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Mesophotic Reefs of the Largest Brazilian Coastal Protected Area: Mapping, Characterization and Biodiversity

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Abstract: Mesophotic reefs are poorly known worldwide despite their great ecological relevance and management importance for coral reef conservation strategies. To aid in filling this gap, we conducted a pioneering, large-scale survey, covering a total of around 315 miles in length, in the largest Brazilian coastal Marine Protected Area (MPA) Costa dos Corais. From the digital bathymetry model (30 to 50 m depth) generated by a multibeam echo sounder, we selected areas of greater geomorphological diversity for a detailed investigative expedition of mesophotic ecosystems. Various sampling techniques were used: single-beam echo sounders for detailing the relief, a remotely operated underwater vehicle (ROV) for habitat type investigation, baited remote underwater video (BRUV) for collecting images of the fish community, and scuba diving to perform transects describing the benthic and fish community. We analyzed reef environments from 20 to 68 m deep. As a result, we present the mapping and geomorphological characterization of two compartments of mesophotic reefs at 21–45 m depth and an image library of mesophotic ecosystems with the species description and indications of whether it is a new record in the region. Biodiversity data were collected covering eight species of sponges, with greater abundance for *Ircinia* spp., *Aplysina* spp., and *Xestospongia muta*; eight from corals, mainly *Siderastrea* spp. And *Montastrea cavernosa*; and 68 species of reef fish, with the Labridae family (including Scarinae—11 species) being the richest. Our results demonstrate the importance of mesophotic reefs for MPA Costa dos Corais reef biodiversity and, with that, the need to protect these areas through the application of local conservation strategies, such as the creation of "no-take zones".

Keywords: mesophotic coral ecosystem; continental shelf; technical diving; remotely operated vehicle; baited remote underwater video

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1. Introduction

A targeted plan was recently launched in a global effort to manage marine ecosystems and create better conditions for the sustainable development of the ocean. The United Nations Decade of Ocean Science for Sustainable Development (2021–2030) aims to reverse the cycle of declining ocean health caused by intense human activity during the Anthropocene [1]. Coral reef ecosystems have undergone unprecedented changes due to disturbances such as climate change, overfishing, coral bleaching, coral predator outbreaks, and biological invasions; in this way, imminent actions including the implementation of policies shaped by the objectives and targets already determined internationally will have enormous importance for the future of coral reefs [2–5]. Faced with these growing impacts, in recent decades, marine researchers have advanced studies advocating for subsidies and protection solutions for shallow coral reefs [4,6,7] and are beginning to question the importance, ecological role, and level of vulnerability of commonly known intermediate coral reefs, such as mesophotic coral ecosystems (MCEs) [8–10].

Mesophotic reefs are light-dependent transition ecosystems typically located between 30 and 150 m [11–15] in tropical, subtropical and temperate regions. They are linked to other benthic mega habitats that provide a wide rotation of fish species, and they support a high proportion of depth-endemic species and a diverse abundance of reef-building species composed of corals, sponges, and algae [10,16–20]. These ecosystems can represent up to 80% of a reef's potential habitat area worldwide, and their fish communities are of interest for conservation due to their ecological particularity of being more susceptible to anthropic impacts [19,21–23]. The increasing development of methodologies and equipment allows us to better understand less explored ecosystems [24,25]. Through a bathymetric survey using a multibeam echo sounder, we identified areas of special interest from the geomorphological diversity presented. This allowed us to more objectively use single-beam echo sounders, a remotely operated vehicle (ROV), baited remote underwater video (BRUV) and scientific diving. Currently, there is a worldwide lack of information on the location and extent of deep-water ecosystems and habitats beyond the shallow region (<25 m depth) [26,27]. The main geomorphological characteristics of the continental shelf, such as submerged reefs and beach rocks, provide important information about habitats for mesophotic biodiversity, although they remain poorly explored and, consequently, far from the effective management of MPAs [12,13,28–30]. Hence, understanding their role is critical to ensure effective protection.

The mapping of mesophotic reef ecosystems is essential to help inform marine managers and decision makers and achieve better conservation strategies, such as the zoning process, and contributes to the mapping of biological communities and the understanding of ecosystem ecology and biodiversity [11,13,31,32]. Despite more than 20 years of research on coral reefs in the MPA Costa dos Corais, the first and most extensive MPA including coastal reefs in Brazil, little is known regarding its mesophotic reefs. Therefore, this work had the following objectives: (1) identify and characterize highly diverse geomorphological habitats; (2) characterize the fauna and flora of these mesophotic habitats; (3) provide a brief description of these mesophotic ecosystems and new species records for these areas. Here, we present a mapping and description of the mesophotic zone up to 68 m along with new species records and discuss aspects of the findings related to biodiversity and the conservation of these environments.

2. Materials and Methods

2.1. Study Area

MPA Costa dos Corais is the largest coastal multiple-use Marine Protection Area and is located in the Northeastern Brazilian subprovince, between the states of Pernambuco and Alagoas (35°37′24″ W–34°30′06″ W; 9°32′49″ S–7°55′09″ S) [22,33–35]. MPA Costa dos Corais covers a large range of different ecosystems, such as mangroves, shallow reefs, seagrass beds, rhodolith beds, and mesophotic reefs, from the coast to the break of the continental shelf [22,33,36]. Its territory is managed under federal government jurisdiction and extends more than 120 km along the coast (Figure 1). Beachrocks and algae beds are the most prominent features in the region, with shallow and deep reefs presenting similar structural complexity and benthic composition [22,33].

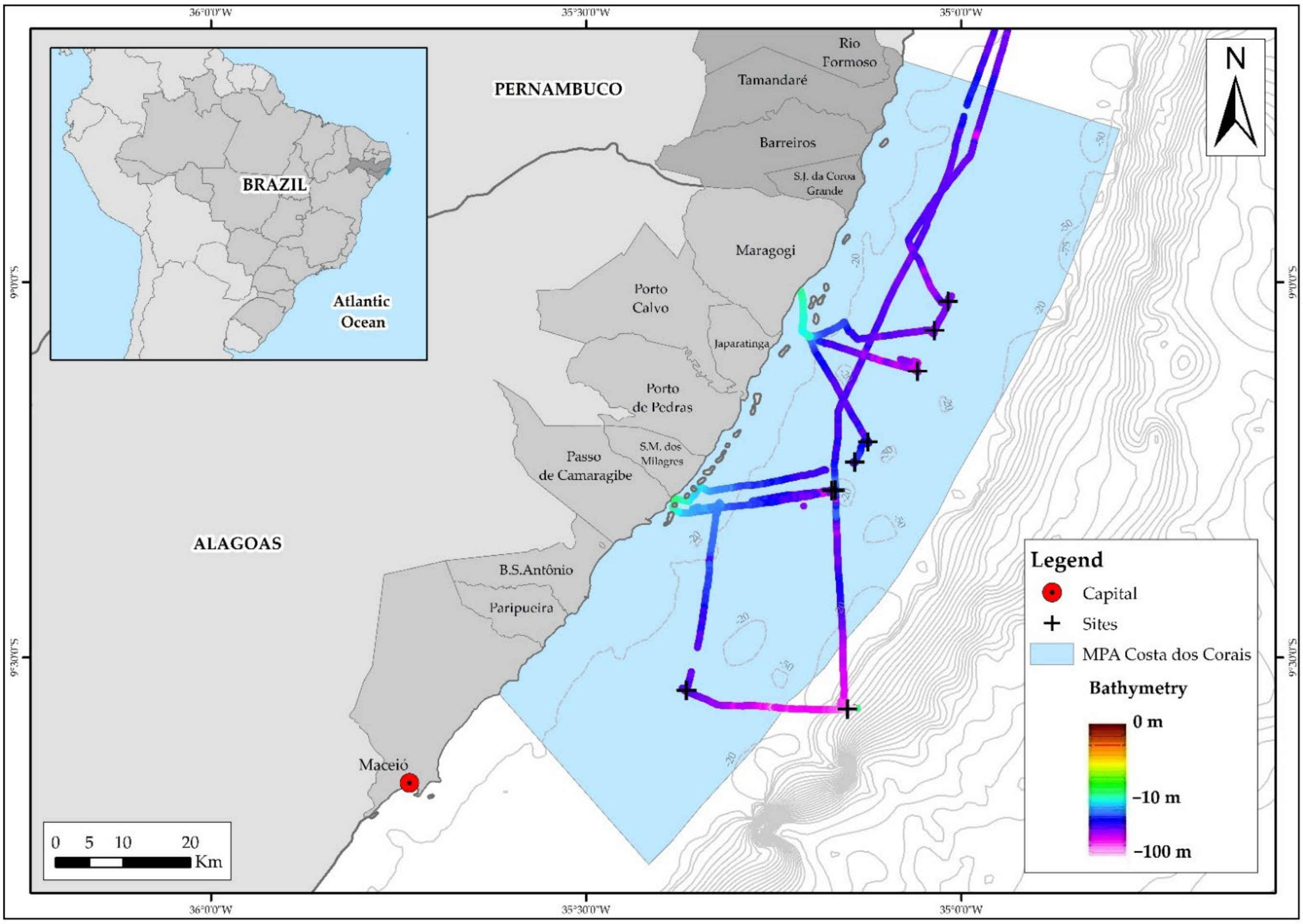

Figure 1. Map of the study area highlighting MPA Costa dos Corais and the route during the Yacaré 2021 expedition—March 2021. Bathymetric detailing of the selected areas is demonstrated from more than 90,000 depth points acquired at MPA Costa dos Corais.

2.2. Sampling Design and Field Measurements

Based on local fishers' information, a first survey line was planned approximately over the 40 m isobaths from a preliminary version of the best available nautical chart [37]. This line was surveyed in the spring of 2019 using multibeam bathymetry aboard the Hydroceanographic Research Ship Vital de Oliveira (nPqHO Vital de Oliveira) of the Brazilian Navy, employing an EM710 multibeam echo sounder from Kongsberg Maritime. Vital de Oliveira data were processed using the CARIS HIPS and SIPS 9.0.10 software [38]. Areas of interest were selected from the linear, ~120 m wide, digital bathymetry model (DBM) created, which had a resolution of 5 m. From the geomorphological diversity presented in the first DBM, 11 (eleven) sectors were selected along the MPA Costa dos Corais for detailed investigation (Figure 2). Subsequently, during the Yacaré 2021 expedition—March 2021, the bathymetric detailing of the selected areas was performed with a Raymarine Axion 9 RV single-beam echo sounder coupled with a GPS and transducer. More than 90,000 depth points were acquired at MPA Costa dos Corais (Figures 1 and 2). The surveys were performed in three areas and eleven sites at the MPA, as follows: area 1—Maragogi (three sampling sites) and Japaratinga (two sampling sites); area 2—Porto de Pedras (three sampling sites) and São Miguel dos Milagres (two sampling sites); area 3—Barra de Santo Antônio (one sampling site) and Parede (at the break of the continental shelf, on the eastern border of the MPA).

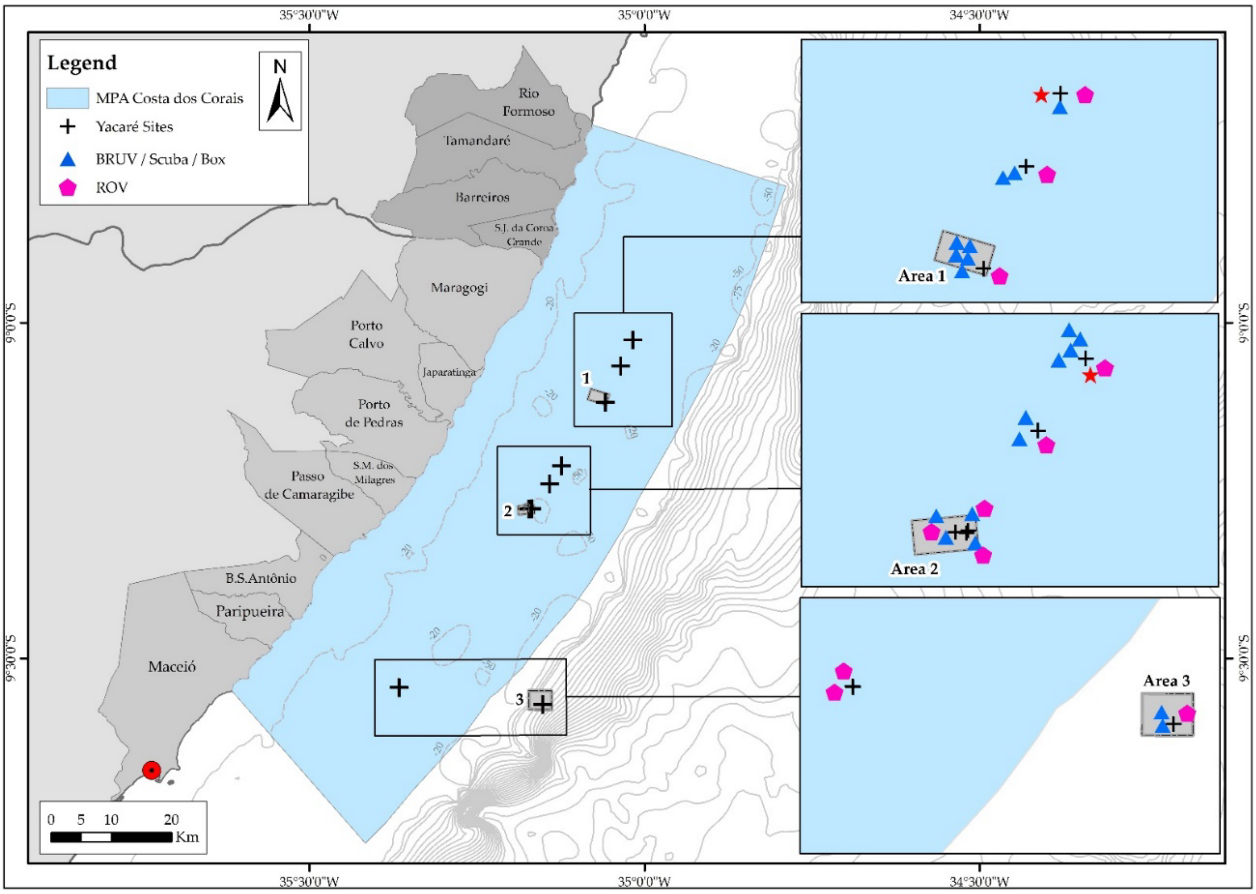

Figure 2. Experimental design with highlighted sampling areas and different methodologies implemented, such as the remotely operated underwater vehicle (ROV), baited remote underwater video (BRUV), and scuba diving.

For the delimitation of the area of the DBMs, a buffer of 75 m was created from the point cloud in each sector and edited to eliminate small void areas. The bathymetric models of the deep areas of MPA Costa dos Corais were created using the "topo to raster" interpolation method in the Arcgis 10.8 software (ESRI, Redlands, CA, USA), based on ANUDEM [39–41]. Interpolation is a process used to create a digital elevation model and predict values in areas where there are no sampled points [42,43]. This process is based on the principle of spatial correlation, through the degree of relationship and dependence between objects closer and more distant from the empty cell [44].

From the bathymetric model, three sectors were selected for the detailing of the geomorphological features based on the diversity of features and the intensity of the sampling method applied at each site (ROV, BRUV, and SCUBA). Two sectors were located in the central shelf and one sector in the break of the continental shelf, at the eastern limit of MPA Costa dos Corais (Figures 1 and 2). Thematic maps were created from the association of the bathymetric and hillshade models in order to highlight and visualize dominating features. The hillshade function is a qualitative method that was employed to view a relief (3D representation) from the shading of the DBM using directed artificial lighting [45].

To confirm sea-bottom features and produce the first detailed data for the locations, an ROV Video Ray Explorer and a color video camera-equipped Trident Underwater Drone were used. The submersibles were operated remotely from the vessel, using controls and umbilical cables. About 6 h of video covering the main benthic characteristics and components of the ichthyofauna were recorded and used for the qualitative description. To sample communities in each mesophotic reef, we also performed belt transects by diving and with BRUV.

For the fish and benthic community, four linear transects were performed. The data were collected by diving in belt transects 20 m long by 5 × 5 m wide (2.5 m on the right and 2.5 m on the left). For the benthic community, we used an adaptation of the "point transect" [46]. In this adaptation, we used a point every 50 cm of the 20 m range and considered a circumference with a radius of 25 cm starting from each point to define which benthic group was the most representative, among which were: epilytic algae matrix (EAM), hard coral, octocoral, macroalgae, coralline algae, zoanthids, sponge, bare rock, sand, sea urchin, and crinoids [47].

BRUV consists of an underwater video camera (GoPro Hero) mounted on a rigid metal frame, along with baits [48,49]. By attracting fish into the camera's field of view, the technique non-invasively records fish diversity and species behavior. The activity time for each implant was approximately 60 min (Figure 2). All data were compiled and analyzed afterwards. Each methodology was developed separately in the following order: the bottom was analyzed by the echo sounder during navigation and, after arriving at the point, the ROV was used to confirm if there was a reef environment on the bottom. Then, the BRUV cameras were deployed in the surroundings, and only after the removal of the BRUV cameras did the divers submerge to obtain the transects. Due to the currents and pioneering activities in the studied environments, it was not possible to precisely establish the distance between the BRUV cameras and the reef formation. However, a minimum of 300 m distance was established between BRUV replications to avoid statistical bias.

Logistical support and research permits were provided by MPA Costa dos Corais/ICMBio (SISBIO 67684).

2.3. Data Analyses

The footage was analyzed using the free VLC media player software (www.videolan.org, accessed on 8 July 2022). The datasets of the most significant members of the benthic cover were formatted as lists of the observed depth, state of conservation (IUCN/ICMBio), and Southwestern Atlantic (SWA) endemism for each one (see Table 1). Corals and sponges are the groups for which it was possible to carry out the identification at the lowest possible taxonomic level.

Table 1. Benthic cover record in the mesophotic zone of Marine Protected Area Costa dos Corais, Brazil. Conservation status IUCN/ICMBio: DD = Data Deficient; EN = Endangered; LC = Least Concern; NE = Not Evaluated; NT = Near Threatened; VU = Vulnerable. Geographic distribution: SWA = Southwestern Atlantic. ? = Data not found.

Type	Species	Max Depth (m)	IUCN	ICMBio	SWA Endemic
Coral	Scleractinia				
	Agaricia agaricites	75	LC	?	no
	Favia gravida	?	LC	LC	yes
	Madracis decactis	125	LC	LC	no
	Meandrina braziliensis	100	DD	DD	yes
	Montastraea cavernosa	180	LC	LC	no
	Mussismilia hispida	92	DD	LC	yes
	Porites astreoides	70	LC	LC	no
	Siderastrea spp.	90	DD	DD	no
Sponge	Haplosclerida				
	Xestospongia muta	100	NE	LC	no
	Verongiida				
	Aiolochroia crassa	135	NE	LC	no
	Aplysina fistularis	120	NE	LC	no
	Aplysina fulva	100	NE	LC	no
	Aplysina sp.	?	?	?	?
	Dictyoceratida				
	Ircinia strobilina	731	NE	LC	no
	Ircinia sp.	?	?	?	?
	Clionaida				
	Cliona sp.	?	?	?	?

The fish families are presented in a systematic order following [50], with genera and species in alphabetical order. Reference [51] was used for the current valid names, as well as for their authorship. Specifically, for the classification of Labridae—including the subfamily Scarinae—reference [52] was followed. A summary of traits, including maximum depth, trophic guild, commercial importance, conservation status—following the International Union for Conservation of Nature's (IUCN) Red List of Threatened Species [53] and the Brazilian Red Book of Threatened Species [54]—and SWA endemism was compiled for each species according to the consulted literature (for example, [35]), as shown in Table 2.

Table 2. Reef fish traits in the mesophotic zone of Marine Protected Area Costa dos Corais, Brazil. Trophic guild: HERB = herbivore/detritivore; MCAR = carnivore; OMNI = omnivores; PLANK = planktivores, MINV = mobile invertebrate feeders, SINV = sessile invertebrate feeders. Conservation status: IUCN/ICMBio: DD = Data Deficient; EN = Endangered; LC = Least Concern; NE = Not Evaluated; NT = Near Threatened; VU = Vulnerable. Geographic distribution: SWA = endemic to the Southwestern Atlantic.

Family	Species	Max Depth (m)	Trophic Guild	Targeted Species	IUCN	ICMBio	SWA
Ginglymostomatidae	*Ginglymostoma cirratum*	130	MCAR	yes	NT	VU	no
Dasyatidae	*Hypanus berthalutzae*	65	MINV	yes	VU	DD	yes
Myliobatidae	*Aetobatus narinari*	80	MCAR	yes	EN	DD	no
Albulidae	*Albula vulpes*	84	MINV	yes	NT	DD	no
Muraenidae	*Gymnothorax moringa*	200	MCAR	yes	LC	DD	no
	Gymnothorax vicinus	85	MCAR	yes	LC	DD	no
Clupeidae	*Harengula clupeola*	50	PLANK	yes	LC	LC	no
Holocentridae	*Holocentrus adscensionis*	200	MINV	no	LC	LC	no
Fistulariidae	*Fistularia tabacaria*	200	MCAR	yes	LC	LC	no
Serranidae	*Cephalopholis fulva*	218	MCAR	yes	LC	LC	no
	Epinephelus adscensionis	189	MCAR	yes	LC	DD	no
	Serranus baldwini	80	MINV	no	LC	LC	no
Malacanthidae	*Malacanthus plumieri*	153	MCAR	yes	LC	LC	no
Carangidae	*Caranx bartholomaei*	70	MCAR	yes	LC	LC	no
	Caranx crysos	100	MCAR	yes	LC	LC	no
	Caranx lugubris	350	MCAR	yes	LC	LC	no
	Caranx ruber	106	MCAR	yes	LC	LC	no
	Decapterus punctatus	90	MCAR	yes	LC	LC	no
Lutjanidae	*Lutjanus alexandrei*	54	MCAR	yes	NE	LC	yes
	Lutjanus cyanopterus	55	MCAR	yes	VU	VU	no
	Lutjanus jocu	70	MCAR	yes	NT	NT	no
	Ocyurus chrysurus	180	MCAR	yes	DD	NT	no
Haemulidae	*Anisotremus virginicus*	40	MINV	yes	LC	LC	no
	Anisotremus surinamensis	60	MINV	yes	DD	DD	no
	Haemulon aurolineatum	70	MINV	yes	LC	LC	no
	Haemulon parra	60	MINV	yes	LC	LC	no
	Haemulon plumierii	70	MINV	yes	LC	DD	no
	Haemulon squamipinna	40	MINV	yes	NE	LC	yes
Sciaenidae	*Equetus lanceolatus*	60	MINV	no	LC	LC	no
Sparidae	*Calamus penna*	87	MINV	yes	LC	LC	no
	Calamus pennatula	85	MINV	yes	LC	LC	no
Mullidae	*Mulloidichthys martinicus*	66	MINV	yes	LC	LC	no
	Pseudupeneus maculatus	90	MINV	yes	LC	LC	no
Chaetodontidae	*Chaetodon ocellatus*	30	SINV	no	LC	DD	no
	Chaetodon striatus	65	SINV	no	LC	LC	no
Pomacanthidae	*Holacanthus ciliaris*	120	SINV	yes	LC	DD	no
	Holacanthus tricolor	92	SINV	yes	LC	DD	no
	Pomacanthus paru	100	SINV	yes	LC	DD	no
Kyphosidae	*Kyphosus sectatrix*	55	HERB	yes	LC	NE	no

Table 2. *Cont.*

Family	Species	Max Depth (m)	Trophic Guild	Targeted Species	IUCN	ICMBio	SWA
Pomacentridae	*Abudefduf saxatilis*	20	OMNI	no	LC	LC	no
	Azurina multilineata	84	PLANK	yes	LC	LC	no
	Chromis multilineata	60	PLANK	no	LC	LC	no
	Stegastes fuscus	55	HERB	no	LC	LC	yes
	Stegastes pictus	85	HERB	no	NE	LC	yes
	Stegastes variabilis	30	HERB	no	NE	LC	yes
Labridae	*Bodianus rufus*	70	MINV	yes	LC	LC	no
	Clepticus brasiliensis	62	PLANK	no	LC	LC	yes
	Halichoeres brasiliensis	60	MINV	no	DD	LC	yes
	Halichoeres dimidiatus	71	MINV	no	LC	LC	yes
	Halichoeres poeyi	71	MINV	no	LC	LC	no
Labridae-Scarinae	*Cryptotomus roseus*	66	HERB	no	LC	LC	no
	Scarus zelindae	55	HERB	yes	DD	VU	yes
	Sparisoma amplum	57	HERB	yes	LC	NT	yes
	Sparisoma axillare	45	HERB	yes	DD	VU	yes
	Sparisoma frondosum	45	HERB	yes	DD	VU	yes
	Sparisoma radians	12	HERB	no	LC	LC	no
Gobiidae	*Elacatinus figaro*	70	MINV	yes	VU	VU	yes
	Ptereleotris randalli	60	PLANK	no	LC	LC	yes
Acanthuridae	*Acanthurus bahianus*	71	HERB	yes	LC	LC	yes
	Acanthurus chirurgus	70	HERB	yes	LC	LC	no
	Acanthurus coeruleus	71	HERB	yes	LC	LC	no
Scombridae	*Scomberomorus brasiliensis*	33	MCAR	yes	LC	LC	no
	Scomberomorus regalis	20	MCAR	yes	LC	LC	no
Balistidae	*Balistes vetula*	111	MINV	yes	NT	NT	no
Monacanthidae	*Cantherhines pullus*	57	OMNI	no	LC	LC	no
	Stephanolepis hispida	293	OMNI	no	LC	LC	no
Ostraciidae	*Acanthostracion polygonius*	80	OMNI	no	LC	LC	no
	Acanthostracion quadricornis	80	OMNI	no	LC	LC	no

3. Results

3.1. Digital Bathymetry Model

The detailed mapping of areas 1 and 2, carried out using a single-beam echo sounder, generated a geomorphological model with a pixel size of 12 m. This model was comparable to the DBM from RV Vital de Oliveira's multibeam echo sounder with a pixel size of 5 m. Although presenting fewer details, a larger area was surveyed, and several geomorphological compartments were identified.

The hillshade interpretation highlighted several features in area 1 and area 2. From the three-dimensional model, three geomorphological compartments were identified, namely: the plateau or reef top (reef proper or reef flat), channel (paleochannel), and isolated head or pinnacle.

3.1.1. Area 1 (Point 3)

The total area of the interpreted reef was 81,500 m^2. The reef plateau comprised the upper portion of the reef, which had rounded features and was characterized by a low or flat slope. The shallowest point in the area was 36 m deep. The paleochannel, associated with the mouth of continental drainages, had a maximum depth of 45 m (Figure 3).

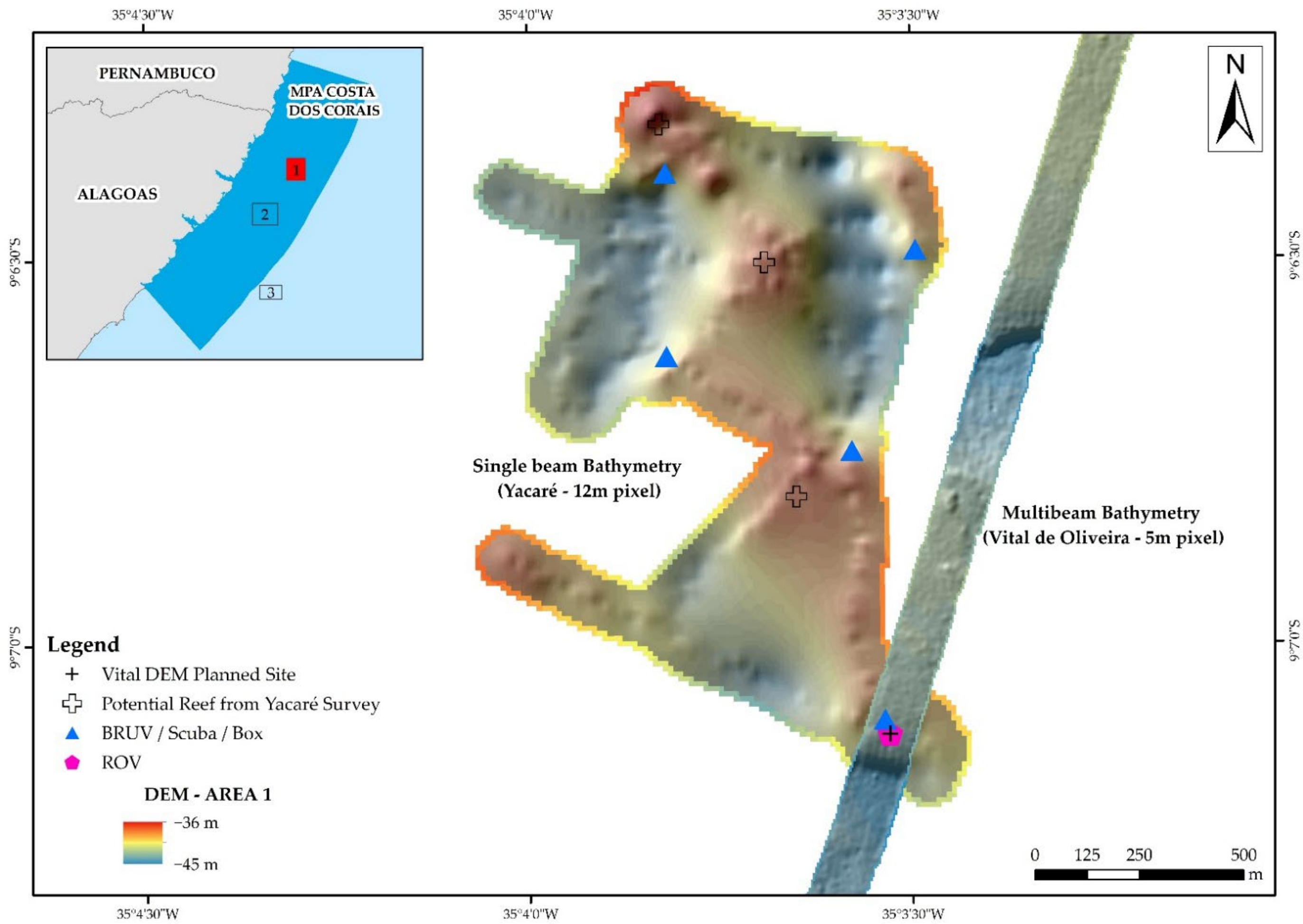

Figure 3. Digital elevation model (DEM) for area 1 with hillshade interpretation highlighting several features, such as the reef top, channels, and isolated head or pinnacle. Red square represents area 1.

3.1.2. Area 2 (Points 7 and 8)

The total probable reef area was 294,500 m^2. The reef plateau comprised the upper portion of the reef, which had rounded features and was characterized by a low or flat slope. In area 2, the shallowest point was 21 m deep, and paleochannels were associated with the mouth of continental drainages. The maximum depth was 45 m. A pinnacle was also present, an isolated feature with a minimum depth of 25 m and relatively smooth slope (Figure 4).

3.1.3. Area 3 (Break of Continental Shelf)

Area 3 corresponded to the eastern limit of the MPA Costa dos Corais and the shelf break of the almost flat continental shelf. The longitudinal profile started from a plateau at 30 m deep representing the continental shelf (Figure 5). Two channels were also observed, the first at 10 m and the second at about 40 m depth. From an abrupt shelf break, the continental slope reached over a depth of 100 m in a very short distance (~50 m).

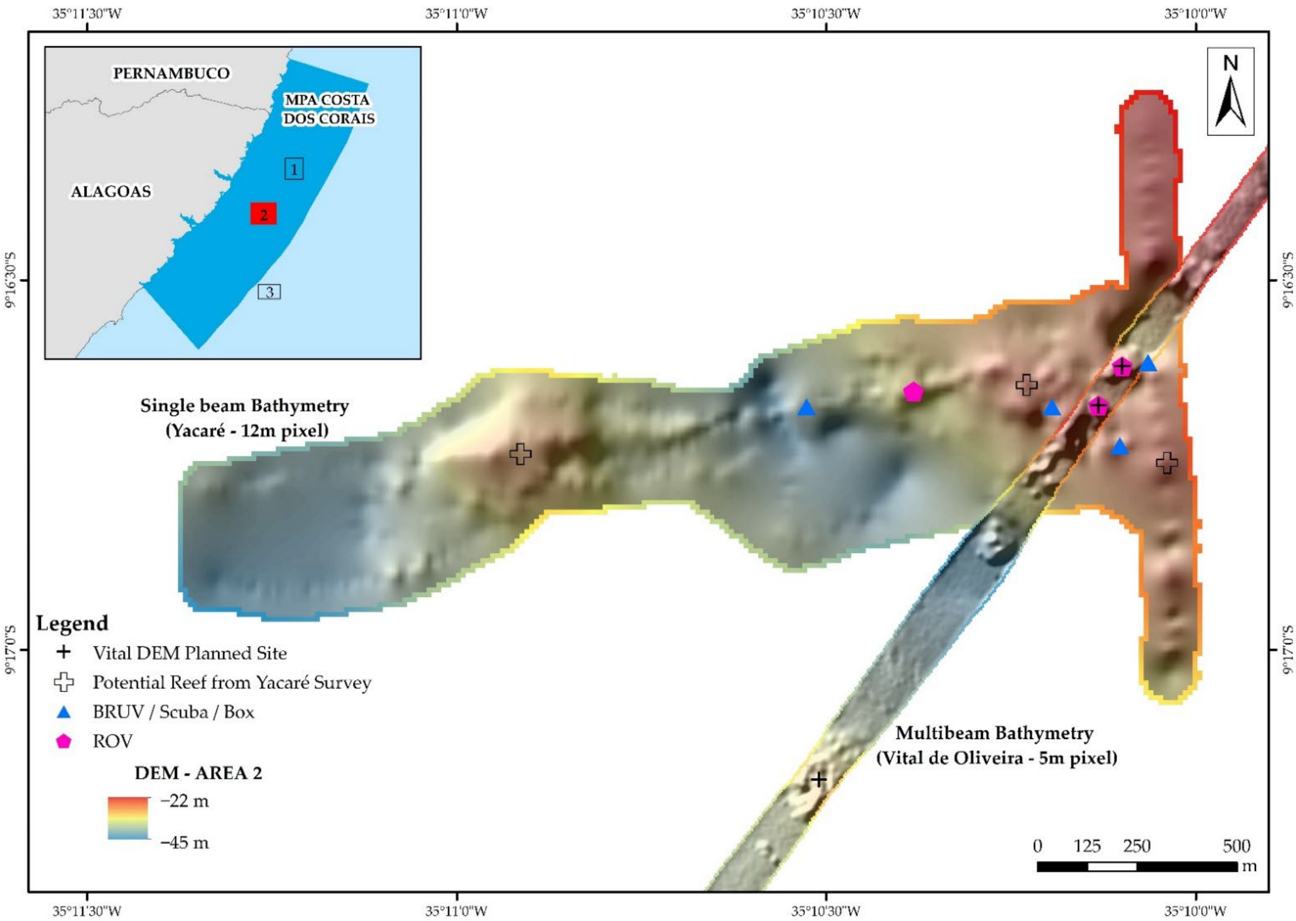

Figure 4. Digital elevation model (DEM) for area 2 with hillshade interpretation highlighting several features, such as the reef top, channels, and isolated head or pinnacle. Red square represents area 2.

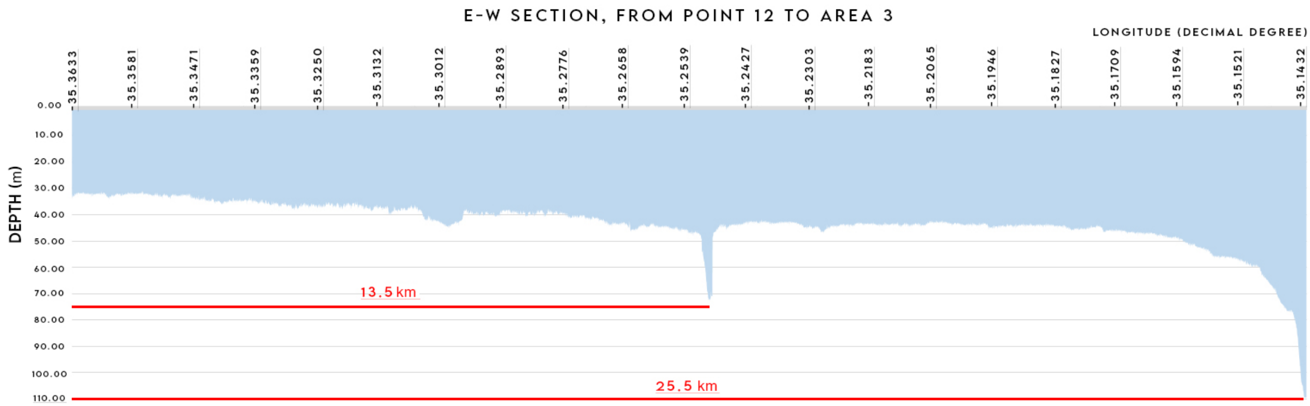

Figure 5. Longitudinal profile of the break of the continental shelf (area 3). Note the 55× vertical exaggeration.

3.2. *Biodiversity*

3.2.1. Benthic Community

We recorded a total of eight coral species and eight sponge species. The benthic assemblage sampled was composed of macroalgae (62%), hard coral (15%), sponge (7%), octocorals, coralline algae, and sand (16%); the other groups (EAM, zoanthids, bare rock, sea urchin, and crionidea) were not recorded in the performed belt transects during the present study, as observed in Figure 6.

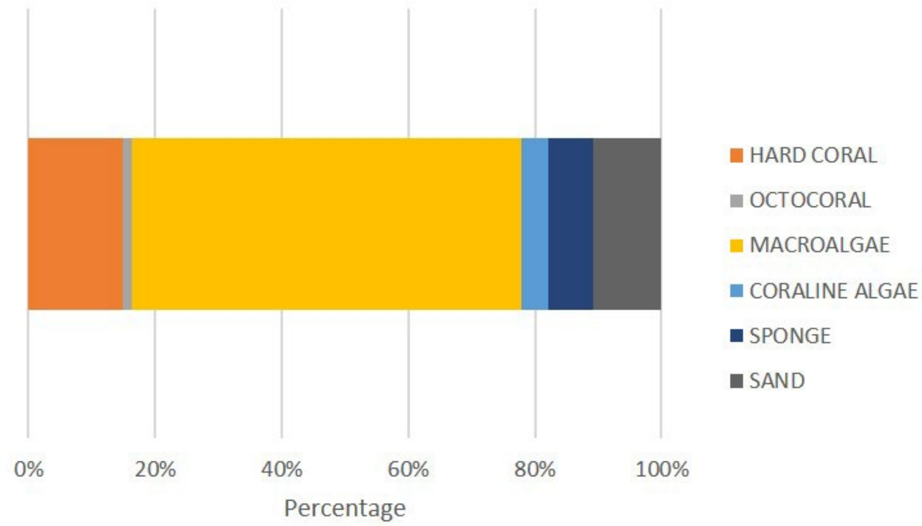

Figure 6. Benthic assemblage composition (%) by group in the mesophotic zone of Marine Protected Area Costa dos Corais, Brazil. EAM, zoanthids, bare rock, sea urchin, and crionidea were not recorded in the transects or other methodologies.

Among the recorded hard coral species, *Siderastrea* spp. was the most representative species (recorded in four areas), together with *Montastrea cavernosa* (recorded in three areas). The largest number of coral species was recorded at Japaratinga (five), while seven sponge species were present at Porto de Pedras (Table 3).

Table 3. Families and species of corals and sponges registered, with identification of the location, minimum depth recorded, and methodology used, in the mesophotic zone of Marine Protected Area Costa dos Corais, Brazil. Depth data available in Table S1 (Supplementary Material).

Family	Species	Min Depth (m)	Maragogi	Japaratinga	Porto de Pedras	São Miguel dos Milagres	Barra de Santo Antônio	Parede
				Corals				
Agariciidae	*Agaricia agaricites*			R				
Faviidae	*Favia gravida*	36.5		S				
Pocilloporidae	*Madracis decactis*	36.5	R	S				
Meandrinidae	*Meandrina braziliensis*				R			
Montastraeidae	*Montastrea cavernosa*	31	R	R, S	R, S			
Mussidae	*Mussismilia hispida*	36.5		S				
Plexaurellidae	*Plexaurella grandiflora*	36.5		S				
Siderastreidae	*Siderastrea* spp.	31	R	R, S	R, S	R		
				Sponges				
Aplysinidae	*Aiolochroia crassa*	31	R	R	S			
	Aplysina fistularis	31	R	S	S	R		
	Aplysina fulva	31		S	R, S			
	Aplysina sp.	31		S	R, S	R		
Clionaidae	*Cliona* sp.		R		R			
Irciniidae	*Ircinia* sp.	31		R	S			
	Ircinia strobilina	31		R	R, S	R	R	
Petrosiidae	*Xestospongia muta*	31	R		S			

R = ROV; S = SCUBA.

The identifiable sponge assemblage comprised eight species. However, the diversity was much higher, but it was not possible to identify most of the species by video, especially the encrusting forms. The reef was dominated by massive forms of sponges, and the most common sponge species were: *Ircinia* spp., *Aplysina* spp., and *Xestospongia muta*.

Aplysina fistularis and *Ircina strobilina* were the most abundant sponge species for the four studied areas. Encrusting species were found associated with scleractinian corals; e.g., *Siderastrea* spp., *Montatrea cavernosa*, and *Agaricia agaricites*. Some representatives of the benthic community observed in the mesophotic zone of MPA Costa dos Corais are shown in Figure 7.

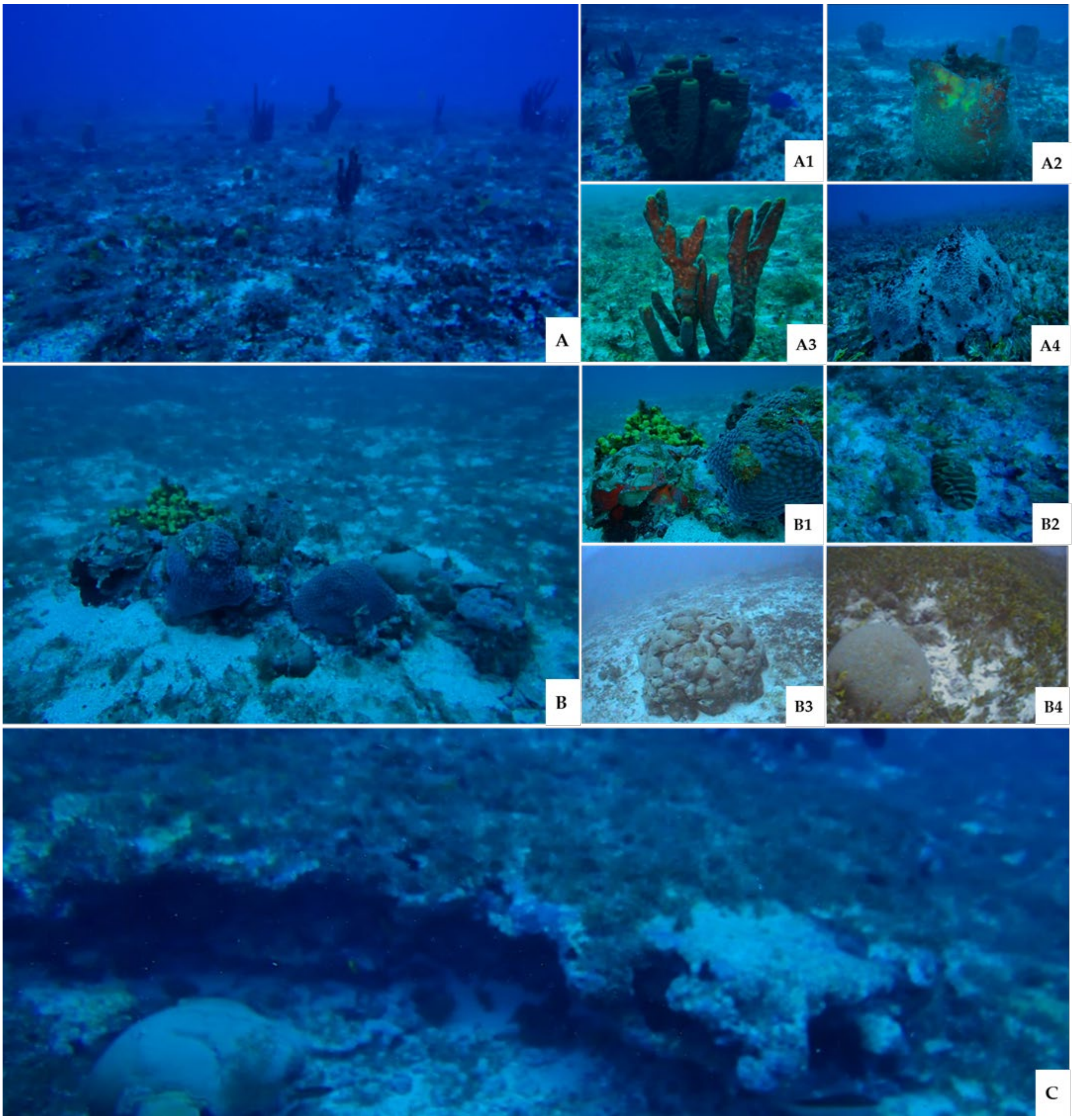

Figure 7. Ecosystems investigated in the mesophotic zone of Marine Protected Area Costa dos Corais using ROVs between 30 and 68 m deep. (**A**) sponge grounds and some representative species: (**A1**) *Aplysina fistularis*, (**A2**) *Xestospongia muta*, (**A3**) *Aplysina* sp., and (**A4**) *Ircinia strobilina*; (**B**) Hermatypicc corals and some representative species: (**B1**) *Montastraea cavernosa*, (**B2**) *Meandrina braziliensis* (**B3**), and (**B4**) *Siderastrea* spp.; (**C**) beachrock.

According to the IUCN's list of endangered species, none of the corals or sponges found in the area of study are at risk of extinction; however, both *Meandrina braziliensis* and *Mussismilia hispida* lack information, appearing as the category "DD" (Table 1).

3.2.2. Fish Community

We recorded a total of 68 fish species belonging to 27 families and 16 orders. The richest families were Labridae (including Scarinae—11 species), followed by Haemulidae (6), Pomacentridae (6), Carangidae (5), and Lutjanidae (4) (Figure 8, Table 2).

Figure 8. Fishes record in the mesophotic zone of Marine Protected Area Costa dos Corais using ROVs, BRUV cameras, and SCUBA between 30 and 68 m deep: (**a**) *Holocentrus adscensionis*, (**b**) *Gymnothorax vicinus*, (**c**) *Cephalopholis fulva*, (**d**) *Halichoeres dimidiatus*, (**e**) *Elacatinus fígaro*, (**f**) *Acanthurus chirurgus*, (**g**) *Caranx ruber*, (**h**) *Haemulon plumierii*, (**i**) *Holacanthus tricolor*, (**j**) schools of *Haemulon squamipinna*, (**k**) *Holacanthus ciliaris*, (**l**) *Acanthurus bahianus*, (**m**) *Acanthurus coeruleus*, (**n**) *Ginglymostoma cirratum*, (**o**) *Abudefduf saxatilis*, (**p**) *Bodianus rufus*, and (**q**) *Balistes vetula*.

Among the recorded species, *Holocentrus adscensionis* (Holocentridae) was the only species that occurred in all areas. The largest numbers of species were recorded at São Miguel dos Milagres (n = 34), followed by Porto de Pedras (33), Japaratinga (30), Maragogi (20), Parede (5), and Barra de Santo Antônio (3). Porto de Pedras and São Miguel dos Milagres also had the largest numbers of exclusive recorded species (9), followed by Japaratinga (8) and Maragogi (2), while Barra de Santo Antônio did not have any exclusive records (Table 4; Figure 8).

Table 4. Family and species of fish registered, along with identification of the location, minimum depth recorded, and methodology used, in the mesophotic zone of Marine Protected Area Costa dos Corais, Brazil. Personal observations are records made by researchers without using any methodology; in environments outside the transect or ROV image, for example. Depth data available in Table S1 (Supplementary Material).

Family	Species	Min Depth (m)	Maragogi	Japaratinga	Porto de Pedras	São Miguel dos Milagres	Barra de Santo Antônio	Parede	Personal Observation
Ginglymostomatidae	*Ginglymostoma cirratum*				R				
Dasyatidae	*Hypanus berthalutzae*	35		B					
Myliobatidae	*Aetobatus narinari*								X
Albulidae	*Albula vulpes*	35		B					
Muraenidae	*Gymnothorax moringa*	35		B					
	Gymnothorax vicinus	35			B				
Clupeidae	*Harengula clupeola*	31				B			
Holocentridae	*Holocentrus adscensionis*	31	R, B	R, S	R, S, B	R, B	R	R, B	
Fistulariidae	*Fistularia tabacaria*	31				B			
Serranidae	*Cephalopholis fulva*	31	R	R, S, B	R, S, B	R, B		R	
	Epinephelus adscensionis	34			B	R			
	Serranus baldwini								X
Malacanthidae	*Malacanthus plumieri*	31	R	B					
Carangidae	*Caranx bartholomaei*	31	R, B	B	R	R, B			
	Caranx crysos	35		R		B			
	Caranx lugubris	31				B			
	Caranx ruber					R			
	Decapterus punctatus			R			R		
Lutjanidae	*Lutjanus alexandrei*		R		R	R			
	Lutjanus cyanopterus			R					
	Lutjanus jocu					R			
	Ocyurus chrysurus	31	R, B	R, B	R, B	R, B			
Haemulidae	*Anisotremus virginicus*	34			R	R, B			
	Anisotremus surinamensis				R	R			
	Haemulon aurolineatum		R	R					
	Haemulon parra	31		R		R, B			
	Haemulon plumierii	31	R			R, B			
	Haemulon squamipinna	35		R, B	R, B				
Sciaenidae	*Equetus lanceolatus*				R				
Sparidae	*Calamus penna*	31	B	B	B	B			
	Calamus pennatula	31	R, B	R		R, B	R		
Mullidae	*Mulloidichthys martinicus*				R	R			
	Pseudupeneus maculatus	31	R	R, B	R	R			

Table 4. *Cont.*

Chaetodontidae	*Chaetodon ocellatus*								X
	Chaetodon striatus	32		S	R, S, B	R, B			
Pomacanthidae	*Holacanthus ciliaris*		R						
	Holacanthus tricolor	31	R	S	R, S	R		R	
	Pomacanthus paru					R			
Kyphosidae	*Kyphosus sectatrix*								X
Pomacentridae	*Abudefduf saxatilis*				R	R			
	Azurina multilineata								X
	Chromis multilineata				R				
	Stegastes fuscus	36,5		S					
	Stegastes pictus		R						
	Stegastes variabilis	36,5		S					
Labridae	*Bodianus rufus*	31	R	S	R, S	R		R	
	Clepticus brasiliensis				R	R			
	Halichoeres brasiliensis								X
	Halichoeres dimidiatus	31	R	R, S	R, S	R			
	Halichoeres poeyi	31	B	R, S, B	R, S, B	R, B			
Labridae-Scarinae	*Cryptotomus roseus*				R				
	Scarus zelindae	31			S				
	Sparisoma amplum	34			B				
	Sparisoma axillare	36,5		S	R	R			
	Sparisoma frondosum	34				B		R	
	Sparisoma radians	34			S, B				
Gobiidae	*Elacatinus figaro*	31	R	R, S	R, S			B	
	Ptereleotris randalli	36,5		S					
Acanthuridae	*Acanthurus bahianus*	35	R	B, R	R	B, R			
	Acanthurus chirurgus	31	R	S	S	R			
	Acanthurus coeruleus	31	R		R, S	R			
Scombridae	*Scomberomorus brasiliensis*	35				B			
	Scomberomorus regalis					R			
Balistidae	*Balistes vetula*	31	R, B	R, S, B	R, B	R, B			
Monacanthidae	*Cantherhines pullus*			R		R			
	Stephanolepis hispidus	34			B				
Ostraciidae	*Acanthostracion polygonius*	34			B	B			
	Acanthostracion quadricornis					R			

R = ROV; S = scuba; B = BRUV; X = confirmed.

The fish assemblage was composed of herbivores (HERB), carnivores (MCAR), omnivores (OMNI), planktivores (PLANK), mobile invertebrate feeders (MINV), and sessile invertebrate feeders (SINV). The predominant trophic guild was MINV which occurred in 31.34% of the families, followed by MCAR (28,36%) and HERB (19,40%), while all other categories showed values below 8% (Table 2, Figure 9).

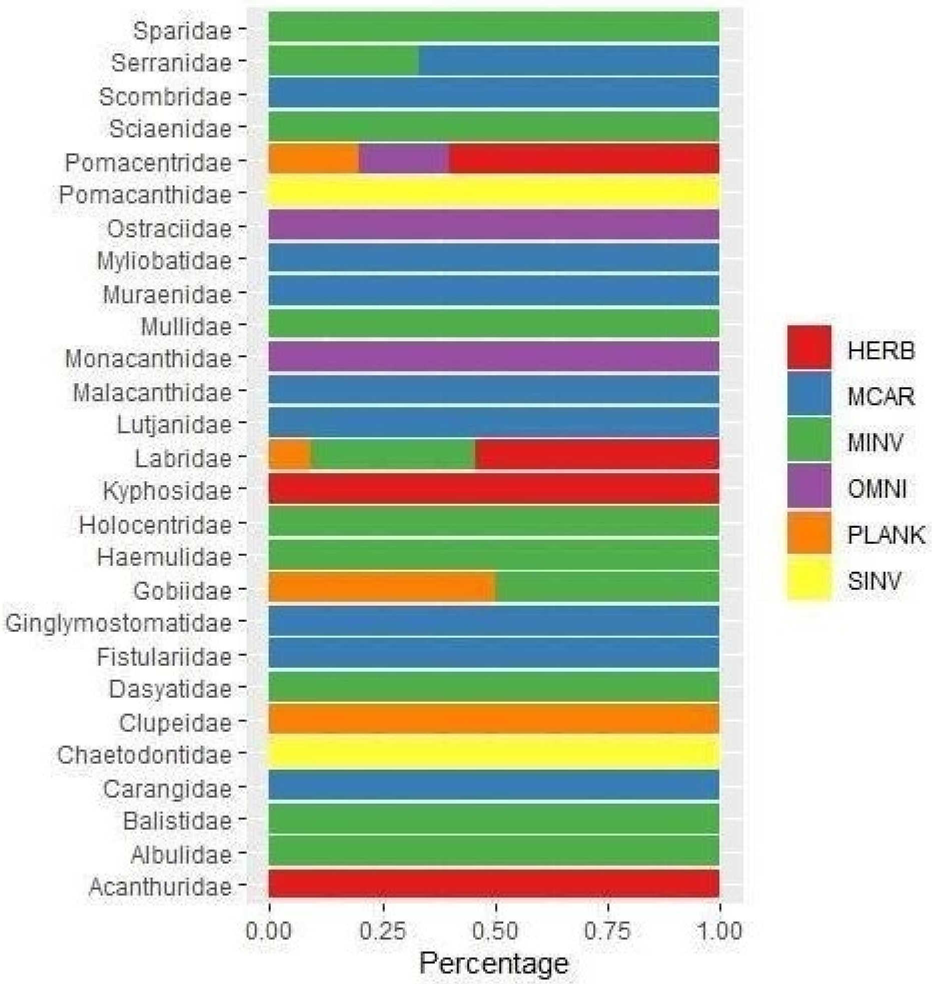

Figure 9. Trophic composition (%) by family in the mesophotic zone of Marine Protected Area Costa dos Corais, Brazil.

According to the IUCN Red List classification [51], 1 species is included as Endangered, 3 as Vulnerable, 4 as Near Threatened, 50 as Least Concern, 6 as Data Deficient, and 4 as Not Evaluated. The Brazilian Red Book of Threatened Species [52] presents 6 species as Vulnerable, 4 as Near Threatened, 44 as Least Concern, 12 as Data Deficient, and 1 as Not Evaluated. Forty-seven species (70.15%) are fisheries targets (Table 2).

4. Discussion

Our data present for the first time the mapping, characterization, and associated biodiversity of mesophotic habitats in the largest coastal Brazilian Marine Protected Area Costa dos Corais. Using a series of different field methodologies—ROVs, BRUV, sonar and scuba diving—we recorded over 16 species of corals and sponges and 68 reef fish species in multiple habitats, such as mesophotic reefs, sponge banks and algae/rhodolith beds. Deeper reefs have been poorly studied on the Brazilian coast and our findings represent the most comprehensive data on mesophotic reefs in MPA Costa dos Corais. While this MPA is the largest on the Brazilian coast, with more than 120 km of coastline, little protection is provided for mesophotic habitats. Currently, the area that corresponds to the mesophotic reefs explored in the study is outside the “no-take” zones of MPA Costa dos Corais. The mesophotic reefs studied herein are known in the MPA management plan as “multiple use areas” that allow fishing activities. Hence, we reinforce the ecological importance of those habitats and the need for full protection.

Historically, zoning in marine protected areas has been conceived as a fisheries management tool to protect exploited stocks, prevent overfishing, and mitigate habitat destruction, allowing the exploitation of exploited populations when fishing pressure and habitat destruction cease [55]. It has also been associated with increased density, biodiversity, body size, biomass, and production within protected areas [56]. The creation of new no-take zones at MPA Costa dos Corais highlights the importance of conservation as a management tool, in addition to seeking to maintain fish stocks and promote the spillover of biomass efficiently, benefiting local fisheries.

The present study data generated the first high-resolution geomorphological model of the mesophotic reefs of MPA Costa dos Corais. The thematic maps produced from the association of the bathymetric and hillshade models demonstrate three geomorphological compartments: the plateau or reef top, paleochannels, and isolated heads or pinnacles. Other research for the coastal region of northeastern Brazil has also contributed to the regional understanding of habitats [12,30,57–59]. Herein, we identify the geomorphology in detail, showing that even at small spatial scales, environmental factors are capable of structuring reef communities. Previous studies have demonstrated the importance of those geomorphological features for reef-associated biodiversity and fishing spawning areas [60–62]. However, much more scientific knowledge on those habitats must be acquired in order to provide managers with better conservation strategies to protect those habitats and the associated biodiversity. For instance, the inclusion of mesophotic reefs as “no-take” zones in the MPA management plan and fishing regulations, including size catch restrictions and quota per fish/fisher, must be urgently implemented.

The occurrence of several endemic and threatened coral/sponges and reef fishes in the study area highlights the ecological importance of the mesophotic reefs of MPA Costa dos Corais. For example, the present study uniquely recorded the Brazilian endemic coral *Meandrina braziliensis* at 32 m depth. It was not possible to carry out the laboratory processes that would be needed for the identification at the specific level of the genus *Siderastrea* [63]. Additionally, large sponge grounds, mostly composed of *Ircinia* spp., *Aplysina* spp. and *Xestospongia muta*, have been documented and mapped at around 40–50 m depth. A previous study [64] mapping the coral reefs at the mouth of the Amazon River reported that large sponge reefs are well-documented in aphotic areas, but they are generally dominated by Hexactinellida (glass sponges), large Demospongiae aggregations that are known as “sponge grounds” or “sponge gardens” and are widely distributed in the North Atlantic. These habitats may encompass up to 50 sponge species, including a strong contribution of *Geodia* spp. A sponge garden hotspot has been recently mapped in West Australia, with 155 different demosponge species from over 350 transects between 18–102 m depth. We believe that the sponge areas found in the MPA Costa dos Corais are similar to a previous report [64], which showed a considerable diversity of sponges in a mesophotic zone. Unfortunately, we were unable to obtain greater precision in the identification of sponges by image. Those habitats have been documented to influence biogeochemical cycling of dissolved nutrients on coral reefs and act as important ecosystems broadly used for marine biodiversity, such as invertebrates and reef fishes [65,66]. Thus, the IUCN data shown for the species *Meandrina brasiliensis* and *Mussimilia hispida* (DD) demonstrate that we must pay special attention to these species to better understand their current conservation status in the SWA.

According to [36], a total of 325 fish species have been listed for MPA Costa dos Corais, including Chondrichthyes (28 species) and Actinopterygii (297). Our data included 68 reef fish species in the mesophotic reefs of the MPA, comprising 21% of all the fish biodiversity of the MPA. As several reef fish species have demonstrated acute decline in the SWA Ocean [67–69], a new management strategy was introduced in June 2019 in Brazil to deter the overfishing of parrotfish species [70]. This innovative strategy, “inverted management”, allows the capture of endangered species inside management areas, such as partially protected marine areas (MPAs), but bans it elsewhere. However, to succeed, the strategy depends on the adoption of a series of challenging management rules, such as co-management, surveillance, high-level fishery statistics data, and long-term monitoring.

Although mesophotic reefs seem to be a conservation alternative in the face of impacts caused at shallow reefs, the authors of [60] conclude that deep reefs are often as impacted as shallow ones, as traces of fishing, sedimentation, exotic species, coral bleaching, and plastic waste have been detected in the Pacific Ocean, Caribbean and Philippines regions, including the study area [71–74]. Furthermore, although there is the possibility of “depth refuge”, the reproductive performance of some coral species decreases with depth; thus, species of shallow environments could not have reproductive success in mesophotic reefs and would be extinguished in the near future. On the other hand, the authors of [27] suggest an optimistic hypothesis where mesophotic reefs could serve as a source of larvae to supply shallow reefs. The authors of [75], in their study on habitat connectivity through the movement and foraging of predators associated with mesophotic reefs, suggest that sharks may be expressive nutrient transporters from shallow habitats to mesophotic environments but to a lesser extent in the opposite direction. Previous studies have suggested a potential for refuge at the deeper reefs in MPA Costa dos Corais [22] due to the distance from the coast, depth limitations, and high fuel costs, limiting fishing activity. Knowledge on mesophotic reefs at the MPA is still very incipient, and the constant monitoring of these areas will allow the evaluation of their effectiveness within this ecosystem and, therefore, a better understanding of their functioning.

5. Conclusions

Our data provide evidence supporting priority conservation areas at the MPA and, therefore, the implementation of “no-take” zones. The creation of those areas at deep reefs highlights the importance of conservation as a management tool by promoting studies and awareness of reef connectivity and recovery, as well as providing maintenance for fish stocks and efficient spillover of biomass, substantially benefiting local fisheries.

Brazil’s reef and marine ecosystems are suffering from climate change and lack of financial resources for research and management actions. In this work, we draw attention to the need for further studies to deploy bathymetric surveys, with the aid of multibeam echo sounders, throughout the MPA Costa dos Corais, with the objective of mapping new regions with relevant biodiversity. In addition, increasing knowledge about protected areas helps in planning mitigation measures against environmental impacts. The Brazilian Navy and some research institutes in the country already have the technology to carry out large-scale mapping. Mapping marine ecosystems is a matter of national sovereignty and of alignment with the Sustainable Development Goals of the 2030 Agenda [76].

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/d14090760/s1, Figure S1: Slope, Terrain Ruggedness and Aspect of area 1. Figure S2: Slope, Terrain Ruggedness and Aspect of area 2; Table S1: Minimum, average and maximum depths by applied methodology.

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