods, which makes comparability difficult and limits their usefulness in determining environmental policy measures [24]. Taking into account the previous efforts in the Mexican Caribbean, and with the aim of standardizing existing methodologies to compare between sites, a new marine biodiversity monitoring program (MBMP) in the Mexican Caribbean was developed, intended to evaluate the health of ecosystems and their resilience.

The MBMP was proposed within the framework of the international project “Strengthening management effectiveness and resilience of protected areas to protect biodiversity under conditions of climate change”, also known as GEF5-Resilience. This project was led in Mexico by the National Commission for Natural Protected Areas (CONANP), implemented by the United Nations Development Program (UNDP) and co-financed by a donation from the Global Environment Facility (GEF). The National Commission for the Knowledge and Use of Biodiversity (CONABIO) joined this initiative to support the design and development of an observation network (in situ and satellite) of marine biodiversity in MPAs, focusing on the establishment of a Marine-Coastal Information and Analysis System (SIMAR), forming part of the National Biodiversity Information System of Mexico (SNIB). SIMAR is an explorer that incorporates algorithms and technological tools for remote perception, biodiversity observation, geo-visualization and analysis of marine and coastal data on a user-friendly interactive web platform, implemented in a cloud architecture. It constitutes an innovative technological development that integrates, analyzes, manages and visualizes large volumes of multiscale data (big data) derived from in situ sampling and monitoring (e.g., physical-chemical environmental parameters and records of biodiversity, and citizen science), satellite observations (ocean temperature and color), as well as climate models (under climate change scenarios) and geospatial information. SIMAR integrates both the operation of information systems and the analysis of marine biodiversity, as well as early warning systems that contribute to responsible and accurate decision-making by communities and governments, included the proposed MBMP (<https://simar.conabio.gob.mx>) [28].

This work integrates the design process of the MBMP and the presentation and discussion of the main elements that comprise it. Its implementation will allow for the periodic and long-term monitoring of the main marine ecosystems of the Mexican Caribbean region and their associated species, in order to determine sites with species communities that are most resilient to climate change and other anthropogenic stressors. We present the selected conservation objects (COs). We highlight the proposed indicators included in the standardized monitoring protocols that summarize the condition of the COs. Finally, we explain the conceived online monitoring data management system. The implementation of the MBMP will allow one to identify and prioritize management actions or strategies to reduce stress in MPAs. Likewise, it will contribute to strengthening existing monitoring and networks in the region, aimed at guaranteeing the conservation of marine biodiversity. With the development of the MBMP, Mexico will support the fulfillment of international conventions and commitments, such as the Convention on Biological Diversity, the Convention for the Protection and Development of the Marine Environment in the Wider Caribbean Region (Cartagena Convention), and the Paris Agreement on climate change, among others. Together, this will contribute to the achievement of the United Nations Sustainable Development Goals (SDGs), in particular the “SDG 14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development”, as part of the 2030 Agenda for Sustainable Development.

2. Materials and Methods

2.1. Scope of the MBMP

The first phase of the MBMP in MPAs in the Mexican Caribbean was carried out between 2017 and 2020. Our study focused on three selected MPAs, proposed as pilot protected areas of the GEF5-Resilience project due to their particularly high priority, in terms of their potential vulnerability and the significance of their biodiversity or the ecosystem services which they provide [29]. Staff from other MPAs in the region were involved in the process, with a perspective to gradually implement the program in other areas as well. The three MPAs under study were:

2.1.1. Costa Occidental de Isla Mujeres-Punta Cancún-Punta Nizuc National Park (MCN-NP)

This MPA is located in the north of the state of Quintana Roo, where the Mesoamerican Reef System shows its northernmost extension. It was created in 1996, due to the presence of coral reefs with great importance to the regional economy. Ecological processes, biological communities and particular physiographic characteristics concur in the area, which suggests its regional and international importance [30]. It comprises a marine area of 8673 ha, distributed in three separated polygons (Figure 1). Polygon 1 covers the western coast of Isla Mujeres, polygon 2 is located in Punta Cancún and polygon 3 in Punta Nizuc. The reefs of the MCN-NP are mainly fringing with three variations: (a) a well-defined channel between the coast and the reef ridge, (b) an incipient channel and (c) without a channel [31]. The shallow water seagrass meadows are dominated by *Thalassia testudinum* [32,33], while in deeper water, *Syringodium filiforme* seagrasses are more present [34]. Four species of marine turtles have been reported: green turtle (*Chelonia mydas*), hawksbill (*Eretmochelys imbricata*), loggerhead (*Caretta caretta*) and leatherback (*Dermochelys coriacea*), all of them endangered according to NOM-059-SEMARNAT-2010, with *C. mydas* being the most common in this area [30]. Regarding elasmobranchs (sharks and rays), the occurrence of accidents with sharks in Punta Nizuc made the MCN-NP authorities aware of their presence in the area and the need to evaluate their populations. Aerial censuses carried out by Hoyos et al. [35] allowed one to determine that the greatest number of sharks could be observed during the winter months (November–May). Similarly, although with a smaller number of individuals, it was possible to register a second aggregation season in the summer months (Jun–Aug). The reports of sightings by fishermen and divers in the area coincided with Hoyos et al. [35] indicating that the bull shark (*Carcharhinus leucas*) is the most abundant species.

2.1.2. Manglares de Nichupté Flora and Fauna Protection Area (MN-FFPA)

This MPA comprises 12 mangrove polygons that border the Nichupté lagoon, which separates the island of Cancun from the Yucatan Peninsula and embraces a total area of 4257 ha (Figure 1). This system has the particularity of being immersed in the urban and tourist area of Cancun, whose origin and main activity are related to large-scale national and international tourism [36]. This region was decreed a protected area due to the presence of an important diversity of terrestrial and aquatic ecosystems, including low deciduous forests, mangroves, *tular* and *petenes*; as well as various springs that constitute the habitat of endemic and threatened species of flora and fauna, subject to special protection or in danger of extinction and listed in the Official Mexican Standard NOM-059-SEMARNAT-2010 [36]. In this MPA, all four mangrove species present in the Mexican Caribbean can be observed: *Rhizophora mangle*, *Avicennia germinans*, *Conocarpus erectus* and *Laguncularia racemosa* [17]. Seagrasses are the dominant aquatic vegetation in the MN-FFPA with the species *T. testudinum*, *S. filiforme*, *Halodule wrightii* and *Ruppia mexicana* [36]. This MPA maintains a close spatial relationship with the MCN-NP through various interactions, in particular by the connectivity between mangrove ecosystems and coral reefs of the surrounding MPAs [37].

2.1.3. Arrecife de Puerto Morelos National Park (APM-NP)

This MPA is located adjacent to the city of Puerto Morelos, State of Quintana Roo, and has a total area of 9066.63 ha (Figure 1) adjoining the southern limit of the MCN-NP. It was created in 2000, with the active participation of the Puerto Morelos community. The inhabitants of this coastal community, anticipating indiscriminate and unplanned coastal anthropogenic growth, jointly proposed with the MPA administration, the implementation of management strategies for the sustainable use and the conservation of natural resources of the area [38]. The MPA includes important and well-preserved reef sites and extensive areas of seagrass beds. The APM-NP reefs form an extended barrier distributed throughout the MPA [31]. Three species of seagrasses (*T. testudinum*, *S. filiforme* and *H. wrightii*) have been described in the area [39]. The dominant species is *T. testudinum*. The densities of *S. filiforme* or *H. wrightii* are usually low when mixed with *T. testudinum*, but can reach a high biomass in narrow coastal strips [34,39]. Four species of marine turtles are reported (*C. caretta*, *C. mydas*, *E. imbricata* and *D. coriacea*), using the beaches of the MPA as a nesting area and the marine area as grazing zone [40]. Regarding elasmobranchs (sharks and rays), 10 species have been described [38], however, the status of their populations or other relevant information is not well documented.

2.2. Methodology

The proposal of the MBMP in the MPAs of the Mexican Caribbean began with the selection of the marine-coastal COs (ecosystems and species) in each of the MPAs of the project (Figure 2). The COs were defined as the MPA values on which the monitoring efforts will focus. The selection process of the COs was carried out based on information provided by CONANP, about the main values present in the MPAs, and following the methodology proposed by Gerhartz et al. [41]. The proposals were complemented by the reviewed literature, including the management programs of the MPAs, as well as previous studies carried out in the region, NGO reports, etc.

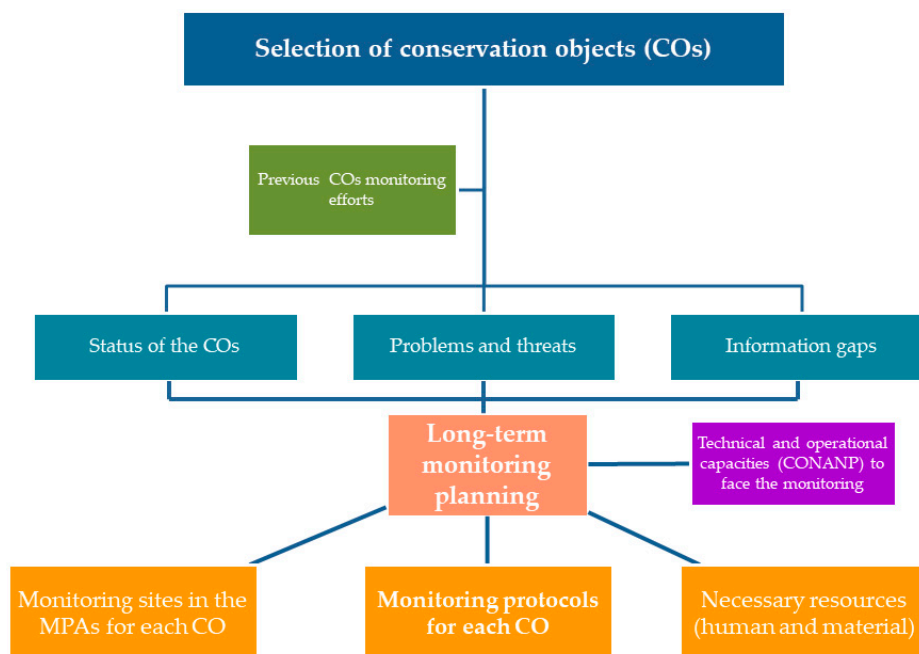


Figure 2. Components for the Development of the Marine Biodiversity Monitoring Program (MBMP) in MPAs of the Mexican Caribbean. Adapted from Perera-Valderrama et al. [42].

Subsequently, during visits to the MPAs, the proposals for the COs were confirmed through expert interviews of directors, field officers of the GEF5-Resilience Project and specialists and rangers involved in the monitoring of marine-coastal biodiversity. Likewise, researchers from research institutions and members of civil society were consulted to collect new information and to confirm

the establishment of cooperative alliances with the perspective for preparing monitoring protocols. With the information obtained and through the review of management programs, reports, research and monitoring publications, an analysis of the status of the COs was carried out and the main information gaps were defined. The most relevant problems and threats at regional and local scale were identified. Historical information from previous monitoring of the COs was compiled, with a view to determine the availability of data as baseline information. The current and historical monitoring sites were determined, and information was related to sampling periodicity of previous monitoring efforts, people or institutions involved, protocols applied, instruments and sensors used, and the resources allocated to monitoring were reviewed (Figure 2).

With all the baseline information compiled, a workshop for the establishment of protocols for the monitoring of marine biodiversity in marine protected areas of the Mexican Caribbean was organized. The objective of the workshop was to define indicators and monitoring protocols based on a combination of in situ data and satellite sampling methods in a participatory manner. The indicators included in the monitoring protocols were designed to assess the effects of conservation and restoration strategies, human impacts, and the resilience of ecosystems and target species with respect to the effects of climate change on MPAs in the Mexican Caribbean region.

The workshop involved 48 experts from 17 academic institutions, including universities and marine research centers, government and non-governmental agencies, and from UNDP—the United Nations agency implementing the GEF-5 Resilience project. Representatives of CONANP, directors of MPAs from the Mexican Caribbean region, as well as specialists and field officers from the GEF-5 Resilience Project attended. During the workshop, groups were structured according to the experience of the participants according to each of the COs. In the work sessions, proposals for health indicators for the COs and supporting information were reviewed on the basis of proposals previously prepared by CONABIO. Methodology proposals also prepared by CONABIO were assessed, based fundamentally on what is already being done in the MPAs. An evaluation was carried out to assess the necessary resources (human and material), to undertake different monitoring proposals. In addition, the necessary sampling sites in each MPA were identified for each conservation target.

To integrate and process future data resulting from the implementation of the monitoring protocols, a database for marine biodiversity monitoring in MPAs of the Mexican Caribbean (BioCARIBE) and a Warning System for Ecological Conditions of Marine-Coastal Ecosystems (EcoSAT) were designed within SIMAR. SIMAR is a web-based information system running over multiple servers, hosted on Amazon Web Service EC2, structured as Web API. These characteristics allow a modular scaling of the components according to the needs of the different projects that make up SIMAR. SIMAR is based on open source technology (its source code is freely available to use, modify, and redistribute) that uses Debian GNU/Linux (a Unix-like operating system), Python (an interpreted, high-level, general-purpose programming language) as the main tool for vector and raster data processing, Apache and NodeJS (as open-source HTTP servers), jQuery and Leaflet (a open-source JavaScript library) as visualization and user interaction tools, and Flask and Django (a high-level Python Web framework) for data disposition in API mode. PostgreSQL, PostGIS, and MySQL (a free and open source relational database management system) are used to contain tabular data, as well as to organize satellite image and vector products.

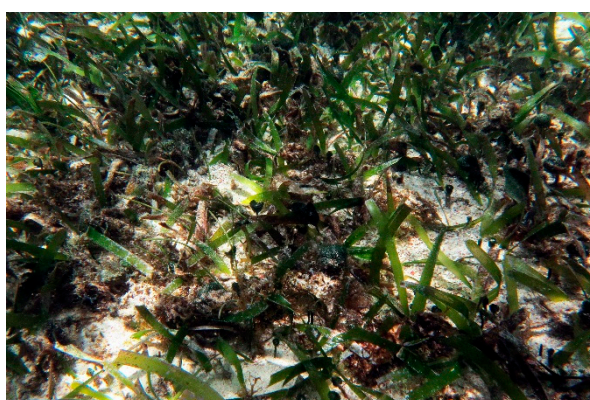
3. Results and Discussion

3.1. Conservation Objects Selected in Each MPA

According to the presence and relevance of the most important natural assets of the MPAs within the GEF5-Resilience project, five priority conservation objects were defined for the Mexican Caribbean region, including ecosystems and species (Figure 3; Table 2):



(a)



(b)

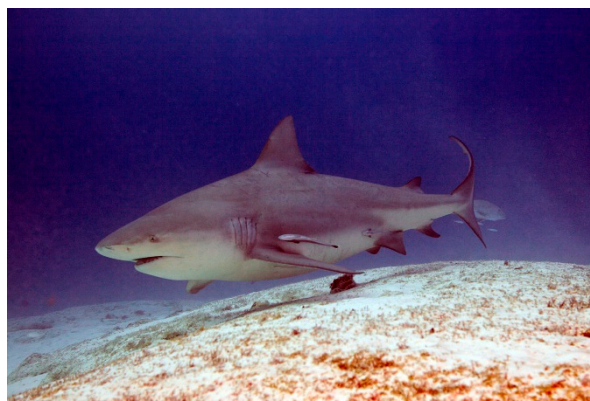


(c)

Figure 3. *Cont.*



(d)



(e)



(f)

Figure 3. Conservation Objects (CO) Defined as Priorities for the Studied MPAs in the Mexican Caribbean. (a) Coral Reefs (*Acropora palmata*). Photo: Hansel Caballero Aragón/CONABIO. (b) Seagrass Beds (*Thalassia testudinum*). Hansel Caballero Aragón/CONABIO. (c) Mangroves (*Rhizophora mangle*). Photo. Claudia Maricusa Agraz Hernández/CONABIO. (d) Marine Turtles (*Eretmochelys imbricata*). Photo: Carlos Javier Navarro Serment/CONABIO. (e) Sharks (*Carcharinus leucas*). Photo: Carlos Javier Navarro Serment/CONABIO. (f) Rays (*Aetobatus narinari*). Photo. Denisse Pohls Pérez/CONABIO.

Table 2. Conservation Objects Defined as Priorities for each MPA in the MBMP for the Mexican Caribbean.

MPAs/COs	CO1. Coral Reefs	CO2. Seagrass Beds	CO3. Mangroves	CO4. Marine Turtles	CO5. Sharks and Rays
Costa Occidental de Isla Mujeres—Punta Cancún—Punta Nizuc National Park	X	X		X	X
Manglares de Nichupté Flora and Fauna Protection Area		X	X		
Arrecife de Puerto Morelos National Park	X	X		X	X

3.1.1. CO1. Coral Reefs

The ecological and economic relevance of the reefs in MCN-NP and APM-NP, as well as the strong pressures to which they are exposed, were the main reasons for selecting this ecosystem as CO. In MCN-NP, the intensive tourist activities in some of the reef areas and surrounding ecosystems, in synergy with the regional stressors associated with climate change, have severely threatened their state of health, endangering their long-term viability [43]. As a result of the incidence of hurricanes Iván (2004), Emily (2005) and Wilma (2005), the latter being the most intense, the MCN-NP reefs were seriously affected and are only just beginning to recover. The implementation of reef restoration projects has contributed to the recovery of the coral reefs. In the APM-NP, the research and monitoring results obtained for more than 30 years allowed us to classify the conservation degree of reefs as “relatively good”. In this area, the “Limones” reef stands out for its high degree of conservation, which has maintained stability along its coral cover in the frontal zone in recent years [44]. However, reefs are also seriously threatened by population pressure, as well as by the economic and urban infrastructure growth of Cancun and Puerto Morelos, which have contributed to its deterioration [45].

3.1.2. CO2. Seagrass Beds

The ecological importance of the seagrass beds in the Mexican Caribbean region, together with the great spatial extension of this ecosystem in the study areas and the multiple threats they face, motivated their selection as CO in the three MPAs. Other important selection factors were the multiple biological, biogeochemical and physical interactions established with coral reefs and mangroves, and the relevance of seagrass for marine primary productivity [46]. In MCN-NP, changes in the coverage, density, biomass and epiphytism of seagrasses, mainly of *T. testudinum*, have occurred, probably due to tourist activities and the impact of natural events such as hurricanes [32]. The seagrass beds of the Nichupté Lagoon System are among the most affected by increasing tourism. They have suffered a significant coverage reduction, sometimes being replaced by large masses of algae that apparently take advantage of the increasing eutrophication [47,48]. In the APM-NP, where this ecosystem is widely distributed throughout the area, significant impacts from hurricanes have been reported [46].

3.1.3. CO3. Mangroves

Mangrove vegetation is the most widely represented plant community in the MN-FFPA, considered in a good state of preservation, even though evidence of profound damages due to the passage of Hurricane Wilma in 2005 can be noted. For this reason, mangroves are considered as the main MPA conservation object, since this ecosystem was the main reason for creating the area, also indicated by its name (Nichupté Mangroves). MN-FFPA staff have carried out significant monospecific reforestation activities planting *R. mangle*, which allowed a recovery of about 95% of the border mangrove vegetation cover, affected by Hurricane Wilma. Comprehensive monitoring efforts have been carried out on mangroves by CONABIO

on a national scale since 2005, implementing the National Mangrove Monitoring System (SMMM) providing long-term monitoring data on extension, distribution and change [49].

3.1.4. CO4. Marine Turtles

The ecological importance of marine turtles and their classification as endangered species suggested their inclusion as CO in the studied MPAs. In MCN-NP, marine turtles have been observed at dive sites, mainly those close to Isla Mujeres, even with mating behaviors. However, their populations have not been studied, so their status is fairly unknown. The implementation of the monitoring protocol in the MPA would focus on the observation of individuals in the marine area, since there are no nesting areas within the park's geographical limits. Within the APM-NP, marine turtles use the MPA beaches for nesting and the marine area of the park as grazing areas [40], which reinforces the relevance of the area for the monitoring of these species. In this last MPA, the studies have been focused on the evaluation of the nesting female populations on the nesting beaches, but the status of the sea turtle populations in the marine area of the park is unknown.

3.1.5. CO5. Sharks and Rays

The presence of elasmobranchs is known in both MPAs (MCN-NP and APM-NP), but their populations have been poorly studied, resulting in an important information gap. Considering the relevance of sharks and rays as top and medium predators in marine ecosystems, occupying the top positions in the food web [50] and due to their importance as a fishery resource, they were proposed to be included as CO.

3.2. *Indicators of the Monitoring Protocols for Each CO*

Monitoring protocols were developed for each CO [42]. The indicators included in each protocol synthesize the information contained in environmental variables (biological, physical and chemical), in order to describe the health of the ecosystems and of the populations of the selected species. These indicators were defined as those with ease of data collection and which facilitate the interpretation of the results (Table 3).

In the protocols [42], each indicator is characterized, including its relevance in estimating the health of ecosystems or populations and the possible meanings of the trends that it may show in time or space. In addition, the proposed methods for the measurement of the variables and the calculation of the indicators are detailed. Materials required to carry out field work and laboratory sample processing are specified. The annexes include details such as the codes for the species, data collection forms, photos, identification keys, etc.

Indicators selected in the monitoring protocols include essential ocean variables (EOVs), established for these ecosystems by the Global Ocean Observing System (GOOS) [15] (<https://www.gosocean.org/>). The way in which the monitoring protocols were designed will allow contributing data to global initiatives such as GOOS, the Marine Biodiversity Observation Network (MBON), and in particular, the Marine Biodiversity Observation Network of the Americas from Pole to Pole (MBON-P2P) (<https://marinebon.org/p2p/>). This network of the Americas was established in partnership with the Oceanic Biogeographic Information System (OBIS) (<https://obis.org/>). The data derived from the monitoring protocols will be accessible both through OBIS and from the Marine Biodiversity Database (BioINFO), integrated into the in situ Ocean Monitoring System (SIDMO) within SIMAR. The monitoring protocols designed are in line with different regional initiatives implemented in the wider Caribbean for the monitoring of the species and ecosystems selected as COs. At the same time, our program has the strength of having been carried out in a participatory manner, incorporating the indicators most used by national institutions and MPA managers in Mexico, and complying with the premise of creating standardized methodologies that allow for a comparison with previous studies in the Mexican Caribbean.

Table 3. Proposed monitoring indicators for each Conservation Object (CO) defined as a priority in the MPAs of the Mexican Caribbean.

CO1. Coral Reefs	CO2. Seagrass Beds	CO3. Mangroves	CO4. Marine Turtles	CO5. Sharks and Rays
Biological Indicators				
1. Living coral cover				
2. Macroalgae cover (functional groups)	1. Relative abundance (by seagrass species and macroalgae groups)		1. Nest density by species	
3. Coral diseases	2. Macroalgae biomass		2. Morphometry of nesting females	1. Diversity of species
4. Coral bleaching	3. Density of beams by seagrass species	1. Basal area	3. Interval between nesting	2. Relative abundance of species
5. Ratio of reef-building/opportunistic coral species	4. Canopy height by species	2. Density of trees	4. Health status of marine turtles	3. Sex ratio
6. Density of urchins	5. Biomass above the substrate	3. Relative abundance by species	5. Stranding	4. Sexual maturity
7. Survival of coral recruits	6. Total biomass of seagrasses	4. Regeneration	6. Hatching success rate	5. Size structure of the population
8. Complexity of the substrate (rugosity index)	7. Ratio of aboveground biomass/total biomass		7. Relative abundance by species	6. Specific composition of the diet
9. Biomass of herbivorous fish			8. Morphometry of captured individuals	
10. Biomass of commercial fish				
11. Biomass of lionfish				
Abiotic Indicators				
1. Sea level		1. Microphotography		
2. Temperature	1. Temperature	2. Hydroperiod		
3. pH	2. pH	3. Interstitial Redox Potential		
4. Salinity	3. Concentration of dissolved oxygen	4. Nutrients	1. Nest temperature	1. Water temperature
5. Concentration of dissolved oxygen	4. Irradiance	5. Interstitial temperature		2. Current strength
6. Transparency	5. Salinity	6. Interstitial salinity		
7. Nutrients	6. Organic matter in the sediment	7. Interstitial pH		
8. Sedimentation rate				

The CO1 protocol includes indicators directed to the evaluation of structural and functional attributes of coral reefs. The reef condition indicators selected provide an early warning system for stressors affecting this ecosystem. They help diagnose possible degradation causes and determine suitable management methods to combat them, and allow evaluating the effect of management measures [25]. Many of these indicators have been included in effective and proven sampling methodologies used in the Western Atlantic region, such as the AGRRA [51], CARICOMP [52] and Reef Check [53] programs. Our coral reef monitoring program is compatible with these methodologies, and our results will be very useful to compare with them and thus maintain efficient regional monitoring.

The CO2 indicators aim to detect changes in seagrasses over time, so that their deterioration or recovery can be documented in the selected areas. Seagrasses are well recognized as indicators of integrated environmental pressures, so monitoring their condition and trends can provide information on the status of the surrounding environment [54]. CO2 monitoring focuses mainly on the biology of marine angiosperms, their composition, abundance, and relationship with other components of the ecosystem. Selected indicators come from established methodologies and studies throughout the Caribbean, supported by the experience of local experts [52,55].

For the CO3 protocol, the indicators were selected with specificity to detect the impacts of climate change and the resilience of these ecosystems in the Mexican Caribbean [56]. The design of the mangrove protocol, taking into account three approaches of different scales (basin, environmental gradient and environmental variation) allows for a more comprehensive monitoring of the ecosystem and the connectivity relationships established with the surrounding ecosystems. The basin approach (evaluating indicators on a larger scale than the MPA) allows evaluating impacts from outside the MPA. The environmental gradient approach (gradient of the environmental variable with the greatest influence on the characteristics of the MPA mangrove) helps to explain the general structure of the MPA mangrove and its response to different impacts. Finally, the environmental variation approach (site-specific) allows the representation and monitoring of the structural trends of the different types of mangroves present in the MPA and their state of conservation.

The indicators selected for CO4 evaluate both nesting female sea turtle populations on nesting beaches and sea turtle populations in the marine ecosystems that they inhabit, mainly coral reefs and seagrass beds. Due to the great accelerated coastal development that the Yucatan Peninsula has experienced, mainly associated with tourism, sea turtles have been subjected to various pressures. The indicators included in the monitoring protocols allow estimating the effect of these drivers of change (anthropic and natural) on the populations of sea turtles and their conservation status in the MPAs in the Mexican Caribbean region. Several of the indicators have been implemented for many years in the Mexican Caribbean region, where there have been efforts to conserve and monitor sea turtles for more than 30 years [57].

Knowledge about the presence of sharks and rays (CO5) has been almost exclusively limited to sightings made by divers and fishermen. Only one evaluation was carried out by Hoyos et al. [35] in the MCN-NP. Taking into account this lack of information, indicators were proposed to characterize the populations, evaluating their composition and structure, and impacts of fishing [58]. The importance of obtaining population estimates of shark and ray species is strongly justified, taking into account their ecological relevance, many of which have unique functions within marine ecosystems and, therefore, have low functional redundancy [59]. The presence of several species of sharks and rays that fulfill the same ecological role, can be indicators of a greater resilience of the ecosystem [60].

The selected abiotic indicators have a considerable influence on the behavior of the biological indicators of each CO, and their variability could be closely related to human actions. The designed protocols allow a monitoring of the relationship between biotic and abiotic variables, in the face of possible anthropic threats, such as coastal development, pollution by urban drains and runoff, as well as the indirect impacts of logging along the coasts, deforestation, agriculture, aquaculture, mining and dredging, among others. Some variables measured will also monitor effects related to climate change.

Coral reefs (CO1) and seagrass beds (CO2) protocols were successfully implemented in the APM-NP during June 2019. With the result of the evaluation of the coral reef monitoring indicators, a comprehensive quantitative assessment of the condition of the APM-NP reefs was performed. The general status of the APM-NP coral reefs could be classified as regular, based on the integral analysis of the condition indicators for benthos and fish [61]. These results will be included in a Coral Reef Status Report Card that will be published annually for each MPA that implements the monitoring. The Status Report Cards will summarize the result of the indicators and their use in calculating comprehensive indexes of the condition of the ecosystems.

3.3. Online Monitoring Data Management System

One of the objectives of the MBMP is to create technological tools that facilitate the capture, processing and access to the information generated by the biodiversity monitoring protocols. For this purpose, EcoSAT was designed within SIMAR to support decision-making on ecosystem conservation, sustainable fisheries and integrated management for the wider Caribbean, and likewise integrates and processes data resulting from the monitoring protocols.

The monitoring data are stored in the Database of the Marine Biodiversity Monitoring Program in MPAs of the Mexican Caribbean (BioCARIBE), which includes the following five modules:

In situ monitoring data form download: user authentication and subsequently downloading the predefined Excel templates file of in situ data.

- **Completed in situ monitoring data form upload:** uploading the completed Excel file with the field data after user authentication. This allows only registered users to integrate new data into the BioCARIBE database.
- **Quality control and data validation:** validating and controlling the quality of the data through operational validation tools.
- **Data integration and processing:** geospatial data are integrated and processed automatically and the indicators are calculated.
- **Data query from in situ monitoring:** users can consult the information contained in the BioCARIBE database and it allows for a temporal geospatial analysis, combining other platform products within SIMAR.

These results progressively enrich the BioCARIBE database, and consequently the Marine Biodiversity Database (BioINFO) located in the in situ Ocean Monitoring System (SIDMO) within SIMAR (<https://simar.conabio.gob.mx>).

4. Final Remarks

The analysis of the previous monitoring carried out in the Mexican Caribbean allowed identifying some weaknesses in the monitoring strategies implemented in the region. Many of the previous studies have focused mostly on coral reef ecosystems and on a local scale. Furthermore, they have been carried out using different monitoring protocols, with different objectives, which have limited the collection and comparison of data throughout the entire region. The results of these previous monitoring have been poorly integrated for decision-making and the availability of data for public consultation is scarce. The databases are managed and modified by few people who have the necessary skills, based on the evident lack of training of many of the interested parties, which in turn limits accessibility to the data and results. The existing monitoring protocols have focused mainly on the evaluation of biological indicators, detecting a significant gap in the evaluation of abiotic variables or environmental monitoring. On the other hand, most monitoring programs have been limited in time, fundamentally associated with the lack of resources and changes of trained staff available to carry them out.

The MBMP in MPAs in the Mexican Caribbean will integrate historical information from previous monitoring in the MPAs with the information provided by the implementation of the new protocols. The monitoring protocols include biotic indicators that best reflect trends in ecological structure and

processes that occur within and between ecosystems or populations. These indicators have been selected in such a way that they show sensitivity and specificity to pressures, so that they can be used efficiently in management and conservation interventions. In addition, abiotic indicators have been defined that characterize the environmental conditions, and additional information must be collected to help interpret the results of the proposed biological indicators.

This participatory process has allowed us to include the interests of conservation and management of MPAs and establishing and maintaining participatory alliances within the scientific sector and civil society. The implementation of the created MBMP will allow one to:

- Increase knowledge of marine ecosystems of the Mexican Caribbean, their biological, physical and chemical processes and the ocean–atmosphere interaction.
- Operationally assess the health status of marine ecosystems of the Mexican Caribbean, based on indicators defined in the monitoring protocols.
- Integrate new technologies and geospatial tools to help to conserve the marine biodiversity of the Mexican Caribbean.
- Support and strengthen existing monitoring and networks in the region (science, governments, civil society, citizens) that guarantee the conservation of marine biodiversity.
- Generate knowledge and establish strategies for a comprehensive sustainable management of the country’s marine and coastal resources in the MPAs of the Mexican Caribbean, in the context of climate change.
- Integrate new marine biodiversity data to the National Biodiversity Information System of Mexico (SNIB), iNaturalist and the Ocean Biogeographic Information System (OBIS).
- Implement operational alert systems to support decision-making on possible threats to human health and the economy of coastal communities (e.g., coral bleaching events, reef health, sargassum stocks, oil spills).
- Support MPAs management decisions and contribute to the organized and sustainable practice of the main economic activities (i.e., tourism and fishing) carried out in the Mexican Caribbean region.
- Support the fulfillment of the Sustainable Development Goals (SDG) included in the Agenda 2030, particularly SDG 14 “Conserve and sustainably use the oceans, seas and marine resources for sustainable development” and the implementation of the United Nations Decade of Ocean Science for Sustainable Development Plan (2021–2030).

Linking the monitoring of biotic and abiotic variables together with the use of mapping tools and remote sensors will contribute to feeding and updating the entire existing cartographic base for the region for the mentioned COs. The results of the indicators will be used in the calculation of health indices for ecosystems, with the goal to quantitatively estimate their current status and to provide early alerts on the appearance of sources of stress. The monitoring program developed includes a web platform with public access to all the information generated, which offers tools for the introduction, processing and analysis of field data. Likewise, the outcomes will contribute to regional strategies for the conservation of marine biodiversity in the Greater Caribbean.

Policy makers and MPA managers increasingly demand reliable numbers that detail the state of biodiversity and ecosystems, as well as the definition of historical trends [62]. For this reason, isolated biodiversity monitoring efforts are insufficiently relevant to the needs of managers and ineffective in integrating information into decision-making [63]. Well-designed ecological monitoring systems can support MPA policy decisions, such as changes to MPA boundaries or regulations, and assessments of policy success or failure [64]. Participatory monitoring systems, where stakeholders help to define monitoring metrics and methods, as well as collect, analyze, and interpret data, hold particular promise as mechanism for evaluating MPAs and catalyzing policy reforms [65]. This approach can effectively integrate the perspectives of stakeholders and scientists, generate necessary data, leverage management capacity, and build collective understanding [66]. The proposed monitoring system [42] will contribute

to the establishment and transformation of the policies required to maintain resilient ecosystems [67] in the Mexican Caribbean region.

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