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Habitat mapping of the Vila Franca do Campo marine reserve (Azores) and recommendations for its improvement

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ABSTRACT

The worldwide implementation of Marine Protected Areas (MPAs) has been used as a conservation measure to preserve marine biodiversity. Due to technological limitations, many early designated MPAs often neglected the distribution of marine habitats. Marine remote-sensing techniques development represents an opportunity to reshape and rethink MPA designs. This study focuses on the Vila Franca do Campo MPA (established in 1983) on São Miguel Island, Azores, using advanced acoustic remote-sensing techniques (MBES, SSS). Mapping of approximately 394 ha revealed a 1–3 ratio between rock and sediment habitats within the MPA, while the adjacent unprotected area showed a ratio of less than 1–2, with significant black coral gardens observed below 40 m depth. According to these results and the ecological importance of the organisms detected, we recommend remodeling the MPA. Furthermore, identifying readily accessible black coral communities provides an opportunity for comprehensive assessments of their contribution to marine biodiversity and conservation resources.

1. Introduction

Coastal areas are of outstanding ecological, economic, and social value, but are subject to both natural and anthropic pressures (Botelho, 2013; Cui et al., 2021; de Andrés et al., 2018; Grothe and Schnieders, 2011; van der Reijden et al., 2021). Increasing coastal urbanization exacerbates the degradation of coastal habitats, a trend driven primarily by the transition from subsistence to industrial activities such as tourism and maritime commerce (Cogan et al., 2009; de Andrés et al., 2018; Halpern et al., 2008; Martín-García et al., 2015; Santos et al., 1995). The decline in ecosystem services underscores the need for comprehensive strategies to manage marine environments effectively (Cogan et al., 2009; Davies et al., 2007; Sampaio et al., 2012; Veloso Gomes et al., 2007). However, the lack of detailed data on coastal ecosystems and their distribution poses a critical challenge in implementing such strategies (Kenny et al., 2003; Neilson, 2014).

Contemporary environmental management methodologies are increasingly adopting an ecosystem-based approach (Baldwin and Oxenford, 2014; Cogan et al., 2009; de Young et al., 2008; Tallis et al., 2010), which integrates all interactions, including those human-induced, linked to the functioning of marine ecosystems rather than addressing them in isolation (Christie and White, 2007; Katsanevakis et al., 2011). This marine spatial management framework aims at the sustainable use of marine resources, ensuring biodiversity conservation while considering socioeconomic, political and cultural dimensions (Buhl-Mortensen et al., 2015; Kaiser et al., 2016; Katsanevakis et al., 2011; Leslie and McLeod, 2007; van der Reijden et al., 2021).

Marine Protected Areas (MPAs), supported by legal frameworks, arise as fundamental conservation instruments, demonstrating their effectiveness in biodiversity preservation. MPAs facilitate the recovery of resources of ecological, socioeconomic and cultural value, balancing the sustainable use of resources with the conservation of ecosystems and their services (Bennett and Dearden, 2014; Borges et al., 2020; Caveen et al., 2013; Gubbay, 2005; Marcos et al., 2021; Martín-García et al., 2015; Stephenson et al., 2019; Ware and Downie, 2020). MPAs establishment depends on the identification of critical areas for conservation according to their species and/or habitats (Hooker et al., 2011; Marcos et al., 2021). Baseline data on the distribution and structure of habitats

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are needed, covering both horizontal (spatial arrangement within seascapes) and vertical dimensions (depth-related changes) (Cui et al., 2021; Doukari and Topouzelis, 2020; García-Charton and Pérez-Ruzafa, 1998; Roff et al., 2003; Stelzenmüller et al., 2013).

Development in acoustic remote sensing and georeferenced optical technologies have enabled significant improvements in the accuracy of seafloor mapping (Cooper et al., 2019; Huang et al., 2013; Ierodiaconou et al., 2007; Kaiser et al., 2016; Kenny et al., 2003; Pickrill and Kostylev, 2007; van der Reijden et al., 2021). Multibeam echosounder (MBES) and Side Scan Sonar (SSS), complemented by optical methods, are the predominant technologies being used (Hossain et al., 2016; Kenny et al., 2003; Misiuk and Brown, 2023; Tang et al., 2021). Through the use of these technologies, high-resolution images of the seafloor (up to 10s of cm) are available, facilitating the characterization of the horizontal and vertical distribution of benthic assemblages associated with distinctive acoustic signatures (Fakiris et al., 2019; Kenny et al., 2003; Pandian et al., 2009; Tang et al., 2021).

MBES technology is effective for mapping wide areas of the seafloor using multiple beams for the acquisition of accurate, high-resolution bathymetric data (Fakiris et al., 2019; Kenny et al., 2003; Pandian et al., 2009; Tang et al., 2021), which allow the mapping of seafloor features, including biogenic structures such as seagrass meadows or corals (Christoffersen, 2013; Feldens et al., 2023; von Deimling and Weinrebe, 2014). Furthermore, recording backscatter intensity helps to characterize sediment properties (Cui et al., 2021; Huang et al., 2013; Kenny et al., 2003; Pandian et al., 2009). In contrast, SSS technology provides higher-resolution maps because of its superior angular resolution and closeness to the seafloor. However, it generally does not produce bathymetric data and assumes that the seafloor is flat (Pandian et al., 2009; Tian and Tsao, 2019).

The Azores archipelago, well known for its biodiversity attributed to its remote, temperate-tropical transition location, exemplifies the importance of MPAs (Abecasis et al., 2015; Santos et al., 1995; Silva, 2013). Notably mentioned are cold-water corals, including 18 identified species of black corals (Antipatharians), colonial cnidarians with organic skeletons, some of which form dense stands in shallow waters (Braga-Henriques et al., 2013; de Matos et al., 2014; Tempera et al., 2013, 2021). These corals are essential to the health of sublittoral ecosystems in tropical, temperate, and cold regions, forming large aggregations called “coral gardens or forests” (Bosch et al., 2023; Czechowska et al., 2020; Rakka et al., 2017, 2020). Despite their ecological importance, and being protected within the Azores Natura 2000 network, detailed biological and reproductive information remains scarce (Bosch et al., 2023; MedPAN et al., 2016; Rakka et al., 2020, 2017). The Azores region has a unique and essential MPA network, covering <25% of coastal habitats, highlighting the need to extend protection following EU directives to achieve adequate coverage of the Natura 2000 network, especially for “reef” habitats (MedPAN et al., 2016; Milla-Figueras et al., 2020).

There are five MPAs on the island of São Miguel. Along the southern coast is the Caloura - Ilhéu de Vila Franca do Campo Resource Management Protected Area (PARM Caloura - Ilhéu de VFC), which includes: a “Special Area of Conservation”, under the EU Natura 2000 network (SAC ‘Caloura - Ponta da Galera’), the limpet No Fishing Reserve (RIL) and the Vila Franca do Campo Habitat and Species Management Protected Area (PAMHS-VFC) (Bamber and Robbins, 2009; Dalmolin et al., 2011; Região Autónoma dos Açores - Assembleia Regional, 2008; Silva, 2013). The PAMHS-VFC, initially established in 1983 and subsequently integrated into the Caloura PARM in 2008, comprises a volcanic islet surrounded by cliffs on a seabed composed predominantly of soft sediments (Arsénio et al., 2002; Dalmolin et al., 2011; de Matos et al., 2014; Silva, 2013). The islet, with an area of 339 ha and depths of up to 50 m, is a critical conservation site for breeding seabirds, such as *Calonectris diomedea borealis* (Arsénio et al., 2002; de Matos et al., 2014; Santos et al., 1995). Despite its designation, knowledge of its seascapes and biological assemblages is limited, with initial descriptions focusing largely on the terrestrial aspects of the islet and the impact of anthropogenic activities (Arsénio et al., 2002; Dalmolin et al., 2011). Studies on the underwater biota and geomorphology consisted mainly of species catalogs (Chang et al., 2022; Dalmolin et al., 2011; Morton, 1990; Morton et al., 1998; Tempera et al., 2013), although habitats of high ecological value were identified, such as rhodolith beds in the flooded crater and reefs dominated by brown macroalgae (e.g., *Gongolaria abies-marina* (S.G. Gmelin) Kuntze) (Neto et al., 2021; Rosas-Alquicira et al., 2009).

This MPA, located in one of São Miguel’s areas of greatest human pressure, faces significant anthropic activities from the nearby port of Vila Franca do Campo. Among these activities are professional and recreational fishing, which focus their efforts on the bordering areas of the MPA, industrial operations, and tourism (with organized visits to the islet of up to 400 people between June and September), aggravated by significant urban development, including planned port expansion and new touristic constructions (Arsénio et al., 2002; Botelho, 2013; Morton et al., 1998; Rodrigues et al., 2009; Silva, 2013).

In this study, acoustic and optical mapping techniques were used to map seafloor habitats in and around the PAMHS-VFC MPA. The purpose was to assess if the current protected area adequately covers key marine habitats, or if adjustments to the MPA design are needed to ensure the effectiveness of conservation measures.

2. Materials and methods

2.1. Study site

The study area comprised a sector of the south coast of São Miguel Island (Azores Islands, Eastern Atlantic Ocean) off Vila Franca do Campo (37°43′12″N, 25°25′58″W; Fig. 1), within the VFC PARM Caloura-Ilhéu and in and around the PAMHS-VFC (Fig. 2). São Miguel Island presents characteristics typical of volcanic islands, such as a very narrow island shelf followed by steep slopes (Instituto Hidrográfico, 2010a, 2010b). The coastline is characterized by rugged slopes and rocky drop-offs, alternating with flatter areas resulting from crumbling or ancient lava flows (Santos et al., 1995).

Sedimentary areas are uncommon in the nearshore, although sediment deposits of coarse sand and gravel can be found near river mouths and are widespread on mid to lower island shelf areas (Quartau et al., 2010).

São Miguel Island has a temperate oceanic climate with small thermal variations (±10 °C), between summer and winter. Annual precipitation average is 950 mm, with higher precipitation between September and March (Dias et al., 2007). The island experiences strong winds throughout the year under varying directions and intensities (Dias et al., 2007; Instituto Hidrográfico, 2010a, 2010b).

The Azores are influenced by three currents: the Azores Drift, a “Gulf Stream” branch breaking off from the North Atlantic Drift; the western eddies from the Canary Current bring waters from Spain and North Africa; and the midwater current brings warm, hyperhaline water from the Mediterranean outflow (Bamber and Robbins, 2009; Bashmachnikov et al., 2004; Lafon et al., 2004; Morton et al., 1998; Santos et al., 1995). The surface seawater temperature varies annually between 15 °C and 23 °C. This oceanic activity derived from sea turbulence and local winds, leads to vertical mixing in the water column during the winter, shifting the summer thermocline from 30 to 60 m to about 200 m depth (Instituto Hidrográfico, 2010a, 2010b).

2.2. Hydroacoustic data acquisition

Hydroacoustic data were collected using a SSS and a MBES deployed on an 8 m fiberglass vessel between the 6th and the December 10, 2021. The survey lines generally followed predefined transects parallel to the coast and following the bathymetric contours (data available from Instituto Hidrográfico da Marinha do Porskamp et al., 2022). Each line

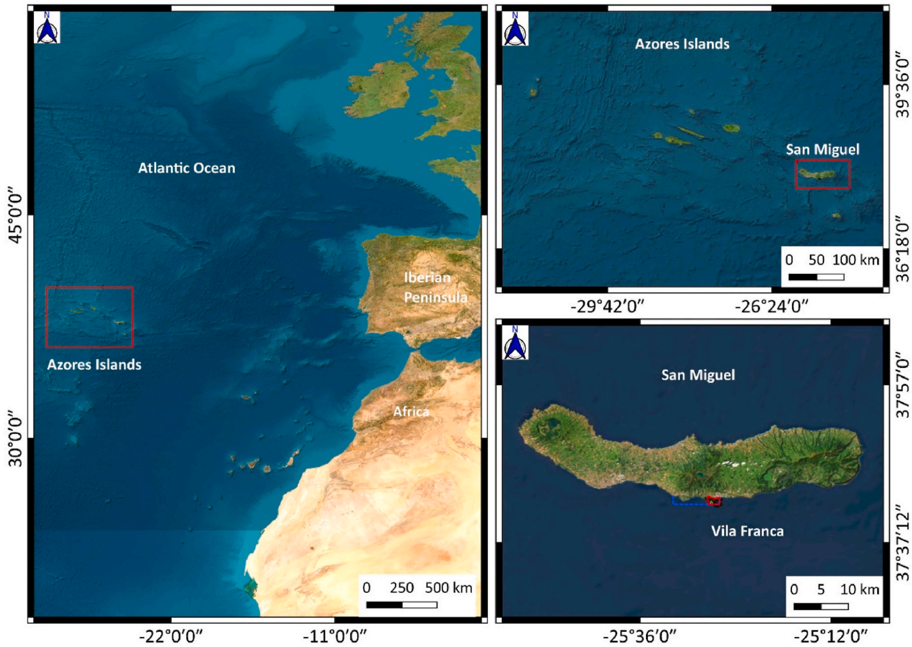


Fig. 1. Progressive sequence of cartographic maps, illustrating the location and geographical features of the study area in Vila Franca (San Miguel, Azores).

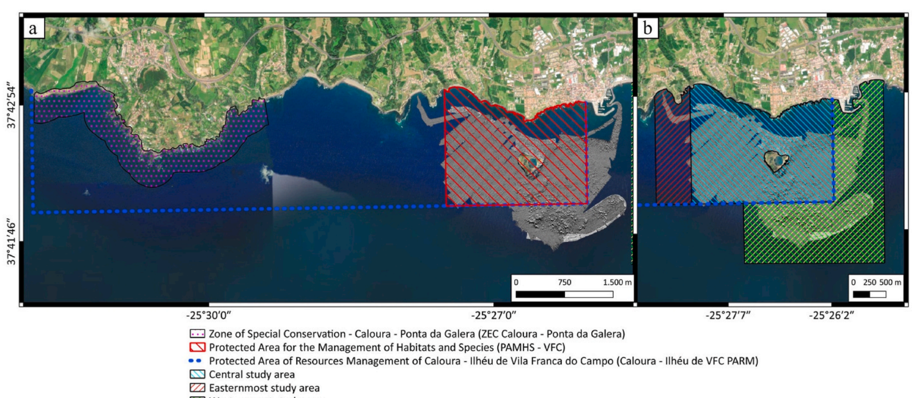


Fig. 2. Location of the study area on the island of Sao Miguel (Azores, Eastern Atlantic Ocean), near Vila Franca with a) Protected areas surrounding the study area; and b) Location of the three main zones sampled.

covered between 600 and 1000 m in length at depths ranging from 5 m to 60 m. The MBES acquires both high-accuracy bathymetric data and backscatter data, while the high-frequency SSS excels in seafloor imaging because of its large object detection and discrimination of seafloor features capabilities, providing high-resolution acoustic images (0.1 m accuracy; Buhl-Mortensen et al., 2015; Kenny et al., 2003; Pandian et al., 2009) of the seafloor (Fig. A1).

The MBES (Norbit iWBMS Bathy) was attached to the starboard side of the vessel, at approx. 0.5 m below the surface, with a custom-made metal mount (Fig. A2) and oriented vertically downwards. The MBES was emitting frequency modulated signals with a central frequency of 400 kHz and a bandwidth of 80 kHz, and an across-track angle of 100°—140° (depending on water depth). Measurements were performed with a sweep time of 500 μs, while the ping rate was controlled by the water depth.

The backscatter data and depth values were recorded by the Norbit iWBMS software. A sound velocity probe integrated into the MBES head was used to correct the sound velocity in the water. Vessel position and motion compensation information was provided by an inertial navigation system (Applanix POS MVSurfMaster). The MBES surveys recorded bathymetry in a depth range from 8.5 to 70 m. Strong heave and roll movements that could not be compensated by the available motion sensor partially impacted data quality, leaving visible artefacts perpendicular to the ship heading in both backscatter and bathymetric data. The data processing required to create bathymetric and backscatter grids (i.e., pitch and roll calibration, automatic and manual removal of outliers, angular correction of intensity values and response curves to a reference angle of 40°) was carried out using the software QPS Qimera v. 2.4 and FMGT v. 7.9. Bathymetric data were processed to a resolution of 1 m.

It has recently been proposed that black coral forests can be detected using the multi-detect (MD) capabilities of multibeam echosounders (Feldens et al., 2023), where the low-intensity target formed by the chitin and protein coral skeleton is recorded as an additional target in the water column, in addition to the main bottom detection. Currently, the detection of MD data does not directly confirm the presence of black corals. However, it does offer locations for further exploration through visual inspection, in this case using underwater video cameras and divers. MD were recorded in the south-eastern survey area. Each line was sailed twice to improve the signal-to-noise ratio of the MDs, which can also be caused by mobile targets such fish or air bubbles. Therefore, a 400% coverage was attained in the overlapping areas covered by repeated lines, while 200% coverage was achieved in non-overlapping areas. MD situated more than 2 m above the seafloor were not considered as previous records on black coral gardens of the same species in the Macaronesia (see Table 1 in Czechowska et al., 2020) do not growth up to 2 m, and MD were manually processed in Qimera to remove detections caused by roll artefacts, following the procedure described in Feldens et al. (2023). The remaining MD were then visualized in QGIS. A 2 × 2 m grid was created covering the study area and MD were counted within each grid cell. Only grid cells containing MD recorded on at least two independent survey lines were retained for the following analysis. The resulting maps indicate areas of targets, including black corals, protruding from the seabed into the water column. The nature of these targets is investigated using underwater video footage.

The SSS, a digital CM2 Towfish (C-Max, UK), was attached to a Kevlar cable and towed behind the boat (Fig. A2) at a height of 15 m–20 m above the seabed, at a vessel speed of less than 3 knots. The towfish emitted signals with a central frequency of 780 kHz and a horizontal beamwidth of 0.3°, covering a range of 50 m each side of the vessel. The software SonarWiz 6 V6.05.0008 (Chesapeake Technology Inc., 2016; Los Altos, CA, USA) was used to log the backscatter data. The same GPS source used for the MBES provided the navigation data used to estimate SSS towfish positioning in the SonarWiz 6 software. The raw backscatter data were processed in SonarWiz 6 applying empirical gain normalization, automatic gain control, bottom tracking, layback correction, and a nadir filter.

All processed and georeferenced acoustic backscatter data were exported as GeoTiff images, with a resolution of 0.5 m per pixel and represented in a QGIS (Quantum GIS Development Team, 2019) to produce interpreted habitat maps and estimate the cover of each habitat type. Due to the presence of artefacts in the data, automatic delineation of habitats resulted in a significant amount of noise. However, given the small area and lack of time constraints, a manual delineation of acoustically distinct habitats was conducted, based on backscatter intensity and texture. This manual approach typically yields results of similar quality relative to automatic procedures (Diesing et al., 2014; Hossain et al., 2014; Schimel et al., 2010).

Processed SSS data were plotted as mosaics represented in greyscale where black corresponds to low backscatter and white to high backscatter. In order to measure the dynamics in areas covered by soft sediments, both ripple height and peak-to-peak distances were measured in the two different types of sedimentary seabed found (Fig. A3). For this purpose, the following formula (Schwarzer et al., 2014) was applied,

$$h = H * {}^{b}\!/_{a + b}$$

where h = height of the boulder, H = height of the towfish above the seafloor, a distance from the towfish to the boulder, b = length of the

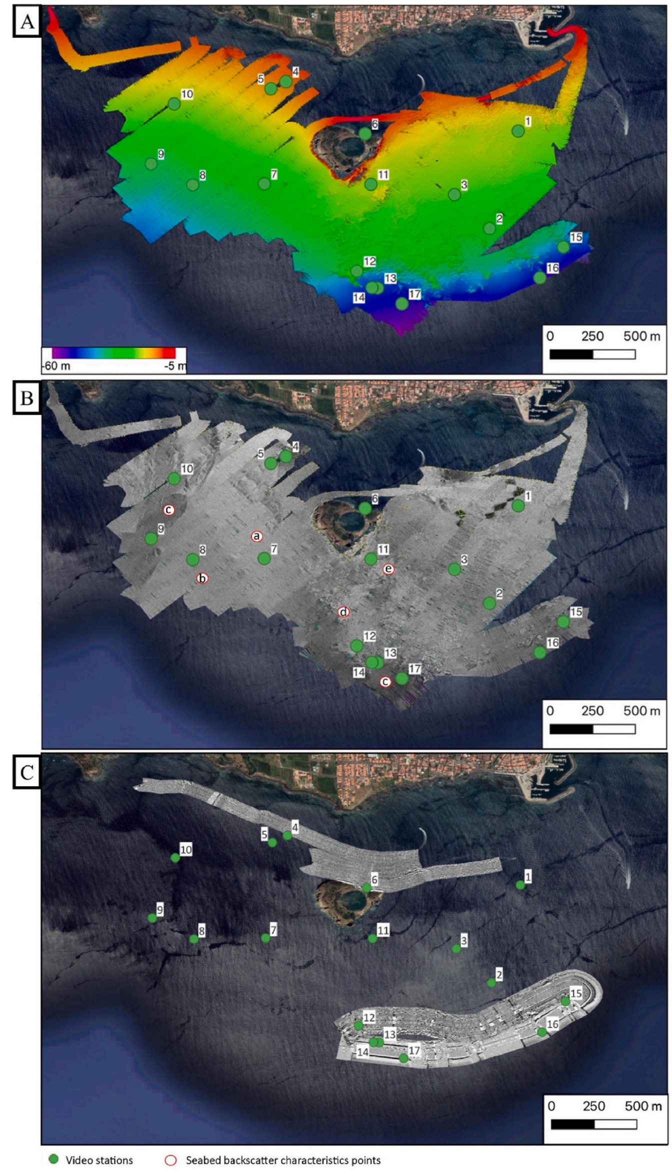


Fig. 3. A: bathymetric data. B: MBES-derived backscatter information. C: SSS-derived backscatter information.

Table 1
Surface (Ha) ± SE of mean, and % of the mapped study area habitat in brackets for each of the 3 study areas.

Habitat	Total area (Ha)	Western area (Ha)	% of total	Central area (Ha)	% of total	Eastern area (Ha)	% of total
Sedimentary seabeds							
Flat soft sediment seabed	94.39 ± 0.32 (23.95%)	0.13 ± 0.008 (1.59%)	0.14%	72.15 ± 0.54 (28.41%)	76.55%	22.11 ± 0.23 (16.75%)	23.46%
Rippled soft sediment seabed	116.09 ± 7.42 (29.46%)	7.65 ± 1.69 (94.06%)	6.58%	90.31 ± 13.62 (35.56%)	77.70%	18.13 ± 9.02 (13.73%)	15.60%
Extensively rippled soft sediment seabed	74.69 ± 2.22 (18.95%)	0.32 ± 0.008 (3.89%)	0.42%	48.21 ± 2.51 (18.99%)	64.55%	26.16 ± 6.16 (19.82%)	35.02%
Soft sediment seabed with undetermined textures	3.58 ± 0.14 (0.91%)			3.58 ± 0.14 (1.41%)	100%		
Hard-rock seabeds							
Rock	105.33 ± 0.029 (26.73%)	0.038 ± 0.004 (0.46%)	0.04%	39.69 ± 0.01 (15.63%)	37.68%	65.61 ± 0.22 (49.70%)	62.29%
Total	394.08 ± 0.07	8.13 ± 0.71	2.06%	253.94 ± 0.076	64.44%	132.01 ± 0.21	33.50%

shadow.

2.3. Ground-truth sampling and analysis

Seabed video imagery captured with a GoPro Hero 8 underwater digital camera (approx. 140° horizontal field of view), with a resolution of 1920 × 1080p@120fps (GoPro, San Mateo, USA) was used to ground-truthing the acoustic seabed facies mapped from the backscatter mosaics. Video transects were positioned using the GPS coordinates of the vessel for later comparison with acoustic maps of substrate types and the benthic communities they support. The camera was mounted on a fishing line, pointing downwards at a 45° angle from vertical, with a diver spotlight installed approx. 2 m above the camera. The camera was deployed at 19 locations, in depths between 8 m and 70 m, and towed for short periods of time (approx. 3 min) while the boat drifted to ensure that sufficient seabed footage was acquired to describe the benthic habitat. Sites were selected to cover areas with different acoustic signatures, after prior identification of key ground-truthing sites from acoustic data that, when combined with the vessel drift data, provided a global view of the habitat areas to be mapped. By combining the data from the MBES, high-frequency SSS with ground-truthing by underwater video image we have been able to generate an accurate map of the habitats due to the complementary nature of the three tools (Buhl--Mortensen et al., 2015; Pandian et al., 2009).

2.4. Biodiversity analysis

Through the visualization of images taken at each sampling site, we identified species (macro-invertebrates and fishes), which were counted (i.e., maximum number of individuals observed per species at each sampling point (Letessier et al., 2015)). Images that lacked relevant data were excluded, including those that only showed the water column, or those that showed images of the seafloor after a direct impact with it. Subsequently, a representative, random subset of images (approx. 30–50 images per site) was analyzed at each site."

3. Results

3.1. Bathymetric and backscatter characteristics

The acoustic survey covered a total area of 394.08 ha, including 64.4% (253.94 ha) of the PAMHS-VFC supplemented by 8.13 ha to the west and 132.01 ha to the east (Fig. 3, Table 1). Hence, we distinguished between three main zones: the westernmost study zone, which falls within the Caloura PARM, the central zone, delimited by the PAMHS-VFC, and the easternmost zone, which is outside any protected area (Fig. 2). Water depths in the surveyed area ranged from 6 m towards the São Miguel Island shoreline and the Vila Franca islet to 52 m in the southeast (Fig. 3). To the west of Vila Franca, the seabed showed few morphological features and slopes gently to the south at 3° or less. To the east of the Vila Franca - islet alignment, the seabed became increasingly complex with extensive hard-rock outcrops. Down to about 35 m water depth, the elevation of the hard-rock outcrops above the surrounding seabed rarely exceeds 4 m. A break in the slope is observed in the SE of the study area, where depths increase rapidly from about 32 m to about 40 m depth along a series of hard-rock outcrops. Below this slope, the spatial distribution of MD in the coral habitat (Fig. 4) showed a maximum occurrence of targets protruding into the water column. The height distribution of MD targets recorded in the acoustic data (Fig. A4), showing the number of unique detections and the difference with the mean seafloor depth in a 2 × 2 m grid cell, shows a reduction of MD targets encountered at depths ≥40 m despite the presence of rocky outcrops. Above the slope, there was less evidence of MD. MD were mostly associated with hard-rock outcrops and can occur both on their sides and on top. Noticeably, not all rock outcrops were associated with MD presence.

The backscatter intensities showed changes in seafloor characteristics that were not apparent from seabed morphology. To the west of the Vila Franca islet, intermediate backscatter intensities prevail ("a" in Fig. 3, Table 2). However, between 18 m and 32 m depth, a NW-SE-oriented boundary marks the transition to a low backscatter facies ("b" in Fig. 3, near video stations 8 and 10; Table 2). Further west, a NNW-SSE elongated feature, 100–1000 m wide, with low backscatter intensities dominated ("c" in Fig. 3, near video station 9; Table 2).

South of the Vila Franca islet and towards the east, hard-rock outcrops can be recognized by high backscatter intensities ("d" in Fig. 3,

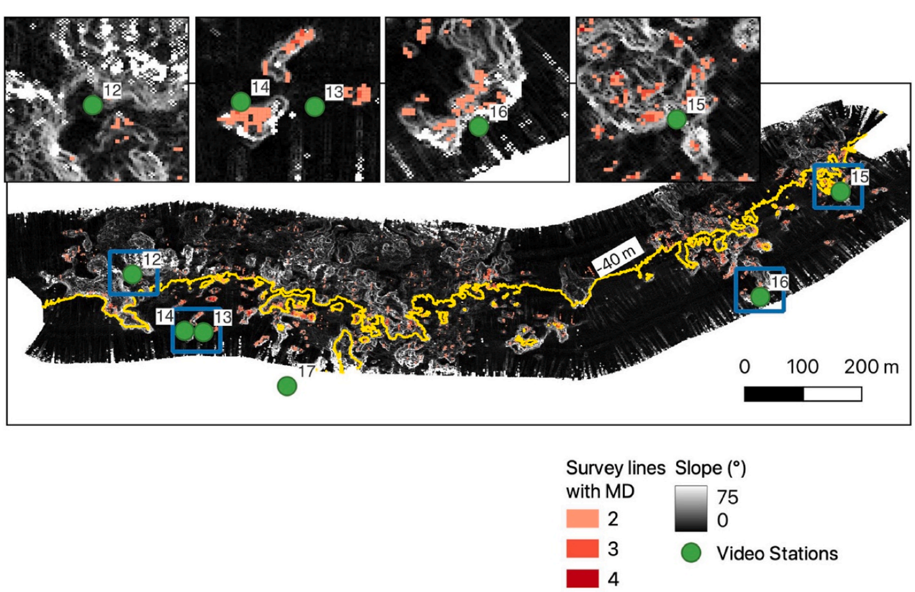
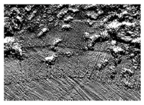
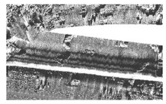
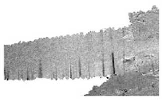
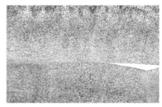
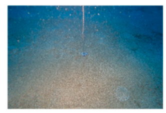
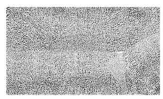
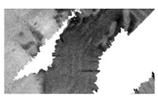
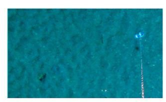


Fig. 4. The MD data are presented on a slope map, showing acoustic targets extending into the water column, which were used as baseline information to direct the video stations to locate the presence of black corals. A yellow line represents the 40 m depth contour line. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Classification and description of SSS backscatter patterns with associated seabed features and sedimentary facies.

Background/ seabed class	Acoustic Patterns (backscatter) MBES	Acoustic Patterns (backscatter) SSS	Ground-truthing patterns	Close to Video station	Acoustic Pattern Description	Features Association	Sedimentary Facies Association
Hard-rock seabed				14	High backscattering (predominantly), rough texture	Rocks, Reefs	Rock and Bioconstructions
Soft sediment seabed				6	Low backscatter, smooth and homogeneous texture.	Flat background	Bioclastic sediments fine/medium grained.
				6	Moderate backscattering, smooth/rough and homogeneous texture.	Dunes and ripples with ridges	Bioclastic and siliciclastic medium to thick-grained sediments.
				4	High backscattering, rough and heterogeneous texture.	Dunes and ripples with ridges oriented in different directions	Bioclastic and siliciclastic medium to thick-grained sediments.

near video stations 1, 12 and 13; Table 2). Between the outcrops, there were intermediate backscatter intensities ("e" in stations 2, 3 and 11). Below the series of hard-rock outcrops to the SE, backscatter intensities drop to low levels (station 17), comparable to those observed near station 9 to the west (Fig. 3, both occurrences marked with "c").

3.2. Habitat description

Five primary seabed facies were identified and categorized into sedimentary and hard-rock seabed types. The sedimentary seabed, making up 73.3% of the area surveyed, consisted of four units. The flat soft sediment seabed, accounting for 24.0% of the surveyed area (Figure A5 and Table 2), displayed a uniform acoustic pattern with low backscatter. The rippled soft sediment seabed, comprising 29.5% of the surveyed area (Figure A5), features moderate backscatter. Its acoustic textures vary from smooth/rough mixtures to uniform (Table 2). This facies was characterized by ripples averaging 0.23 ± 0.01 m in height, with a ridge spacing of 1.33 ± 0.05 m (Table A1). Another unit was the extensively rippled soft sediment seabed, which represents 19.0% of the surveyed area (Figure A5). It was distinguished by a high backscatter

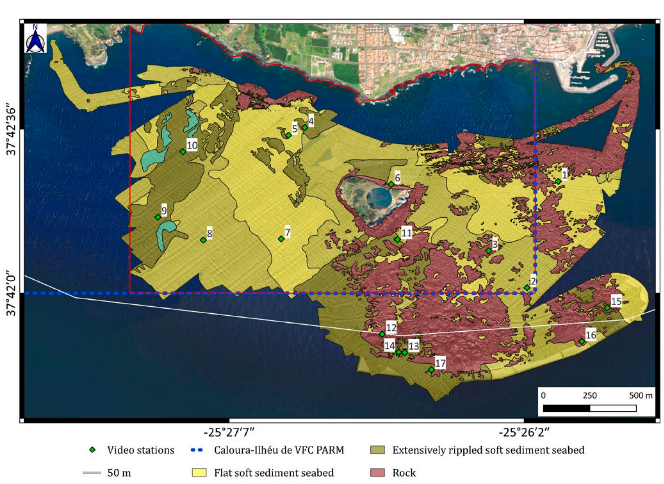


Fig. 5. Habitat map of the study area, showing the five habitat classes observed and the protected areas.

acoustic pattern and a rough, heterogeneous texture (Table 2). The ripples had an average height of 0.41 ± 0.03 m and a ridge spacing of 1.09 ± 0.06 m (Table A1). Lastly, there were soft sediment seabeds with undetermined textures with a homogeneous acoustic pattern similar to the soft-sediment seafloor but with stronger backscatter, making up 0.9% of the area (Figure A5). Hard-rock seabed facies included rocky reefs, and isolated scattered boulders, presenting a heterogeneous acoustic pattern with a strong backscatter. Hard-rock seabed covered a smaller area than the different sedimentary facies seabeds, and in some cases, contained small soft sediment pockets (Fig. A5, Table 2). The spatial distribution of the seabed facies within the study area is illustrated through a detailed mapping, with specific details on their spatial extent provided in a comprehensive table (Fig. 5; Table 1).

Over the western zone, the seabed comprised medium-grained sediments, as assessed by underwater video images (video stations 7–9), with sparse hard-rock outcrops covered by turf algae (Table 1, Fig. 5, A5).

The central zone (PAMHS-VFC) was also dominated by soft sediment bottoms (Fig. 5, Table 1). This zone can be divided into two sub-zones (eastward and westward), considering the central position of the Vila Franca islet. As in the western area, the westward area continues the conformation of previous soft sediment, being crossed by two large zones of rippled soft sediments (Fig. 5, A5). Additionally, four patches of soft sediment with unspecific texture were detected (Fig. 5). The hard-rock seabeds were identified as submarine extensions of the bedrock features observed offshore. Conversely, in the eastward area, flat soft-sediment seabeds (with finer grain size compared to video stations 7–9 in the east) were identified surrounding the islet, as well as the soft-sediment to hard-rock interface surrounding the islet (Fig. 5). The hard-rock seabed appeared to be mostly colonized by turf algae (Fig. A5). Toward the southwestern boundary of the Central zone (PAMHS-VFC), two rock outcrops were identified (approx. 25 m depth), which contained several patches of fine (low backscatter) sediment and were separated by a belt of flat soft sediment seabed (Fig. 5, A5). Ground-truthing by video revealed that these rock reefs were covered by turf algae (Fig. A5).

In the easternmost zone, we found similar proportions between rock and sedimentary seabeds (Table 1). Sediment bottoms were flat and dominated by coarse biogenic grains. Furthermore, rock bottoms extend from the coastline beyond the limits of the PAMHS-VFC, to a depth of approximately 65 m (Fig. 5). Ground-truthing (from video stations

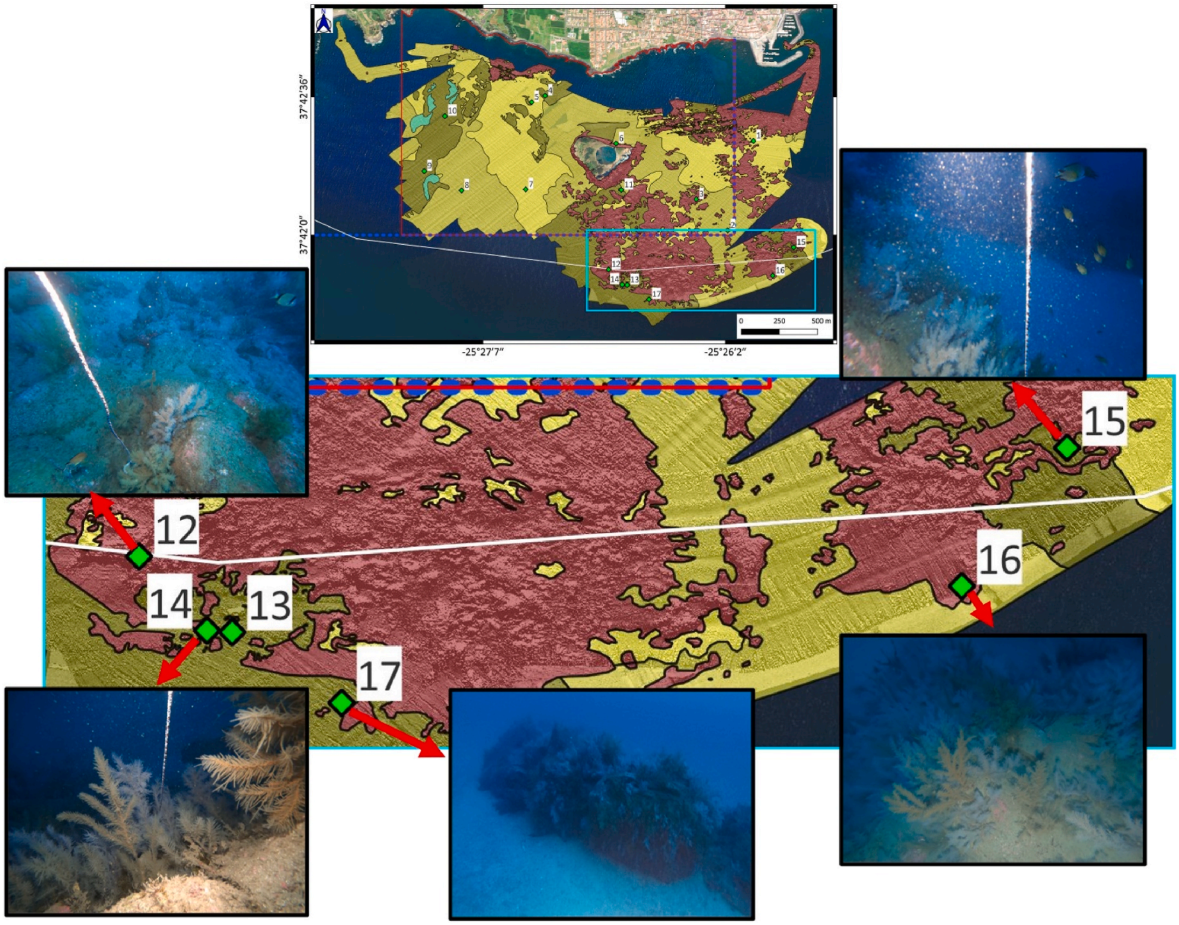


Fig. 6. Ground-truthing imaging from the video stations located within the identified coral habitat.

12–17) indicated that the rock outcrops gradually changed from a non-calcareous turf cover to a combined cover of macroalgae (e.g., *Acrosorium* spp., *Asparagopsis* spp.) and black coral colonies from 50 m depth onwards, resulting in a circalittoral black coral garden (Fig. 6, Table A2). The coral-dominated habitats comprised two main morphologies (e.g., *Antipatella* spp. and *Tanacetipathes* spp.; (Tempera et al., 2013)) that colonized rocky substrates in equal proportions (Table A2). In shallow water, coral colonies were smaller in size (approx. < 20 cm) and mostly isolated (Fig. 6, Table A2). With increasing depth, both the size of coral colonies (approx. 50 cm) and their density increased, almost completely covering the rocky reefs (about 85–100% coverage; Fig. 6, Table A2).

3.3. Biodiversity description

Sampling sites were classified according to three habitat types: soft sediments, rocks, and black corals. A total of twenty species were identified, with three species exclusive of soft sediments, three to rocky substrates, and seven species exclusively observed in black coral habitats (Fig. 7, Table A.3). In addition, a similar maximum number of individuals was observed in rocky and black coral habitats (93 and 91 individuals, respectively), which contrasts with a lower number in sandy substrates (41 individuals; Fig. 7, Table A3).

4. Discussion

This study highlights the occurrence of habitats of conservation interest that were scarcely documented in the area surrounding the MPA PAMHS - VFC, down to 65 m depth (Buhl-Mortensen et al., 2015; Pandian et al., 2009).

The sediment habitats in the MPA are characterized by an unstructured and impoverished epifauna, dominated by vagrant taxa that tolerate unstable sediments, and not well characterized as a community (Bamber and Robbins, 2009; Kenny et al., 2003). Rock outcrops are normally recognized for their ecological value and high biodiversity, providing a substrate for epifauna, and playing a refuge, nourishment, and nursery role due to their structural complexity (Cosme De Esteban et al., 2023; di Franco et al., 2016; Guidetti, 2000). However, the shallow rocky reefs inside the MPA were mostly smooth rock colonized by abundant and dense turf, which does not allow the assembly of other sessile organisms such as macroalgae and sessile invertebrates (e.g., sponges, hydrozoans, and bryozoans (Dalmolin et al., 2011). Deeper, on the southern edge and beyond of the MPA limits, the rocky reef epibionts progressively changed with depth, from attached macroalgae and sparse colonies of black corals (approx. 50 m), to high-density coral colonies that mostly cover the rocky outcrops from 60 m onwards. These forests of stationary, suspension feeding organisms, create complex 3D hotspots of marine biodiversity (Rossi et al., 2021), offering a wide range of microhabitats for sessile epifauna, cryptofauna and endoparasites, as well as refuge, nourishment and nursery role for motile species such as invertebrates and fishes with commercial value (Fig. 7) (Biber et al., 2014; Buhl-Mortensen et al., 2016; le Guilloux et al., 2010; Sampaio et al., 2012; Söffker et al., 2011).

The Azores archipelago is remarkably diverse in terms of corals (about 150 species) compared to other parts of the Northeast Atlantic (Brito and Ocaña, 2004; Hall-Spencer et al., 2007; Tempera et al., 2021). However, on the island of Sao Miguel, only one black coral forest, composed mainly of Antipathella subpinnata (Anthozoa, Antipatharia), has already been described in the north of the island, but at deeper

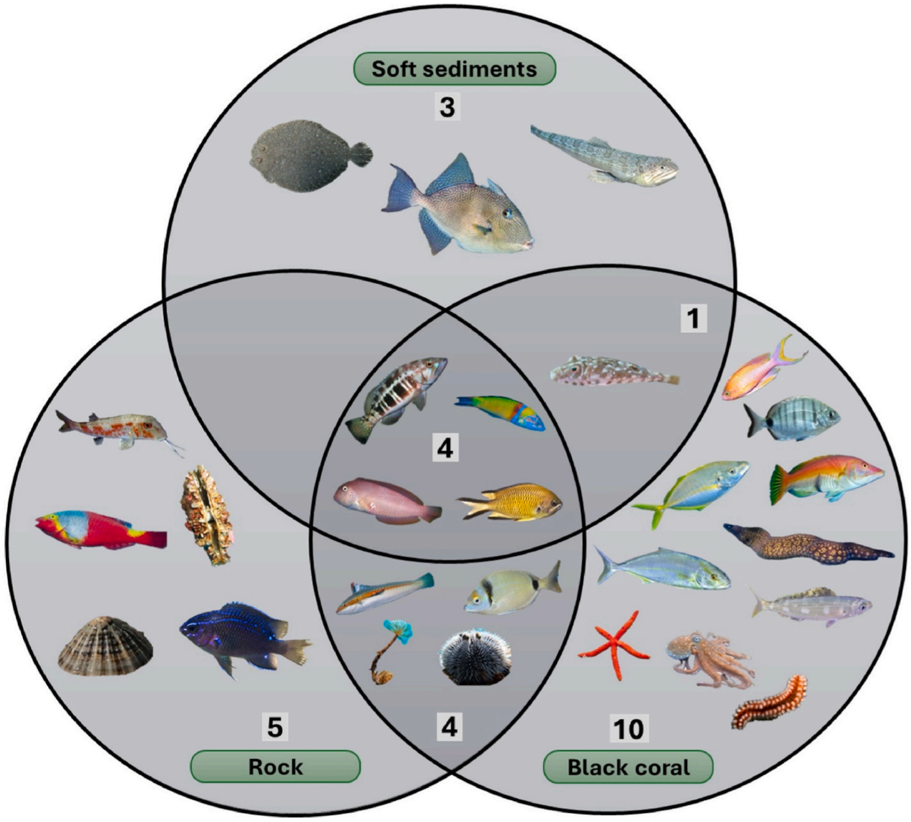


Fig. 7. Venn Diagram illustrating the distribution of unique and shared species across the three habitats.

depths (between 70 m and 770 m) compared to those surveyed in this study (de Matos et al., 2014). The results obtained in this study results showed a shallowest black coral forest (about 50 m) composed by at least two species belonging to the Myriopathidae family (Brito and Ocaña, 2004).

The difficulty in mapping these coral ecosystems, particularly in the past, may have contributed to the exclusion of ecosystems of high ecological value, such as these rocky reefs covered with black coral, which are located outside the boundaries of the PAMHS-VFC MPA. Indeed, unlike calcium carbonate skeleton coral reefs, which are acoustically recognizable on traditional morphological and backscatter maps (Feldens et al., 2023; Glogowski et al., 2015; Lim et al., 2020), black corals are difficult to identify due to the coral's protein-chitin skeleton and their occurrence within steeply sloping seafloor outcrops (Czechowska et al., 2020). Therefore, they are different to recognize in traditional backscatter maps of both MBES and SSS, as the feint signal from the chitin skeleton is masked by the surrounding seafloor (Czechowska et al., 2020). Water column imaging — novel for applications in habitat mapping (Porskamp et al., 2022), due to data volume and lack of standard analysis procedures — uses the high sensitivity of the multibeam echo sounder transceiver to record weak acoustic signals scattered in the water column, suitable to map internal water column stratification (Colbo et al., 2014) or even migrating zooplankton (Weinrebe, 2020). Black corals forests were found to scatter sound signals as well (Feldens et al., 2023). Normally, these signals are filtered by the bottom-detection algorithm of modern MBES which are optimized to map the seafloor.

Plotting the MD (detected in at least two independent survey lines, to account for e.g., the presence of fish bladders that can also cause additional received soundings) gives information about stationary targets protruding from the seafloor into the water column. Underwater video-image acquired in this research, confirm these targets to at least include black coral forests in the study area. Combined with ground truthing, these maps can serve as a baseline for the distribution of black coral forests (Feldens et al., 2023). In the study area, the video imagery (Figs. 3 and 6) indicates a decrease in coral abundance and height ≥40 m depth, also observed by Czechowska et al. (2020). This decrease is consistent with a reduction in MD targets found at depths ≥40 m despite the presence of rocky outcrops. This suggests a widespread presence of black coral forests <40 m depth at the majority of rocky outcrops.

A further, and plausible reason explaining the omission of these key marine animal forests (MAFs; (Rossi et al., 2017)), would be related to the main objective for which the Vila Franca do Campo MPA was established originally in 1983 (Região Autónoma dos Açores - Assembleia Regional, 1983). The MPA was implemented to preserve the islet terrestrial natural values, such as the high richness of endemic plants (Arsénio et al., 2002; de Matos et al., 2014; Silva, 2013) and the existence of nesting migratory pelagic seabirds (Buhl-Mortensen et al., 2015; Giacomo et al., 2021). Along with the presence of these valuable biota, analytical studies of the main bio-geological resources (relief, fauna, and flora) of the islet were sufficient for the establishment of the protected area (Região Autónoma dos Açores - Assembleia Regional, 2008). For this reason, the MPA core area has been delimited at the maximum low tide line of the islet (Ministério Do Ambiente, 2008). An additional buffer area (approx. 350 m, see Fig. 1) was put in place to facilitate its isolation from potentially harmful external influences (Bennett and Mulongoy, 2006; Burger et al., 2010; Fernández-Juricic et al., 2005; Martino, 2001; Norris, 1993; Rodgers and Schwikert, 2002) while only enabling small anthropogenic interactions (Bennett and Mulongoy, 2006; Claudet et al., 2008; Correll, 2005), and neglecting surrounding marine habitats.

5. Conclusions and recommendations

The current ecosystem approach for conservation states that an effective habitat management and monitoring strategy relies on the creation of maps based on the fixed (e.g., topology) and variable (e.g., temperature) environmental features or requirements of the habitats located in the area to be protected (Cosme De Esteban et al., 2023; Galparsoro et al., 2014; Hooker et al., 1999; Lecours et al., 2015; Vierling et al., 2008). Accordingly, the establishment of MPAs, as we have shown in this study, which have omitted these criteria can result in an ineffective protection (Katsanevakis et al., 2011). In this sense, it is inaccurate that the design of the buffer zone of Vila Franca do Campo MPA remains identical throughout the boundaries of the core area and does not vary according to the significance of the surrounding marine habitats (Heinen and Mehta, 2000; Li et al., 1999; Martino, 2001). Overlooking key marine habitats of large ecological and socioeconomic value (e.g., rhodolith and black corals, (Neto et al., 2021; Rosas-Alquicira et al., 2009); this study) may cause their degradation and even complete disappearance (Agardy et al., 2005; Barragán, 2014), in particular when an increase in fishing and tourist activities has been recorded in the area in the last decades (de Andrés et al., 2018).

Therefore, based on the results of this study and the evidence of the essential habitats to be protected, it is recommended that the boundaries of the PAMHS-VFC MPA be redefined, including a more detailed assessment of the black coral communities in deeper areas and monitoring of the various anthropogenic activities in the area. Since the marine part of the protected area was created to preserve the terrestrial area, its restructuring should not neglect this protection. This is why we propose a reduction of the marine part in the western zone and an expansion in the eastern and southern parts (Fig. 8). This would achieve the protection of the new reefs found together with the epibenthic habitats described above, without sacrificing the protection of the western area due to the fact that it is under protection within the Caloura - Ilhéu do VFC PARM protected area. Consequently, this restructuring of its boundaries, together with future biological and anthropic studies inside and outside the proposed new area, will support the conservation of marine resources and the sustainable management of this emblematic coastal area.

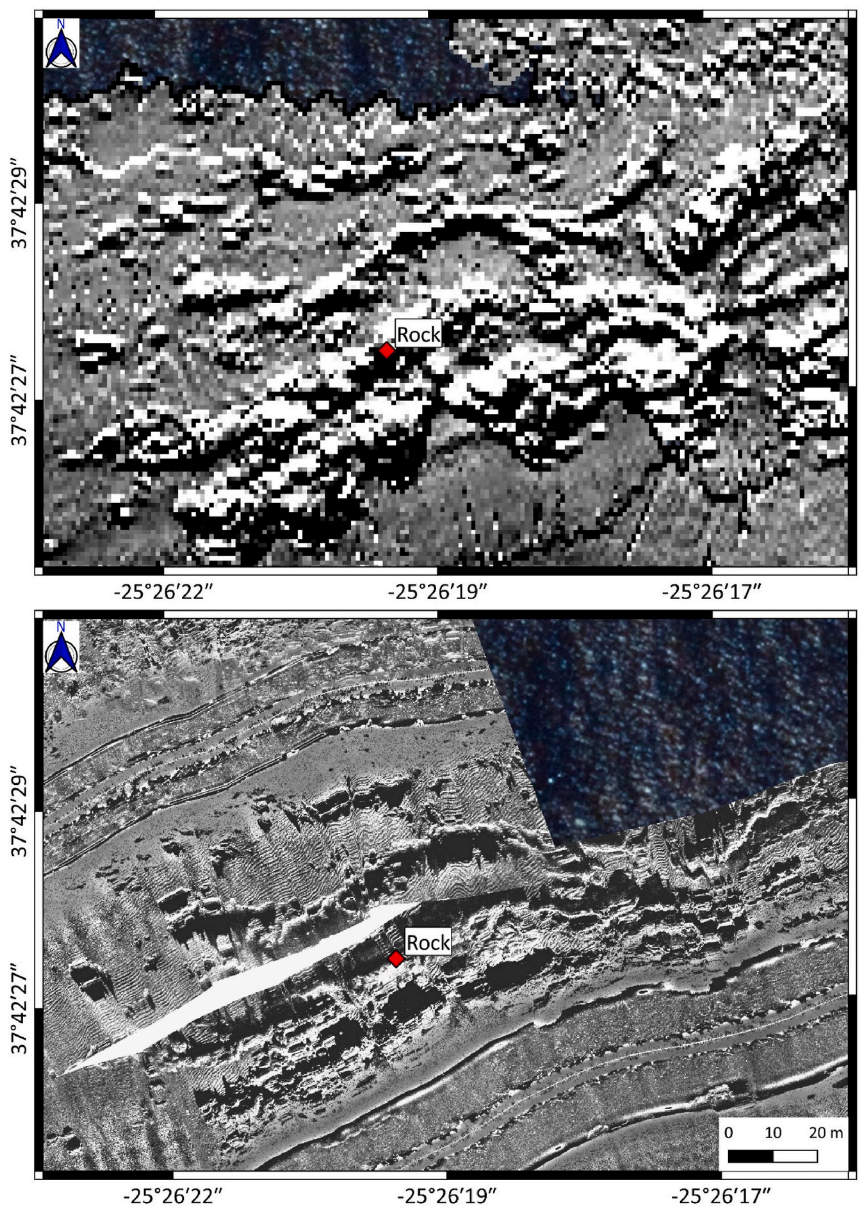


Fig. A.1. Differences between MBES (top) and SSS-derived (bottom) backscatter information.

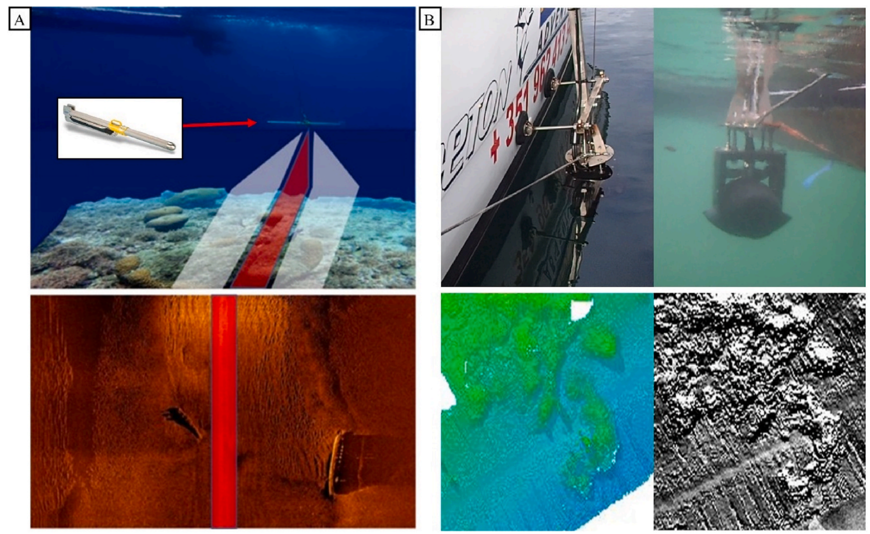


Fig. A.2. SSS acquiring data process. B: MBES acquiring data process and installation.

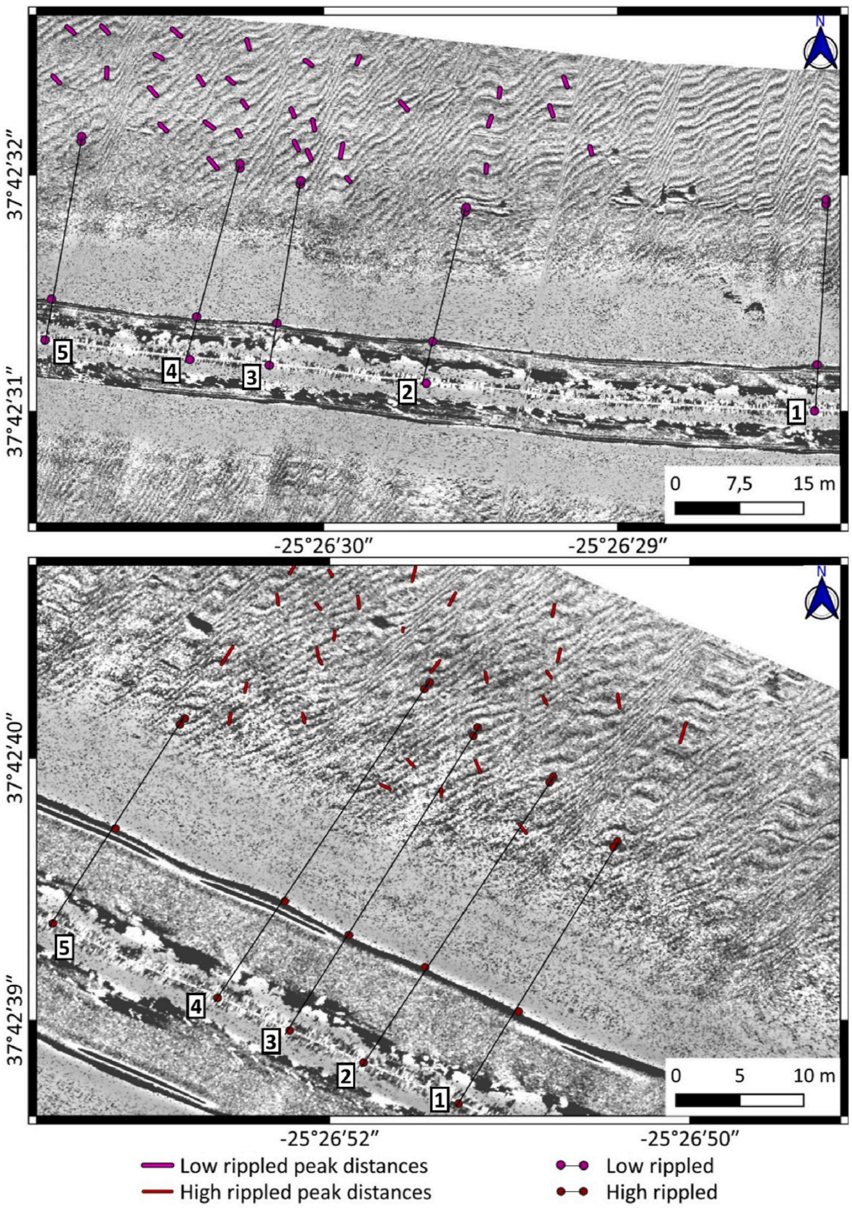


Fig. A.3. Ripple peak-to-peak distance and height measurement points from SSS transects.

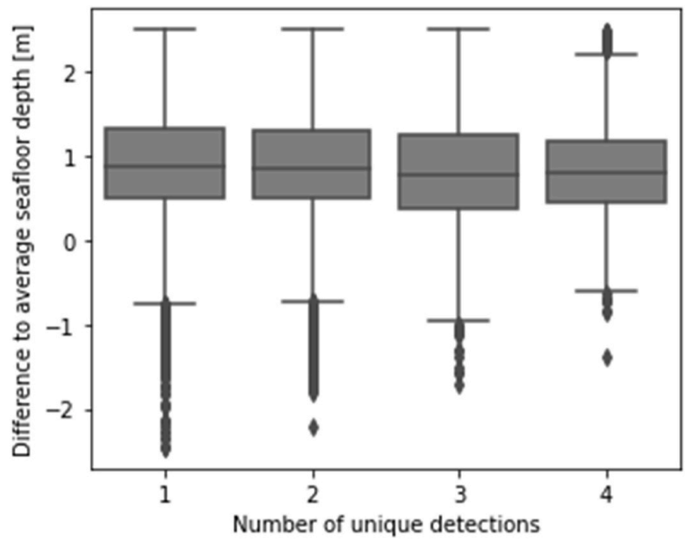


Fig. A.4. Summary of the height distribution of MD targets recorded in the acoustic data showing the number of unique detections (two or more are required), and the difference from the mean seafloor depth in a 2 × 2 m grid cell.

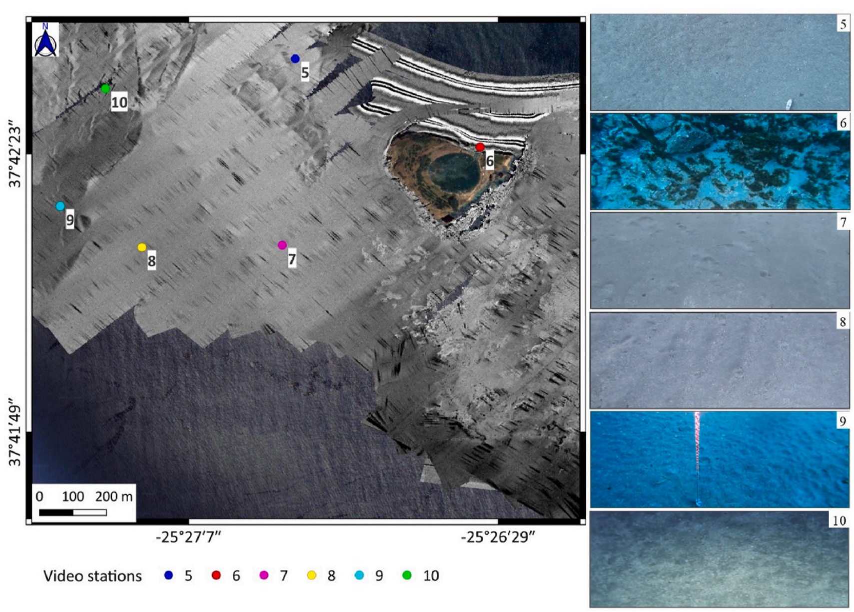


Fig. A.5. Differences between the different backscatter characteristics pertaining to habitats observed. 5: Rippled soft sediment seabed; 6: Rock seabed cover by turf; 7: Flat soft sediment seabed; 8: Rippled soft sediment seabed; 9–10: Extensively rippled soft sediment seabed.

Table A 1
Ripple height measurement points in meters from SSS transects, calculated following the formula of Schwarzer et al. (2014) (H = height of the towing fish above the seafloor, h = height of the boulder, a = distance from the towing fish to the boulder, b = length of the shadow).

Station	Low rippled					High rippled				
	1	2	3	4	5	1	2	3	4	5
H	6.51	6.31	6.39	6.30	6.95	10.30	10.63	10.49	10.94	10.78
a	19.02	20.60	20.50	22.25	23.60	17.67	20.63	21.87	23.57	11.21
b	0.79	0.77	0.74	0.74	0.78	0.73	0.71	0.91	0.79	0.58
$h = H * b/_{a+b}$	0.26	0.23	0.22	0.20	0.22	0.41	0.35	0.42	0.35	0.53
Ave. ± (SE)	0.23 ± (0.01)					0.41 ± (0.03)				

Table A 2
Mean of black coral forests features showing the occurrence frequency of the forests and each of both species in the forest on the rocky seabed; and the coverage and height of the forest (1: 0–20 cm; 2: 20–50 cm; 3: >50 cm).

Station	Depth (m)	Frequency	Time (s)	Species 1	Species 2	Coverage	Coral average height range
12	35.50 (sloping)	86.27%	102	52.27%	47.73%	19.83%	1.87
14	46.80	90.74%	341	47.96%	52.04%	75.05%	1.82
15	45.00 (sloping)	84.71%	477	54.15%	45.85%	54.76%	1.95
16	53.50	91.77%	243	34.08%	65.92%	83.61%	2.81
17	52.70	0.00%	114	50.00%	50.00%	100%	3

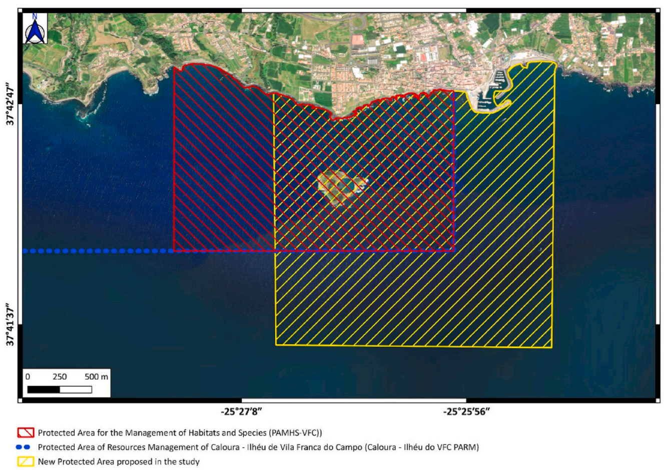


Fig. 8. Reshaped limits of the Protected Area for the Management of Habitats and Species proposed in this study.

Table A 3
Biodiversity Data Summary showcasing sampling points, primary habitats, and maximum counts of individuals and species, encompassing both ichthyofauna and invertebrates.

Station	Habitat	Ichthyofauna		Invertebrates	
		Total N	Spp	Total N	Spp
1	Soft sediment	41	*Chromis limbata*		
			Serranus atricauda		
			Bothus podas		
			Xyrichtys novacula		
2	Rock	13	*Chromis limbata*	1	*Polychaeta (Sabellida)*
			Serranus atricauda		
			Diplodus vulgaris		
3	Rock	93	*Chromis limbata*	6	*Polychaeta (Sabellida)*
			Serranus atricauda	1	*Echinodermata (Echinoidea)*
			Thalassoma pavo	2	*Gastropoda (Patella)*
			Similiparma lurida		
			Sparisoma cretense		
			Coris julis		
			Mullus surmuletus		
			Sphoeroides marmoratus		
4	Soft sediment	3	*Thalassoma pavo*		
			Sphoeroides marmoratus		
			Xyrichtys novacula		
			Bothus podas		
5	Soft sediment	0	-		
6	Rock	16	*Serranus atricauda*	1	*Bivalvia (Pinnidae)*
			Thalassoma pavo	2	*Polychaeta (Sabellida)*
			Similiparma lurida	1	*Echinodermata (Echinoidea)*
			Sparisoma cretense		
7	Soft sediment	3	*Xyrichtys novacula*		
			Sphoeroides marmoratus		
8	Soft sediment	4	*Balistes capriscus/ carolinensis*		
			Sphoeroides marmoratus		
			Xyrichtys novacula		
9	Soft sediment	7	*Sphoeroides marmoratus*		
			Xyrichtys novacula		
10	Soft sediment	3	*Sphoeroides marmoratus*		
11	Soft sediment	2	*Sphoeroides marmoratus*		
			Synodus synodus		
12	Black coral	46	*Diplodus vulgaris*		
			Chromis limbata		
			Thalassoma pavo		
			Serranus atricauda		
			Boops boops		
			Coris julis		
			Bodianus scrofa		
			Seriola dumerili		
			Sphoeroides marmoratus		
13	Rock	3	*Serranus atricauda*		
			Xyrichtys novacula		
14	Black coral	22	*Diplodus vulgaris*	1	*Echinodermata (Asteroidea)*
			Chromis limbata	1	*Cephalopoda (Octopoda)*
			Serranus atricauda	4	*Polychaeta (Amphinomida)*
			Coris julis	1	*Polychaeta (Sabellida)*
			Boops boops		
			Xyrichtys novacula		

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Table A 3 (*continued*)

Station	Habitat	Ichthyofauna		Invertebrates	
		Total N	Spp	Total N	Spp
15	Black coral	40	*Thalassoma pavo*	3	*Polychaeta (Amphinomida)*
			Serranus atricauda		
			Diplodus vulgaris		
			Chromis limbata		
			Pseudocaranx dentex		
			Boops boops		
			Coris julis		
16	Black coral	91	*Serranus atricauda*	4	*Polychaeta (Amphinomida)*
			Diplodus vulgaris	1	*Echinodermata (Echinoidea)*
			Chromis limbata	1	*Echinodermata (Asteroidea)*
			Muraena helena		
			Diplodus cadenati		
			Seriola dumerili		
			Anthias anthias		
			Boops boops		
17	Black coral	0	*Bodianus scrofa*		

CRediT authorship contribution statement

Marcial Cosme De Esteban: Writing – review & editing, Writing – original draft, Investigation. **Peter Feldens:** Writing – review & editing, Investigation. **Ricardo Haroun:** Writing – review & editing, Supervision. **Fernando Tuya:** Writing – review & editing. **Artur Gil:** Writing – review & editing, Resources. **Francisco Otero Ferrer:** Writing – review & editing, Writing – original draft, Supervision, Investigation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Marcial Cosme De Esteban reports financial support was provided by Canarian Agency for Research Innovation and Information Society. Francisco Otero Ferrer reports financial support was provided by European Union.

Data availability

Data will be made available on request.

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