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Characterization and mapping of bathyal benthic communities of Cabo Verde (NW Africa)[☆]

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ABSTRACT

Benthic communities, such as those dominated by cold-water corals (CWC) and sponges, contribute to the habitat complexity and diversity of deep-sea ecosystems, with characteristic taxa serving as indicators of Vulnerable Marine Ecosystems (VMEs). Many areas on the West African margin remain under-surveyed for the presence of deep-sea benthic communities and, hence, VMEs, limiting the implementation of marine spatial plans. In this study, the benthic communities of SW Cabo Verde (NW Africa), in particular Cadamosto Seamount (SW Brava Island) and the slopes of the islands of Fogo and Brava, were characterized and mapped, providing an assessment of the potential differences in benthic community composition between the two systems (seamount vs island slopes). We employed machine learning approaches (multivariate regression trees and a Random Forest classification) using data on morphospecies composition and densities retrieved from Remotely Operated Vehicle (ROV) video data collected from 2,100 to 1,450 m depth, as well as environmental data on substrate type, terrain, and water column parameters. Ten different benthic communities were identified in the study area, with cnidarians, porifera, and echinoderms as the dominant taxa. Higher densities of CWCs and communities with higher species richness were observed on the seamount compared to the adjacent island slopes. Depth, substrate type, pH and dissolved oxygen were identified as the key environmental variables driving habitat heterogeneity. Additionally, communities composed of characteristic taxa with VME attributes were observed, including (i) sponge aggregations, (ii) scleractinian, (iii) octocoral and black CWC gardens, and (iv) sea pen fields. Despite the apparent low impact of fishing activities in the study area, lost fishing gear was noted in areas where CWCs were observed in higher densities. This study provides important information for the implementation of area-based conservation measures in Cabo Verde, following the application of the precautionary principle.

1. Introduction

Given the vulnerability of deep-sea benthic communities to adverse impacts from bottom contact fishing gears, the United Nations General Assembly (UNGA Res. 59/25, Art. 66, 2004; UNGA resolution 61/105, 2007) called upon Regional Fisheries Management Organizations (RFMOs) to protect Vulnerable Marine Ecosystems (VMEs) (FAO, 2009). Vulnerable Marine Ecosystems are defined based on (1) uniqueness or

rarity, (2) functional significance of the habitat, (3) fragility, (4) life-history traits of component species that make recovery difficult and (5) structural complexity.

Cold-water corals (CWC) and deep-sea sponges are characteristic taxa of benthic communities, contributing with an important ecological role to deep-sea ecosystems. For instance, coral gardens and sponge aggregations can form structurally complex habitats (Buhl-Mortensen et al., 2010; Price et al., 2019; Morato et al., 2021) that contribute to

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deep-sea biogeochemical cycles (de Kluijver et al., 2021; Hanz et al., 2022) and support high biodiversity (Buhl-Mortensen & Mortensen, 2005; Roberts et al., 2009; Beazley et al., 2013). These habitats act as refugia and nursery for commercially important species (D'Onghia, 2019) and are thus considered important fishing grounds (Huvette et al., 2016; Capezzuto et al., 2018). However, many CWCs and sponges are long-lived (Roark et al., 2009; Fallon et al., 2010; Hitt et al., 2020) and fragile species (Hennige et al., 2020; Morrison et al., 2020), with slow growth rates (Orejas et al., 2011; Lartaud et al., 2016), which increases their vulnerability to the impacts of fishing activities (Orejas et al., 2009; D'Onghia et al., 2017; Linley et al., 2017). For these reasons, they can be considered indicator taxa for the presence of VMEs (FAO, 2019).

To establish science-based management plans for the sustainable use of marine resources, it is paramount to characterize and map deep-sea benthic communities in order to identify VMEs and areas of high ecological importance. Area-based conservation measures, such as Marine Protected Areas (MPAs), are effective tools for protecting VMEs by reducing human pressures, preventing habitat degradation, and supporting long-term habitat recovery (Davies et al., 2007; Huvette et al., 2016; Beazley et al., 2021). However, there is still a lack of knowledge about the global distribution of VMEs, amplified by a regional bias, as most mapping and characterization studies have focused on the North Atlantic (Lim et al., 2020), which hampers effective conservation planning.

Nonetheless, recently, more studies have focused on the characterization and mapping of VMEs in under-sampled areas, particularly in equatorial and southern oceanic regions (e.g. Victorero et al., 2018; Ramiro-Sánchez et al., 2019; Salinas-de-León et al., 2020; Bridges et al., 2021; Tapia-Guerra et al., 2021; Pearman et al., 2022; Hanafi-Portier et al., 2023). Along the Atlantic coast of Africa, the increase in sampling effort over the past two decades has shown the presence of CWCs in nearly all Exclusive Economic Zones (EEZ) (Freiwald et al., 2021). However, most scientific studies on deep-sea benthic communities in the region focus on reef-forming CWCs along the continental slope (Jones et al., 2014; Buhl-Mortensen et al., 2017, 2023a; Wienberg et al., 2018; Hanz et al., 2019; Hebbeln et al., 2019, 2020; Orejas et al., 2021; Vinha et al., 2023), limiting the comprehensive understanding of VME occurrence in other environmental settings. At the same time, several factors already place deep-sea benthic communities in West Africa at high vulnerability, because of the potential impacts from bottom trawling (Zeeberg et al., 2006; Gascuel et al., 2007; Axelsen & Johnsen, 2015), illegal, unreported and unregulated (IUU) fisheries (Doubouya et al., 2017; Petrossian, 2018; Okafor-Yarwood, 2019), piracy (Doubouya et al., 2017; Denton & Harris, 2021), offshore oil and gas exploration and exploitation (Tekka, 2012; Ovadia, 2014), climate change (Sweetman et al., 2017) and, in the future, deep-sea mining (Zongwe & Mutambara, 2023).

Off NW Africa, the Cabo Verde archipelago takes a unique position. It benefits from increased biological productivity through its exposure to the NW African upwelling system (Pelegrí et al., 2017) and from seafloor topography-induced upwelling events that enhance phytoplankton blooms at a local scale (Schütte et al., 2016; Cardoso et al., 2020; Mohn et al., 2021). The environmental conditions of Cabo Verde attract a wide range of marine organisms to the region, contributing to its status as a "marine biodiversity hotspot" (Roberts et al., 2002). Flagship species of Cabo Verde include sea turtles (Rocha et al., 2015; Patino-Martinez et al., 2022), marine mammals (Wenzel et al., 2020; Ryan et al., 2023) and seabirds (González-Solís et al., 2009; Militao et al., 2017), as well as different fish species (Wirtz et al., 2013; Freitas, 2014; Czudaj et al., 2021), some of commercial importance, such as skipjack and yellowfin tuna (Menezes et al., 2015; González et al., 2020). However, little is known about the benthic communities of Cabo Verde, either in shallow (Morri and Bianchi, 1995; Monteiro et al., 2008; Freitas et al., 2019; Lopes et al., 2021), mesophotic (Gómez-Gras et al., 2025) or deep waters (Molodtsova, 2006; Sampaio et al., 2019; Scépanski et al., 2024; Vinha

et al., 2024).

This study aims to address the present-day knowledge gap about the deep-sea benthic communities of Cabo Verde, by characterizing and mapping the bathyal communities (1,400 to 2,100 m depth) of SW Cabo Verde, with a focus on Cadamosto Seamount (SW Brava) and on the island slopes of Fogo and Brava. In particular, our study aims to answer the following research questions: (1) what is the deep-sea benthic community composition of SW Cabo Verde? (2) what is the spatial distribution of benthic communities? and (3) which environmental factors drive the spatial patterns of community composition? Given the environmental settings of the study area, we also aim to provide insights on (4) how benthic communities differ between seamounts and adjacent island slopes, as previous studies have shown that benthic communities on seamounts can differ (Hall-Spencer et al., 2007; O'Hara, 2007; McClain et al., 2009; Howell et al., 2010; Rowden et al., 2010; Miller & Gunasekera, 2017; Tapia-Guerra et al., 2021; Hanafi-Portier et al., 2023), but not always (Bowden et al., 2021; Mazzei et al., 2021), from the ones observed on nearby slopes. Finally, we further determine and discuss (5) which of the identified communities present VME attributes and what is their vulnerability to anthropogenic impacts in the study area, making our study relevant for area-based conservation planning in Cabo Verde.

2. Methods

2.1. Study area

The Cabo Verde archipelago (Fig. 1) consists of ten volcanic islands located in the Central Atlantic Ocean, off the coasts of Mauritania and Senegal. The archipelago is positioned at the intersection of major oceanographic features, including the Canary Current (CC), the North Equatorial Current (NEC) and the Cape Verde Frontal Zone (CVFZ), from the north, and the Guinea Dome (GD) and the Mauritania Current (MC), from the south (Pelegrí et al., 2017). These oceanographic conditions, combined with the influence of the NW African coast upwelling system, contribute to the enhanced marine productivity patterns of Cabo Verde, making it a region of high ecological interest.

In 2021, the iAtlantic project (<https://iatlantic.eu>) conducted the multidisciplinary expedition iMirabilis2, on board the Spanish Research Vessel (R/V) Sarmiento de Gamboa, where the deep-sea benthic ecosystems off SW Cabo Verde were explored (Orejas et al., 2022) (Fig. 1B). During this expedition, dives with the Remotely Operated Vehicle (ROV) Luso (Estrutura de Missão para a Extensão da Plataforma Continental (EMPEC), <https://www.empec.pt>) focused on exploring the deep-sea benthic communities of Cadamosto Seamount and the island slopes of Fogo and Brava. These areas were surveyed to characterize and map bathyal benthic communities, and to compare their composition and spatial distribution across the two geomorphologically distinct systems (seamount vs island slopes).

2.2. Survey design and data collection

For the characterization and mapping of deep-sea bathyal megafaunal communities, a total of 8 ROV dives were conducted to collect video data for further analysis (Fig. 1C). The areas explored with the ROV were selected considering prominent geological features on the seafloor. Dives explored two different settings – the flanks of a seamount and the flanks of volcanic islands – focusing on the depth range from 2,100 to 1,400 m, to allow comparison between benthic communities on the two systems at the same bathymetrical distribution. Five dives were conducted on Cadamosto Seamount (SW of Brava Island) and three dives were conducted on the island slopes (two on the slopes of Fogo and one on the slopes of Brava). The dives on the seamount were planned so that the different flanks of the seamount, with different orientations, would be surveyed. However, due to the size of the islands, the travel times that would be required and the general

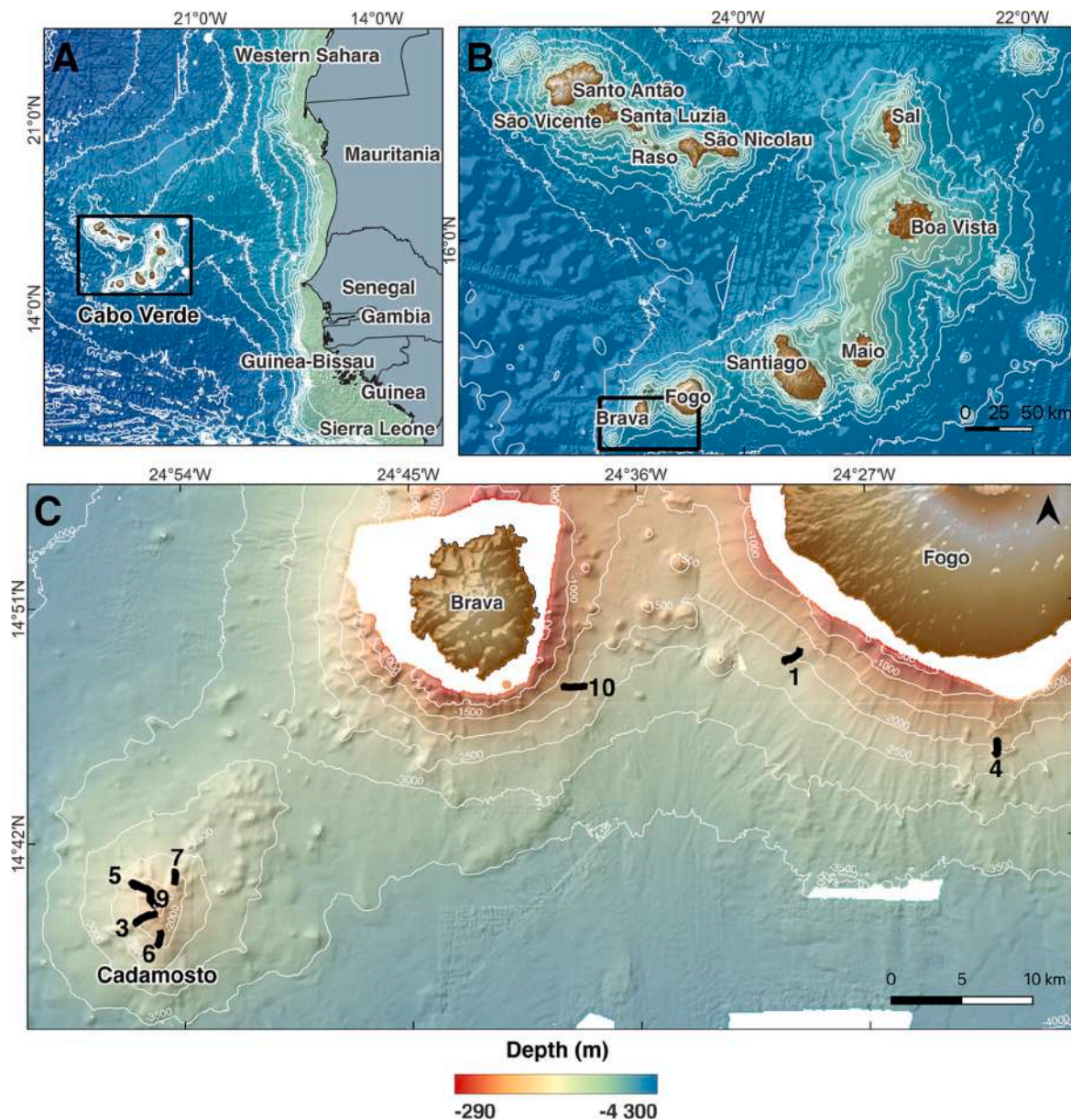


Fig. 1. Study Area maps. (A) Location of the Cabo Verde archipelago (black square) in NW Africa. (B) Cabo Verde archipelago with the black square indicating the study area of the iMirabilis2 expedition. (C) Dives conducted during iMirabilis2 for the characterization and mapping of deep-sea benthic communities, highlighted by black lines with the corresponding ROV dive number. The GEBCO 2023 bathymetry grid (GEBCO Compilation Group, 2023) was used in panels A and B (~ 500 m resolution), whereas the bathymetry grid in panel C was acquired during the iMirabilis2 expedition, at 100 m resolution (Huvenne et al., 2023).

wind and wave directions, the island flanks could not be surveyed from all directions, resulting in lower sampling effort on the islands.

To record videos and images of the seafloor, the ROV was equipped with a High Definition (HD) (Argus HD) and a 4 K (4kcameraArgus) video cameras and with a digital stills camera (Canon PowerShot G11), with two laser scaling devices placed 60 cm apart.

2.3. Video analysis and processing

Video data acquired during ROV dives were analyzed quantitatively using the open-source software BIIGLE (biigle.de) (Langenkämper et al., 2017). A preliminary qualitative analysis was done to identify, to the lowest possible taxonomic level, all the morphospecies observed on video. These identifications were used to create a “label tree” on BIIGLE to be used during the quantitative video analysis stage, together with an

additional label tree created for the identification of the substrate type, that included the following categories: soft substrate, sand with pebbles and cobbles, sand with boulders, boulders, iron-rich rocks and volcanic rock. The morphospecies and substrate type catalogue used for video analysis is publicly available on Zenodo (Vinha et al., 2022).

For quantitative video analysis, video transects were divided into 10-minute video clips that were analyzed in random order to avoid observer bias (Durden et al., 2016). Laser pointers were used to calibrate the area of the seafloor considered for video analysis, ensuring that only a 1.5 m wide strip of the field of view of the ROV video was analyzed. Annotations of morphospecies and substrate type were done only for periods during which the ROV maintained an altitude below 2 m, moved at constant speed, and had its HD camera facing forward, with the ROV’s roll (longitudinal axis) and pitch (lateral axis) remaining below 15°. Video footage with low visibility (e.g., caused by sediment resuspension

or technical problems with the ROV) or recorded during sample collection was not considered for video analysis. Therefore, the start and end times of these moments were annotated to be removed from the final video transect during the data processing stage.

To ensure an accurate georeferencing of the annotations after video analysis, an initial data processing step was done to smooth the ROV navigation data using a moving average with a window size of three points. After, an *ad hoc* Python script was used to merge the smoothed ROV track with the corresponding time-stamped video annotations. Additionally, the sections identified during video annotations to be discarded were removed from the ROV track, ensuring that the final transect represented the true annotated path of the ROV (see [Supplementary Fig. S1](#) for the final video sections considered for analysis). Using the buffer tool of QGIS, transect lines were then turned into 1.5 m-wide polygons, reflecting the seafloor area annotated during video analysis. The final transect polygons were then divided into sequential sections of equal areas, representing sampling units (SU), using the “Polygon Divider” plugin in QGIS. Considering the resolution of the bathymetric grid available (100 m) (see [section 2.4](#)), 100 m² was selected as the area of each SU in order to capture environmental variation in community characterization, while also keeping the analysis on a local scale focus.

A total 46.5 h of ROV video were recorded. After removing sampling events, low visibility, and technical problems, 28.5 h of video data were considered for analysis, covering 19,900 m² of the seafloor ([Table 1](#)). A higher survey effort was deployed on Cadamosto Seamount, compared to the island slopes, resulting in a total of 12,600 m² of the seafloor considered in the final transects on the seamount, representing approximately 0.07 % of the total seamount area within the same explored depth range (2,100 to 1,400 m), in comparison to 7,399 m² on the island slopes.

2.4. Morphospecies and environmental data

Morphospecies abundances and environmental data were extracted for each SU (100 m²) to obtain two data matrices for multivariate community analysis: one with morphospecies densities (i.e., number of individuals/100 m²) and another one with the corresponding environmental parameters extracted at the geographic center point of each SU. Rare morphospecies, i.e., morphospecies with equal or less than two observations in the entire annotated video dataset, were not considered for multivariate analysis, to ensure meaningful ecological results and avoid disproportionate effects caused by rare observations ([Legendre & Gallagher, 2001](#)). Empty SU, i.e., SU with zero annotated individuals, were also removed from the final data matrices, given that they do not provide meaningful ecological information for community structure

analysis. Out of the 199 SU considered (see [Table 1](#)), 18 SU were empty (1 in Brava, 11 in Fogo, and 6 on Cadamosto Seamount) and were therefore excluded, resulting in a total of 181 SU considered for the final analysis.

Three sets of environmental data were used to investigate how species density and composition relate to the environment.

First, terrain variables were derived from a Multibeam Echosounder Bathymetry (MBES) grid, at 100 m resolution, acquired during iMirabilis2 ([Huvenne et al., 2023](#)). Different terrain variables were derived from the MBES bathymetry: slope, aspect (as northness and eastness), topographic position index (TPI) at fine and broad scale, roughness and Terrain Ruggedness Index (TRI). Using R Version 4.1.1 ([R Team, 2022](#)), slope and aspect (as northness and eastness) were calculated using the function ‘SlpAsp’ from the “MultiscaleDTM” R package ([Ilich et al. 2023](#)), all using a window cell size of 3x3 grid-cells. TPI was calculated at both fine (window cell size = 3, i.e. 300 m) and broad (window cell size = 15, i.e. 1,500 m) scales, using the ‘tpi’ function from the “SpatialEco” R Package ([Evans and Murphy, 2021](#)). The TRI was calculated using the ‘terrain’ function from the “raster” R package ([Hijmans, 2025](#)), with a window cell size of 3x3 grid-cells. The averaged value of each terrain variable was extracted for each SU and considered for the final environmental matrix.

Second, data on water column parameters were collected during ROV dives using the sensors (SAIV Conductivity, Temperature and Depth (CTD) SD204 and additional Idronaut sensors for dissolved oxygen (DO) and pH) installed on ROV Luso, providing *in situ* measurements of these parameters. These sensors were last calibrated in November 2019, 21 months before the cruise, in line with the manufacturer’s 24-month calibration recommendation. However, it is possible that some sensor drift may have occurred, which could decrease the confidence values of the absolute measurements. Nonetheless, the data presented here is still useful for interpreting relative variations in these parameters across communities. The mean values of temperature, conductivity, DO and pH were calculated for each SU and considered for the final environmental matrix.

Third, substrate type point data annotated during video analysis were merged with the polygons representing the final video transects, to create a continuous annotation of substrate data for the whole explored area with the ROV. Then, the proportion (%) of each substrate type category at each SU was calculated.

2.5. Data analysis

2.5.1. Community analysis

To account for imbalances in the density of different morphospecies, a Hellinger transformation was applied to the morphospecies density

Table 1

Survey design information, per ROV dive and location, with information on depth range, total area covered during ROV dives, final transect area and length, as well as number of sampling units (SU) with a 100 m² area considered for multivariate community analysis. Final transect area and length correspond to the transect obtained after data processing to remove discarded data from the ROV track.

ROV Dives	Location	Depth range (m)	Area covered during ROV dives (m ²)	Final area considered for analysis (m ²)	Final transects length (km)	Number of SU (100 m ²)
Dive 1	Island slopes	2,134 – 1,893	3,190	2,200	1.47	22
Dive 3	Seamount	2,016 – 1,451	4,153	3,900	2.60	39
Dive 4	Island slopes	1,964 – 1,728	3,068	2,600	1.73	26
Dive 5	Seamount	2,019 – 1,735	9,157	2,800	1.87	28
Dive 6	Seamount	2,029 – 1,760	3,755	2,400	1.60	24
Dive 7	Seamount	1,777 – 2,051	2,080	1,300	0.87	13
Dive 9	Seamount	1,735 – 1,468	3,050	2,200	1.47	22
Dive 10	Island slopes	2,022 – 1,654	3,146	2,500	1.67	25
Seamount		2,029 – 1,451	22,195	12,600	8.40	126
Island Slopes		2,134 – 1,654	9,404	7,300	4.87	73
TOTAL			31,599	19,900	13.27	199

matrix (see [section 2.4](#)). Transforming species abundance data using a Hellinger transformation addresses compositional constraints and reduces sensitivity to scaling effects ([Legendre & Gallagher, 2001](#)). A permutational analysis of variance (PERMANOVA) was used to investigate statistical differences in morphospecies composition between the two systems (seamount and island slopes) and the three explored locations (Cadamosto Seamount, Brava and Fogo Island slopes). This was executed using the function 'adonis2' in the "vegan" R package ([Oksanen et al., 2019](#)).

To identify different benthic communities, we used Multivariate Regression Trees (MRT), according to [Borcard et al., \(2018\)](#). First used in ecological community analysis by [De'ath \(2002\)](#), MRT is an extension of decision trees and a constrained regression modelling technique, providing a flexible approach for analyzing complex relationships in multidimensional data by partitioning species abundance data into distinct classes (communities) based on their environmental variables. To ensure independence among environmental variables, we first assessed pairwise correlations using the Spearman rank correlation coefficient, given that the data did not meet the assumptions of normality. A threshold of 0.7 was selected, as correlations above this value are generally considered indicative of high collinearity ([Dormann et al., 2013](#)). Pairs of variables with collinearity higher than this threshold were assessed and, for each, the variable with the highest ecological relevance was retained, while the other was removed. The final variables considered for analysis were: depth, broad-scale TPI, northness and eastness, DO and pH, and the six substrate type categories annotated during video analysis ([section 2.3](#)) ([Supplementary Fig. S2](#)). Using morphospecies density data and the final set of independent environmental variables, MRT were implemented in R using the package "mvpart" installed from git-hub (github.com/cran/mvpart). The benthic communities classified by the MRT were ordered into a Principal Component Analysis (PCA) ordination plot, with arrows representing the loadings of each morphospecies to the principal components, to identify its contribution to each community. The minimum, maximum and mean density of each morphospecies within a community were also calculated, to identify the characteristic taxa of each community. Diversity (Alpha diversity, Shannon entropy (H), Shannon (N1) and Simpson (N2)) and evenness (Pielou evenness (J), Shannon (E1) and Simpson (E2) evenness) metrics were used to investigate patterns of biodiversity in each community.

2.5.2. Predictive habitat mapping

To create a full-coverage predictive habitat map for the identified communities in SW Cabo Verde, a Random Forest (RF) model ([Breiman, 2001](#)), in classification mode, was developed. Identifying benthic communities, through MRT (see [section 2.4.1](#)), and predicting the distribution of each community through a RF classification follows a "classify first, predict later" approach, shown to be useful to predict deep-sea benthic community distribution at local scale ([Gonzalez-Mirelis et al., 2011](#); [Goode et al., 2021](#)). For the RF classification, data on the spatial distribution of each community were used as the response variable ([Supplementary Fig. S3](#)) and the same set of independent environmental data used in the MRT, except pH and DO, were used as predictors. Full-coverage maps of environmental data for the modelled spatial extent are necessary to create model predictions. However, such maps were not available for data on substrate type, pH and DO, since only point data along ROV tracks were available for these variables. Therefore, using substrate type annotations obtained from the video analysis and terrain variables as environmental predictors, a RF classification was used to generate a full-coverage substrate type predictive map ([Supplementary Fig. S4](#)). Nevertheless, water column parameters data (pH and DO) were not extrapolated and were not included in the RF model, to prevent the inclusion of additional model biases.

A 10-fold cross-validation was used to train and test the RF classification model, using model accuracy and Cohen's Kappa as evaluation metrics. This approach allows model performance to be validated

against different subsets of data, and Cohen's Kappa provides a measure that considers class imbalances, making it suitable for RF classifications. A prediction was then made for each one of the 10 folds, and the final model prediction corresponds to the mean probability of each class across folds, with the class with the highest average probability being selected as the final predicted class. Spatial Autocorrelation (SAC) was not accounted for in the final model predictions. However, k-fold cross-validation methods have been shown to reduce bias in performance metrics of RF models, even for datasets with high levels of SAC ([Mushagalusa et al., 2024](#)). The standard deviation was used as a measure of agreement/disagreement between predictions and was converted into proportions (%) of uncertainty to create an uncertainty map.

The spatial extent considered for the predictive habitat maps was the full extent of Cadamosto Seamount as well as the area around the islands of Fogo and Brava, with the predictions being limited from 2,100 to 1,400 m depth to match the range where input data were obtained and to avoid further extrapolation of the model's results.

3. Results

3.1. Video analysis and comparison between locations

A total of 185 different morphospecies were identified during video analysis, of which 60 % of the morphospecies belonged to Cnidaria and Porifera, and a total of 74 % of CWC morphospecies belonged to Octocorallia, representing 24 % of the overall morphospecies observations during video analysis ([Supplementary Fig. S5](#)). From the identified taxa, 52 morphospecies were considered rare (less than two occurrences) and, therefore, were removed from the final dataset, meaning that a total of 128 morphospecies were considered for multivariate community analysis (see [next section](#)).

Differences in morphospecies composition between the three locations (Cadamosto vs Fogo vs Brava) (PERMANOVA: $F = 8.768$, $p = 0.001$) and between seamount and island slopes (PERMANOVA: $F = 11.750$, $p = 0.001$) were statistically significant. A total of 155 morphospecies were observed on the seamount, while 77 were observed on Brava and 76 on Fogo. While these results could be potentially influenced by variations in sampling effort among locations and systems, morphospecies accumulation curves, standardized by SU, showed that Cadamosto Seamount presents the highest morphospecies richness (number of morphospecies identified) in comparison to the island slopes, with Fogo presenting the lowest morphospecies richness ([Fig. 2](#)). The highest morphospecies richness observed in a single SU was 37 morphospecies/100 m² on the NE side of Cadamosto Seamount ([Supplementary Fig. S6](#)). The most frequently observed taxa at the three locations belonged to Cnidaria, representing 41 % of the morphospecies observed on Cadamosto Seamount and 46 % on Fogo and Brava. On the seamount, the second most observed taxonomic group was Porifera (24 % of morphospecies), whereas on the islands' slopes, Echinodermata represents the second most abundant group (23 % and 21 % for Fogo and Brava, respectively).

3.2. Multivariate regression trees to identify benthic communities

Ten different benthic communities were identified by the MRT ([Fig. 3](#)). Depth was the first threshold in the MRT, where the first split node included three communities (Community 1, 2 and 3) located above 1,683 m depth, whereas the remaining seven communities were deeper than 1,683 m. Communities shallower than the depth threshold of 1,683 m, were then split by northness, first, and the proportion of "Boulders" as a substrate type category, subsequently, with Community 3 being characterized by having over 26 % of the seafloor with this substrate category. Deeper communities (depth > 1,693 m) were distinguished by a pH threshold, with three out of the seven communities observed under pH lower than 7.80. After, depth appears again as a threshold, with Community 4 and 5 shallower than 1,852 m but deeper than 1,683 m

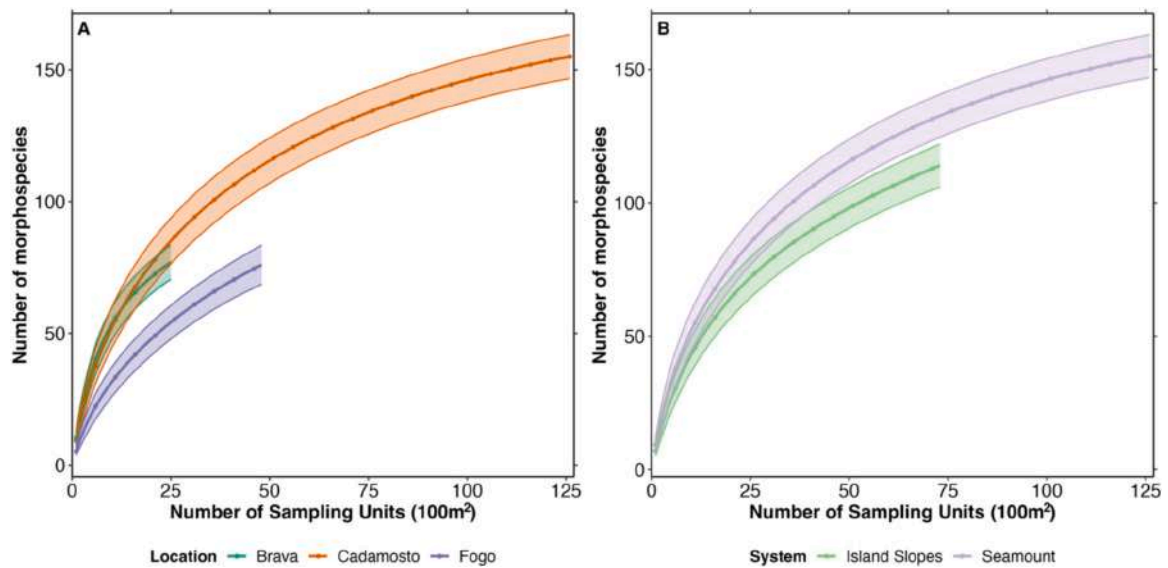


Fig. 2. Morphospecies accumulation curves for (A) each location (Cadamosto, Brava and Fogo) and (B) for each system (Seamount and Island Slopes), with 95% of confidence intervals.

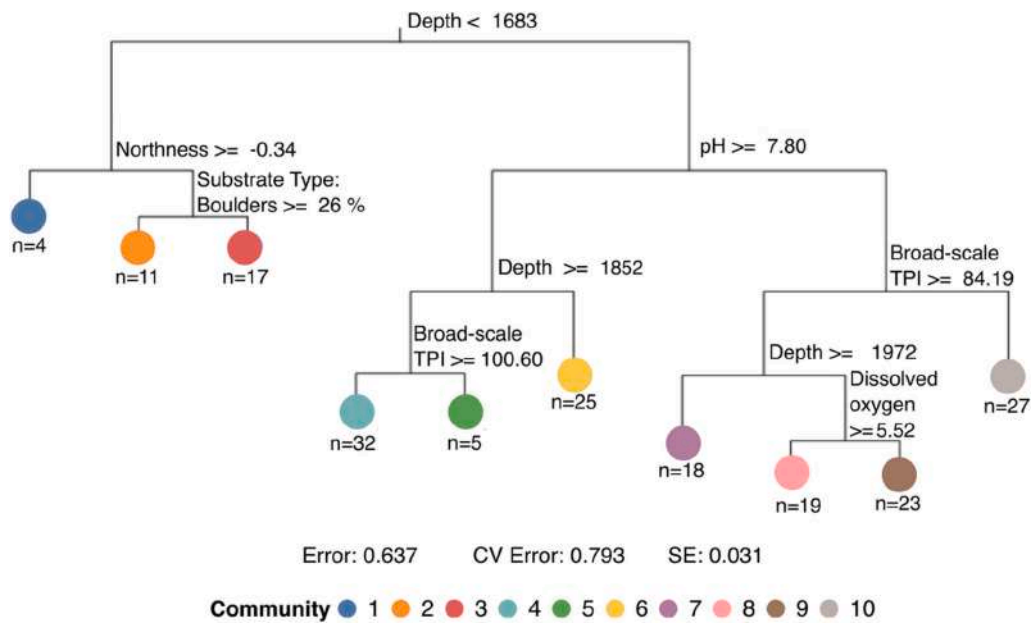


Fig. 3. Multivariate Regression Trees (MRT), with the respective environmental thresholds, to identify the deep-sea benthic communities of the study area, with n representing the number of sampling units (SU) included in each community type.

(the first depth threshold), whereas Community 6 was found deeper than 1,852 m. Communities 4 and 5 were then differentiated by TPI, at broad scale, with Community 5 associated with bathymetric highs (TPI > 100). The four communities occurring under pH ≥ 7.80 were also differentiated by broad-scale TPI, with Community 10 associated with topographic elevations on the seafloor with TPI ≥ 84.19, while the three remaining communities were again distinguished by depth. Therefore, considering all depth thresholds in the tree, Community 8 and 9 were the deepest communities of all the identified ones (deeper than 1,972 m). These two communities were then split by a DO threshold of 5.52 mL/L, with the latter community being associated with higher values.

3.3. Characterization of benthic communities and predictive community mapping

Out of the ten identified communities, five communities were exclusive to Cadamosto Seamount (Community 1, 3, 4, 5 and 6), whereas two communities were exclusive to Fogo (Community 7 and 8). None of the identified communities was exclusive to Brava. The Principal Component Analysis (PCA) ordination plot (Fig. 4) highlights the differences between communities. The morphospecies score, represented as arrows, allowed the identification of the most characteristic morphospecies of each community, with PC 1 explaining 15.2 % of variance in the communities and PC 2 explaining 9 %.

A RF classification predicted the full-coverage distribution of the

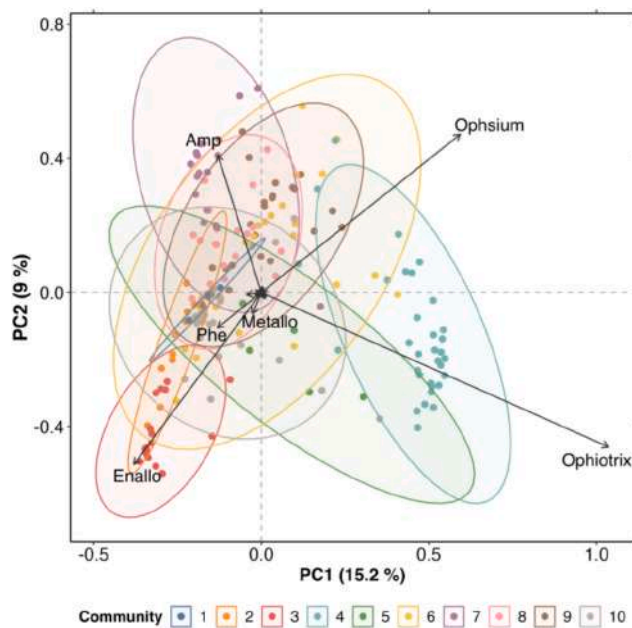


Fig. 4. Principal Component Analysis (PCA) of morphospecies data where each color represents the community identified by the MRT analysis and arrows the most contributing morphospecies (Amp = *Amperima* sp.; Enallo = *Enallopsammia rostrata*; Metallo = *Metallogorgia* spp.; Ophiotrix = *Ophiotrix* spp.; Ophiomusium = *Ophiomusium* spp.; Phe = *Pheronematidae* sp.) for each community.

identified communities in the study area (Fig. 5). The model's performance metrics showed that, on average, the model correctly predicted classes 88 % of the time, according to model accuracy (0.88 ± 0.06), suggesting, as well, a good agreement between predicted and observed classes, according to Cohen's Kappa (0.86 ± 0.07). Depth and broad-scale TPI were identified as the most important variables to predict the distribution of communities, according to the Mean Decrease in Gini (Supplementary Fig. S7), consistent with results obtained for the MRT. In general, model uncertainty was low (Fig. 5, C – D), with most areas presenting an uncertainty in the category 0–20 %, indicating a good agreement in the classification done between cross-validation folds. The summit of Cadamosto, the east side of Fogo and some flanks of the islands' slopes were the areas with the highest model uncertainty.

Here, a description of the characteristic morphospecies and environmental characterization of each community, as well as their observed and predicted distribution, is provided.

a) Community 1.

The observed and predicted distribution of Community 1 corresponds to the summit of Cadamosto Seamount, representing the shallowest (1,450 to 1,490 m depth) and the smallest predicted extent of all identified communities (Fig. 5). This community mostly occurs on "Iron-rich rocks" and under the lowest DO concentrations (4.71 ± 0.07 mL/L) (Fig. 6). Community 1 presents low diversity and evenness indices (Supplementary Fig. S8), with 90 % of observed morphospecies belonging to Porifera (Fig. 7A). The characteristic morphospecies of Community 1 is a carnivorous sponge of Cladorhizidae, showing a mean density, i.e., individuals \pm standard deviation/100 m² (SU), of $217 \pm 240/100$ m² (Fig. 7B), and a maximum density of $567/100$ m². Other associated fauna includes the shrimp *Nematocarcinus* sp. ($10 \pm 12/100$ m²) and the octocoral *Paramuricea* spp. ($8.5/100$ m²).

b) Community 2.

Community 2 was observed both on Cadamosto Seamount and Brava, between 1,470 and 1,670 m depth. However, besides the areas where it was observed, the RF model also predicted the distribution of this community in an area north of Fogo, as well as some patchy areas between the two islands (Fig. 5). The presence of iron-rich rocks was

observed in Community 2, but together with the presence of sand as a mixed substrate type (Fig. 6). This community is mainly composed of cnidarians, representing 72 % of the total morphospecies density, with the octocoral *Paramuricea* spp. being the most abundant morphospecies, with a frequency of 44 % and a maximum density of $61/100$ m² (Fig. 7). Other CWCs are present, although in lower densities, including black coral *Stichopathes* spp. (9 % frequency) and the scleractinian coral *Enallopsammia rostrata* (5 % frequency).

c) Community 3.

Community 3 was observed and predicted from 1,550 to 1,650 m depth on Cadamosto Seamount. Observations showed that this community is associated with a high percentage of boulders (mean frequency 59 ± 23 %) and volcanic rocks (mean frequency 23 ± 21 %) as the main substrate type categories (Fig. 6). The predictive map also showed that the distribution of this community is associated with TPI values higher than 50, according to the model's partial plots (Supplementary Fig. S9). The scleractinian coral *E. rostrata* is the characteristic species of this community, as highlighted on the PCA ordination plot (see Fig. 4). On NW Cadamosto, this CWC was observed forming large coral gardens (Fig. 8), with a maximum observed density of $264/100$ m². Other CWCs present in this community included a fan-shaped species of Primnoidae sp. (maximum density $21/100$ m²; 8 % frequency), *Paramuricea* spp. (maximum density $11/100$ m²; 4 % frequency) and *Metallogorgia* spp. (maximum density $4/100$ m²; 2 % frequency), as well as the antipatharian *Stichopathes* spp. (maximum density $15/100$ m²; 4 % frequency).

d) Community 4.

Community 4 is an ophiuroid-dominated community with a predicted distribution on the deepest sections of Cadamosto Seamount, on the western slopes of Brava and the northern sides of both islands, between 1,900 to 2,100 m depth (Fig. 5). Over 90 % of specimens observed were echinoderms, due to the high density of the brittle star *Ophiotrix* spp. ($142 \pm 239/100$ m²), representing over 75 % of the total morphospecies observations (Fig. 7).

e) Community 5.

Community 5 was only observed and predicted on Cadamosto Seamount. Here, the observed bathymetric distribution ranges from 1,920 to 1,950 m depth (Fig. 6), while predictions showed a wider depth distribution, from 1,500 to 2,000 m depth (Fig. 5). This community is associated with the highest values of broad-scale TPI (from 100 to 120). Community 5 presents the highest morphospecies richness and diversity (Supplementary Fig. S8). However, this community presents lower morphospecies evenness compared to other communities (e.g., Communities 8, 9 and 10). The most frequent morphospecies is the octocoral *Metallogorgia* spp. (maximum density of $50/100$ m², 15 % of frequency), forming coral gardens at the NE end of Cadamosto, as shown in Fig. 8. Other CWCs associated with these *Metallogorgia* spp. gardens included the black coral *Stauropathes* spp. ($17 \pm 21/100$ m²) and the golden coral *Chrysogorgia* spp. ($7 \pm 9/100$ m²). Community 5 also presents a high density of demosponges, with a particular prevalence of four morphotypes (Demospongiae (massive/globular) 2, 3 and 6 and *Geodia* spp. 2). Like Community 4, Community 5 also has a high density of the brittle star *Ophiotrix* spp. (maximum density $116/100$ m²), but in Community 4 the abundance of CWCs is much lower. Both Community 4 and 5 are associated with volcanic rock as the main substrate category (Fig. 6).

f) Community 6.

At an intermediate depth, between 1,600 and 1,900 m, Community 6 presents a widespread predicted distribution on Cadamosto, with the least coverage on the eastern slopes of the seamount (Fig. 5). The distribution of community 6 is also predicted along the whole extent of the islands' slopes. In this community, 18 % of the organisms observed consist of the brittle star *Ophiomusium* spp., with a mean density of $4 \pm 7/100$ m², mainly present on sand with pebbles and cobbles and sand with boulders. The most conspicuous CWC in community 6, present on volcanic rocks, was *Metallogorgia* spp., with 14 % frequency.

g) Community 7.

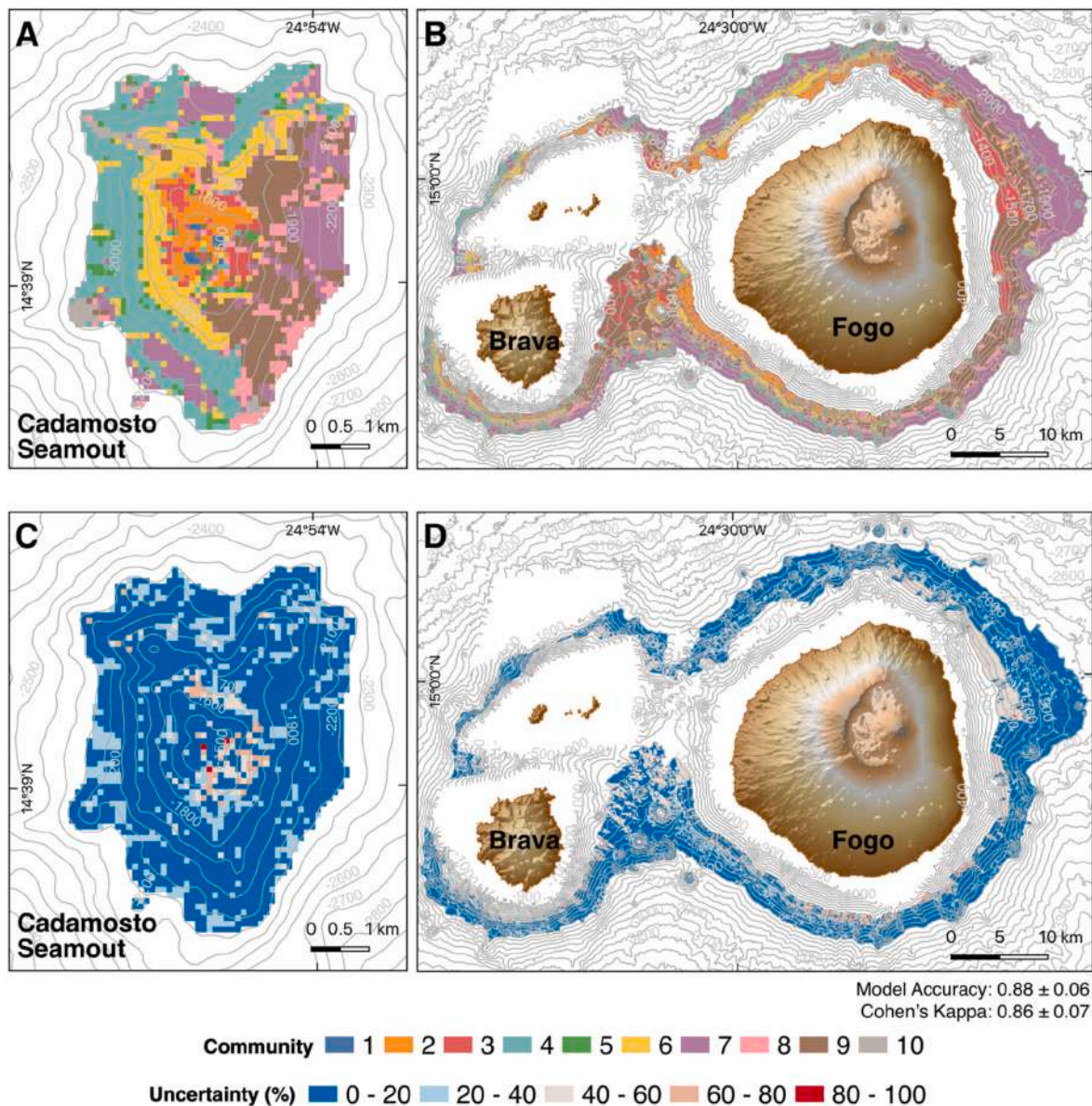


Fig. 5. Predictive Community map for (A) Cadamosto Seamount and (B) Fogo and Brava slopes, with the (C – D) corresponding uncertainty map.

Communities 7 and 8 were observed on the slopes of Fogo, between 1,750 and 1,900 m depth. However, according to the model's predictions, these communities are the ones with the largest predicted areas, corresponding to 55 % of the total modelled area.

On Cadamosto Seamount, the predicted distribution of Community 7 spans all around the deepest explored section of the seamount, but with less coverage on the northern side. The distribution of Community 7 is also predicted around the island slopes, within the same depth range, but with the most extensive distribution on the NE side of Fogo (Fig. 5). This community is associated with low values of TPI (mean TPI of 1.43 ± 12.93) and gradient slope ($12 \pm 3.55^\circ$), with over 75 % of the substrate characterized as soft substrate. The holothurian *Amperima* sp., observed on soft bottoms, is the characteristic morphospecies of this community with a 48 % frequency and maximum density of 21/100 m². Other prominent observations included the sea pens of the Protoptilidae family, the soft coral *Anthomastus* spp. and whip-shaped bamboo corals of the Isididae spp. family.

h) Community 8.

Community 8 is predicted in some areas of Cadamosto Seamount, in particular on the deepest sections (between 1,900 and 2,100 m) and towards the eastern and western slopes, but with a more scattered distribution. On the island slopes, Community 8 presents a wider bathymetric range, with a predicted distribution from 1,500 to 2,000 m depth. Here, the predicted areas cover the southern slopes of the islands and the area between Brava and Fogo. Despite also presenting a high proportion of soft substrate (26 ± 35 %), the most abundant observed substrate category is sand with boulders (38 ± 29 %) (Fig. 6). Community 8 presents the highest evenness metrics of all the investigated communities (Supplementary Fig. S8), meaning that the morphospecies composition and density of this community is balanced. Sixty-five percent of morphospecies belong to Cnidaria and the most abundant is Cerintharia 2, with 14 % frequency. Cold-water coral morphospecies include the antipatharian *Stauropathes* spp., *Acanella arbuscula*, species of the Isididae spp. family and octocorals *Paramuricea* spp. and *Metallogorgia* spp., all settling on the boulders associated with the boulders-and-sand substrate type, as shown in Fig. 8. A species of

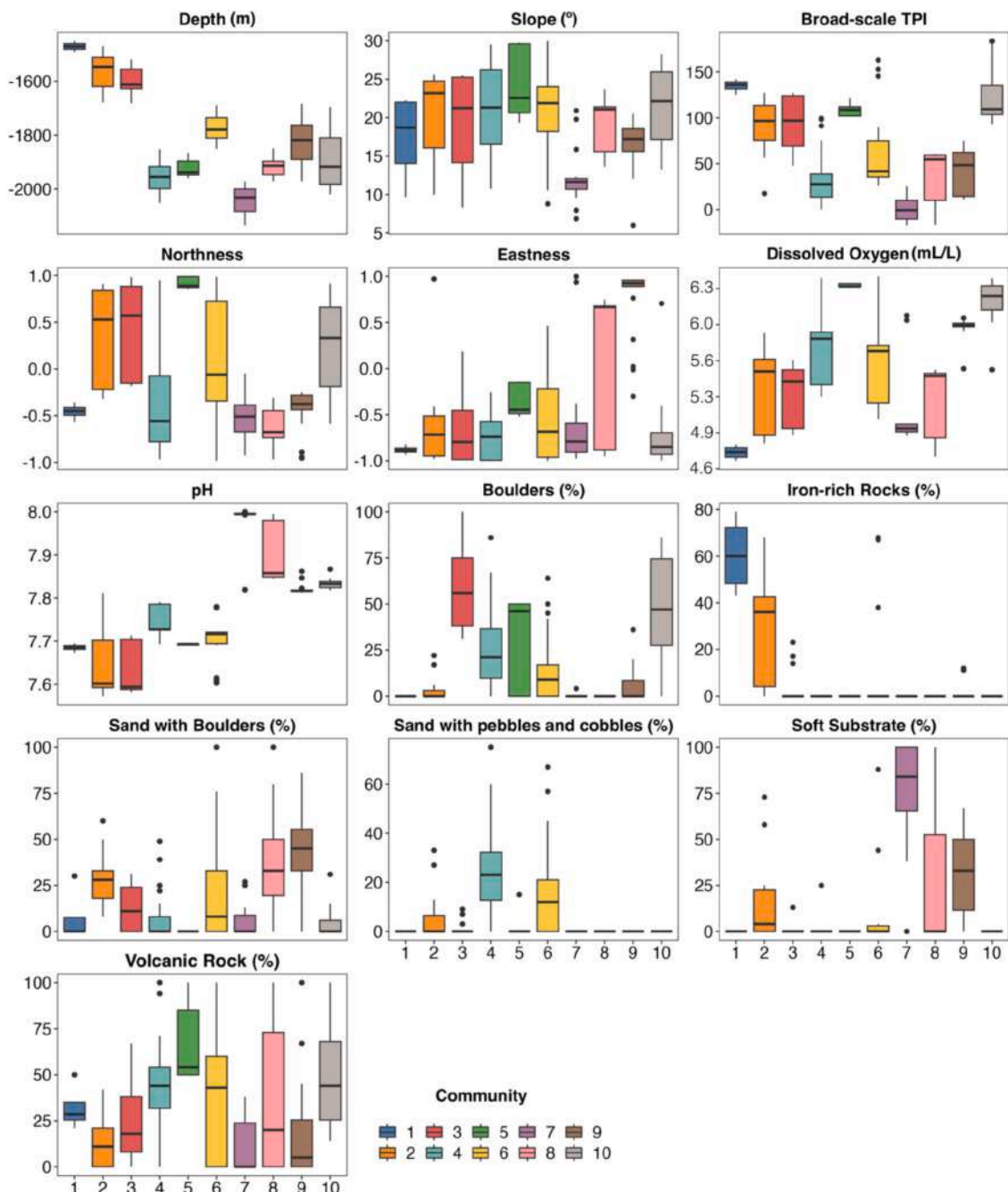


Fig. 6. Environmental data associated with each of the communities identified by the Multivariate Regression Trees (MRT) analysis, in particular, depth, terrain variables (broad-scale topography position index (TPI), northness, eastness and slope), water column variables (dissolved oxygen and pH) and percentage (%) of substrate type categories (iron-rich rocks, sand with boulders, sand with pebbles and cobbles, soft substrate and volcanic rock).

xenophyophore in the Syringamminidae family and the ophiuroid morphotype *Ophiomusium* spp. were also observed on soft substrate.

i) Community 9.

Both on Cadamosto Seamount and on the island slopes, the distribution of Community 9 is predicted on the east-facing slopes, from 1,800 to 2,100 m depth. The most common substrate categories of Community 9 are sand with boulders ($46 \pm 18\%$) and soft substrate ($30 \pm 20\%$) (Fig. 6). The characteristic CWCs are *Metallogorgia* spp. and the bamboo coral *Keratoisis* spp. 4, with the ROV video showing tall colonies (> 1 m tall) of this CWC (as represented in Fig. 8) on Brava. However, 44 % of the observed morphospecies represented echinoderms (Fig. 7), with the

most abundant ones being the brittle star *Ophiomusium* spp. and crinoids from the family Hyocrinidae spp.

j) Community 10.

Community 10 is one of the communities with the least predicted extent, representing ~ 1 % of the total modelled area. Its distribution is predicted from 1,900 to 2,100 m depth, on the NW side of Cadamosto, where it was observed, and in the area between the two islands (Fig. 5). The presence of this community is associated with broad-scale TPI > 100, indicating that the predicted distribution of Community 10 relates to the presence of mounds and elevations on the seafloor. Over 80 % of morphospecies of Community 10 belong either to Cnidaria or Porifera,

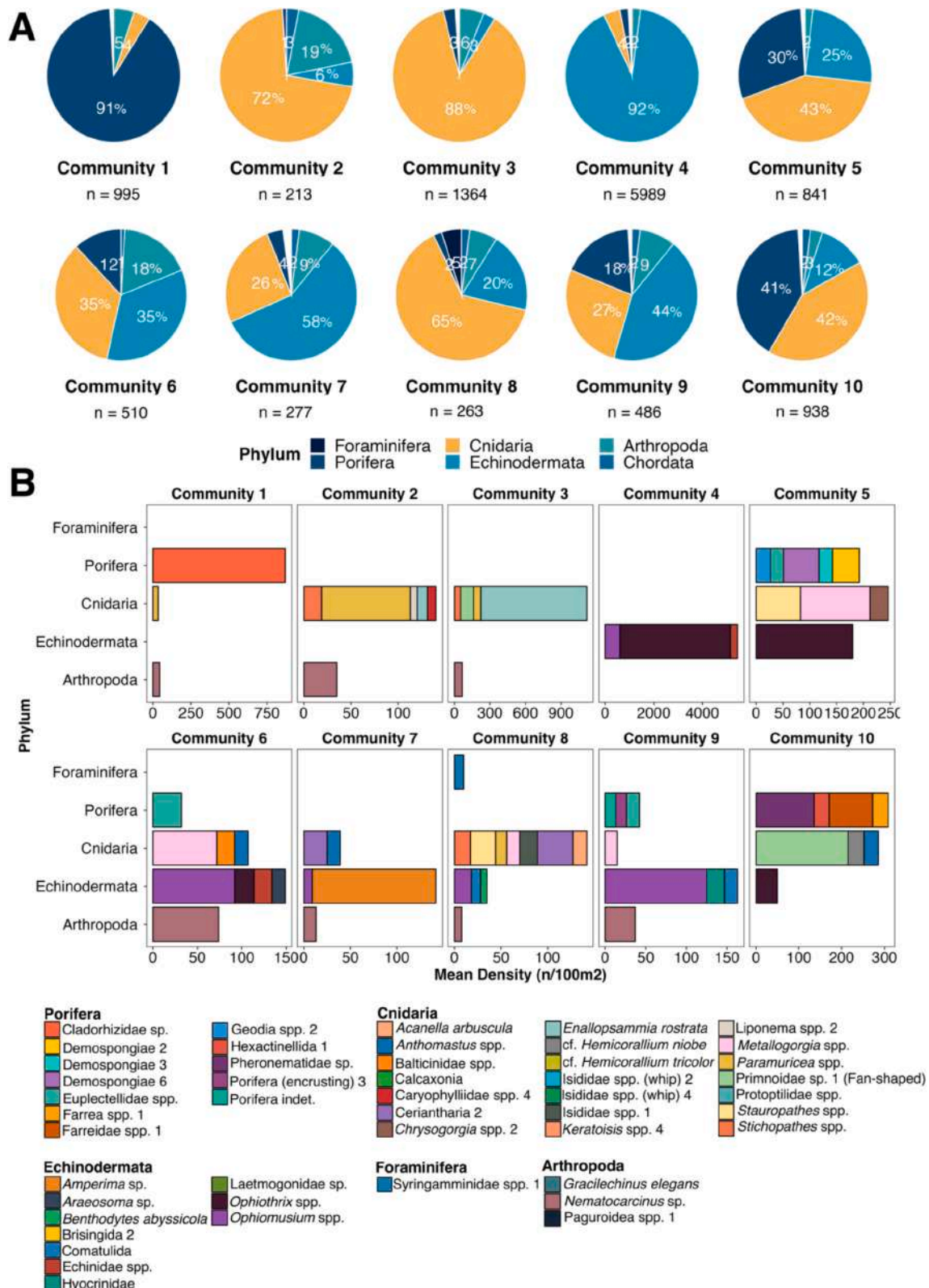


Fig. 7. Morphospecies composition of each community as (A) Frequency (%) of morphospecies from each phylum and (B) mean density (individuals (n)/100 m²). For data visualization purposes, only taxa with a frequency higher than 3 % are represented. The x-axis presents different density ranges. For the complete list of morphospecies, with respective densities, see **Supplementary Table S1**.

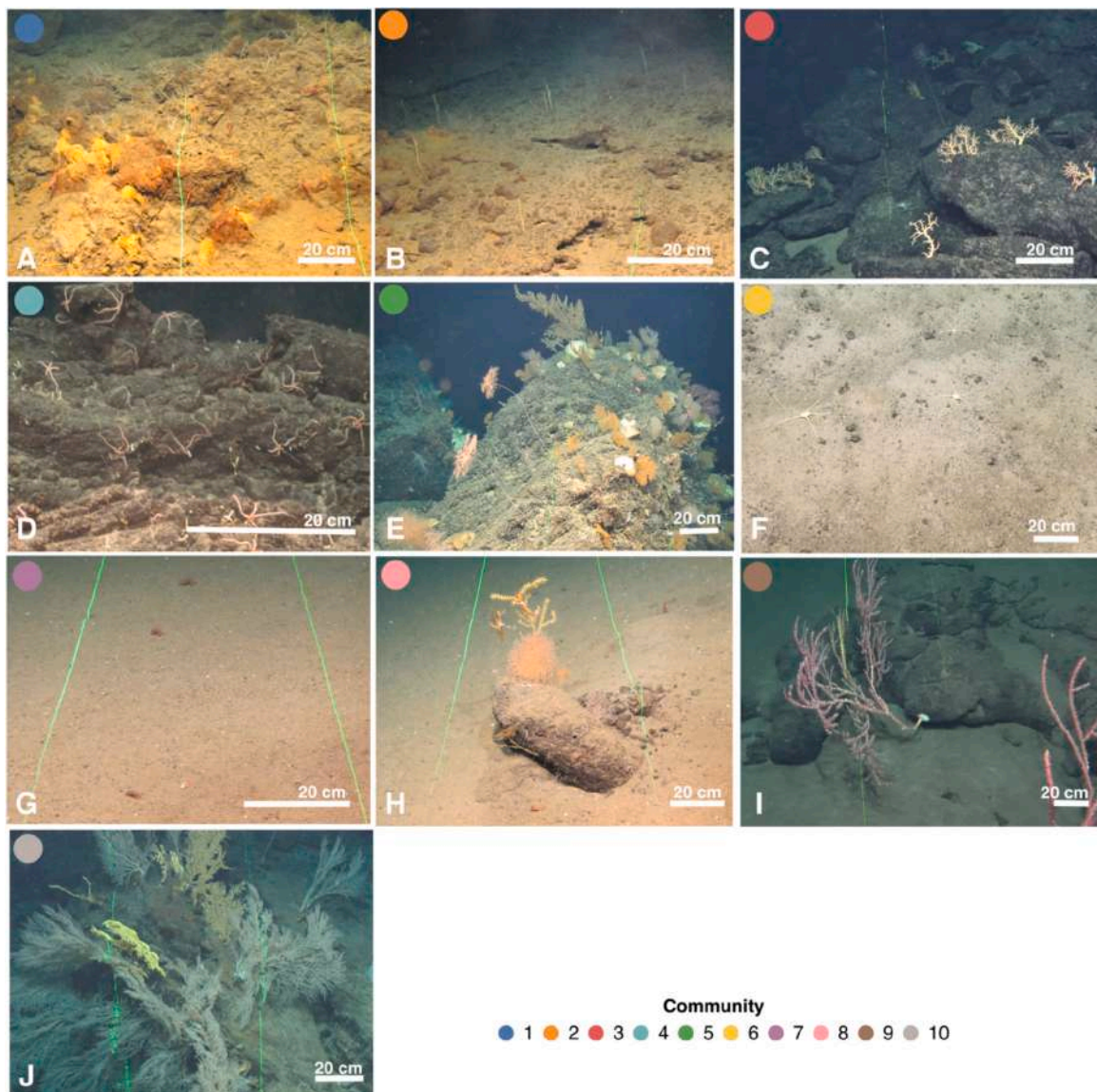


Fig. 8. The identified communities: (A) Community 1, dominated by a carnivorous sponge of the family Cladorhizidae, found on iron-rich rocks at the summit of Cadamosto; (B) Community 2, dominated by cnidarians, with *Paramuricea* spp. as the most abundant octocoral; (C) Community 3, characterized by the scleractinian *Enallopsammia rostrata*; (D) Community 4, dominated by the brittle star *Ophiothrix* spp.; (E) Community 5, corresponding to high-diversity coral assemblages dominated by the octocoral *Metallogorgia* spp., black corals and demosponges; (F) Community 6, marked by the presence of *Ophiomusium* spp. brittle stars; (G) Community 7, widely distributed soft-bottom community dominated by the holothurian *Amperima* sp.; (H) Community 8, composed by different cnidarian morphospecies, including the bamboo coral *Acanella arbuscula*; (I) Community 9, characterized by tall bamboo coral *Keratoisis* spp. colonies and (J) Community 10, dominated by high densities of Primnoidae octocorals and glass sponges on vertical walls. Photo Credits: iMirabilis2/EMEPEC/iAtlantic.

accounting for a frequency of 42 % and 41 %, respectively. Over 20 % of individuals included an octocoral in the Primnoidae family (fan-shaped) (see Fig. 8), observed forming a coral garden (maximum density 167/100 m²) on a vertical wall at the NW of Cadamosto. Other conspicuous CWCs of Community 10 are the precious corals cf. *Hemicorallium niobe* and cf. *Hemicorallium tricolor*, *Anthomastus* spp. and, although with less abundance, the black coral *Stichopathes* spp. and the octocoral *Metallogorgia* spp. Glass sponges represent the most observed sponge group, with an elephant ear sponge in the family Pheronematidae (maximum density 31/100 m²; 14 % frequency) and Farreidae spp. 1 (maximum density of 37/100 m²; 11 % frequency) as the most abundant morphospecies.

4. Discussion

4.1. Deep-sea benthic communities of Cabo Verde and key environmental drivers

In this study, we identified ten different benthic communities between 1,400 and 2,100 m depth in SW Cabo Verde, with cnidarians, sponges and echinoderms as the dominant taxa. Seamount communities presented higher abundances of CWCs and higher morphospecies diversity in comparison to the island slopes. For the same depth ranges, the observed morphospecies in our study resemble the faunal and seafloor descriptions of seamounts and island slopes of other Macaronesia archipelagos (Azores, Madeira and Canary Islands) (Hall-Spencer et al., 2007; Braga-Henriques et al., 2013; Bridges et al., 2023), where high

densities of octocorals on a volcanic rocky seafloor were also reported. At the same time, the presence of scleractinian CWCs (*E. rostrata*) on large volcanic boulders and pillow lavas also presents similarities with observations reported on the Galapagos archipelago in the eastern Equatorial Pacific Ocean (Salinas-de-León et al., 2020).

Morphospecies composition on Cadamosto Seamount was statistically different from that observed on the slopes of the islands of Brava and Fogo. Indeed, Cadamosto communities presented higher densities of CWCs and sponges and, overall, higher morphospecies richness (e.g., Communities 3, 5 and 10). On the other hand, the communities on the island slopes presented a patchier distribution and lower densities of CWCs, with lower morphospecies richness, but higher evenness of taxa composition. Similar observations have been made between seamount and nearby slope communities in other regions (Rowden et al., 2010; Tapia-Guerra et al., 2021; Hanafi-Portier et al., 2023), where differences related to seafloor geomorphology were the main factor driving differences in benthic communities. Similarly, in our study, differences in substrate type between the two systems could be one possible explanation for the observed faunal differences. For instance, island slopes generally presented higher proportions of “soft sediment” as a substrate type category, which may be linked to flank collapses and landslides (Masson et al., 2008) and the closer proximity to terrigenous inputs. Consequently, these more sedimentary environments could explain the faunal composition of island communities, including the presence of CWC morphospecies typical of soft substrates, such as sea pens and the bamboo coral *A. arbuscula*.

On Cadamosto Seamount, CWC gardens were present on the northward-facing slopes, associated with bathymetric elevations (high positive values of TPI) and a high percentage of volcanic rock substrate (Fig. 6). Filter-feeders benefit from being on elevated seafloor features by increasing food capture (Wilson et al., 2007), which could explain higher densities of CWCs associated with higher values of TPI. On the contrary, the southern slopes of Cadamosto presented lower densities of CWCs but, instead, dense aggregations of ophiuroid-dominated communities. As a hypothesis, taxa replacement between the north and south of Cadamosto could be explained by underlying seamount hydrodynamic mechanisms driving the distribution of CWCs on the seamounts of Cabo Verde (Vinha et al., 2024), providing, therefore, a higher delivery of phytodetritus to the benthic communities on the northern slopes. Victorero et al. (2018) proposed a similar hypothesis for Annan Seamount, located south of Cabo Verde, where species replacement was driven not only by substrate type and TPI, as in our study, but also by terrain orientation, hinting at the importance of hydrodynamics in driving the presence or absence of suspension feeders. Likewise, the observed differences between seamount and island slope communities could also be related to specific seamount hydrodynamic mechanisms driving different genetic connectivity (Miller & Gunasekera, 2017) and food supply patterns (Hall-Spencer et al., 2007; Rowden et al., 2010; Tapia-Guerra et al., 2021; Hanafi-Portier et al., 2023), which could contribute to higher food delivery to seamount communities and, thereby, higher CWC densities.

Depth and water column pH and DO were also drivers of community zonation and distribution. In this study, there is a clear bathymetrical stratification of benthic communities, with the presence of a community dominated by the scleractinian coral *E. rostrata* (Community 3) in the shallowest explored depth interval (1,500 to 1,600 m), and the presence of the highest densities of octocoral-dominated communities deeper than 1,750 m and associated with the highest concentrations of DO (5.52 to 6.40 mL/L) (see Communities 5, 9 and 10 in Fig. 6). Depth is often regarded as the most important variable for deep-sea benthic community composition (e.g., Braga-Henriques et al. 2013; Quattrini et al. 2017; Victorero et al. 2018; Bridges et al. 2021; Goode et al. 2021; Simon-Lledó et al. 2023), primarily because it serves as a proxy for several important environmental properties. Among these, food supply, which generally decreases with depth, is considered an influential driver of benthic community composition (Sherwood et al., 2008; Romero

Romero et al., 2021). In addition, water mass distribution, as a consequence of changes in depth-related changes in water column physical and chemical properties can also represent physical vertical boundaries for ecophysiological tolerance and genetic dispersal of populations (Quattrini et al. 2017; Puerta et al. 2022), resulting in environmental filtering of communities across bathymetric changes (Arantes et al. 2009; Buhl-Mortensen et al. 2015; Auscavitch et al. 2020; Puerta et al. 2020).

The information presented in this study provides a first detailed description of the deep-sea benthic communities of this understudied region in West Africa. However, a few study limitations must be considered. For example, the taxa identification done here was solely based on video and photo analysis, and, as such, it likely underestimates the total reported number of species present in the study area, which is a common issue in deep-sea benthic characterization studies based on imagery (Untiedt et al., 2021). In addition, this study only covers a very limited proportion of the seafloor, as in most ROV surveys for the characterization of benthic fauna. To address this limitation, we generated a full-coverage predictive habitat map for the explored depth range, providing a good approach for using ROV observations to predict community distribution at a broader scale (Gonzalez-Mirelis et al. 2011; Goode et al. 2021). Nonetheless, model predictions were built upon modelled data of substrate type, which already introduces biases into the models, and water column parameters were not included in the predictions since full-coverage datasets at a resolution matching the model's scale were not available. Although this predictive map provides important information on the distribution of benthic communities in the study area, it is important to follow a precautionary approach when using this map for marine spatial planning, given the need to collect additional ground-truthing data to enhance model accuracy and validation. This is especially important in areas of high model uncertainty (see Fig. 5, C-D), such as the summit of Cadamosto Seamount or the area between Fogo and Brava islands. Therefore, future surveys should prioritize these locations to improve the ecological knowledge of benthic communities and support more informed conservation planning.

4.2. Vulnerable marine ecosystems

This section discusses how some of the observed taxa in SW Cabo Verde meet the established VME criteria (FAO, 2009; uniqueness or rarity, functional habitat significance, fragility, limited recovery potential, and structural complexity), qualifying them as VME indicator taxa for the study area. Although FAO guidelines do not establish density thresholds for these indicators, most studies aiming to develop VME numeric thresholds (e.g., Price et al., 2019; Rowden et al. 2020) have adopted region-specific approaches to define them. Therefore, in our study, communities with VME attributes are identified based on the presence of morphospecies with traits that match the FAO criteria and with higher species density aggregations relative to other surveyed areas in the study region. The identified communities with the presence of VME indicators are presented (Table 2), providing a region-specific approach to VMEs in Cabo Verde.

4.2.1. Cladorhizid sponge aggregations

At the summit of Cadamosto Seamount, at 1,400 m depth, an exceptionally high density of cladorhizid sponges was found, accounting for the highest densities of observed specimens in our study (maximum density of 567/100 m²). These sponge aggregations match the VME criteria due to their uniqueness, since they were not observed elsewhere in the study area. They also contribute to a higher structural complexity of the habitat and were found associated with the octocoral *Paramuricea* spp., also found in high densities (maximum density of 23/100 m²) in this community (Community 1). Cladorhizid sponges were found in an environmental setting dominated by hydrothermally altered rocks, supporting the status of Cadamosto Seamount as an active volcanic system (Faria & Fonseca, 2014; Grevemeyer et al., 2010; Kwasnitschka

Table 2

Vulnerable Marine Ecosystems (VMEs) indicator taxa and type, with corresponding community, observed in SW Cabo Verde, as well as observed density range (individuals (n)/100 m²) and percentage (%) of the predicted area occupied by the corresponding community, based on the predictive community maps.

VME type	VME Indicator Taxon	Observed density range of indicator taxa (min – max) (n/100 m ²)	Communities with the presence of VME indicator taxa	Total % of the predicted area of the associated communities	
Cladorhizid sponge aggregations	Cladorhizidae sp.	17–567	1	0.22	
Scleractinian coral gardens	<i>Enallopsammia rostrata</i>	2–264	3	2.36	
Octocoral and black CWC gardens with sponge aggregations	Octocorals	<i>Acanella arbuscula</i>	1–5	2, 5, 8, 9, 10	46.47
		<i>Anthomastus</i> spp.	1–12		
		cf. <i>Hemicorallium niobe</i>	1–10		
		cf. <i>Hemicorallium tricolor</i>	1–4		
		<i>Chrysogorgia</i> spp. 2	1–20		
		Isididae spp. 2	1–17		
		<i>Keratoisis</i> spp. 4	1–5		
		<i>Metallogorgia</i> spp.	1–50		
		<i>Paramuricea</i> spp.	1–61		
		Primnoidae sp. 1 (Fan-shaped)	1–167		
	Black	<i>Stauropathes</i> spp.	1–47		
	Corals	<i>Stichopathes</i> spp.	1–15		
	Sponges	Demospongiae	1–21		
		(Massive/globular) 2			
		Demospongiae (Massive/globular) 6	1–23		
Euplectellidae spp.		1–11			
<i>Farrea</i> spp. 1		1–10			
Farreidae spp. 1		1–37			
Hexactinellida 1		1–8			
Phoronematidae spp.		1–31			
Sea pen fields	Balticinidae spp.	1–18	6, 7, 8	46.86	
	Isididae spp. (whip) 4	1–5			
	Protoptilidae spp.	1–3			

et al., 2024). Indeed, observations of cladorhizid sponges are typical of hydrothermal vent systems and seeps (Vacelet et al., 1996; Schander et al., 2010), where cladorhizid sponge aggregations can occur in high densities (Vacelet et al., 1996). Although the ecological role of cladorhizid sponges is not yet fully known, it is known that they can exhibit different trophic strategies, ranging from carnivorous feeding to association with chemoautotrophic bacteria (Vacelet et al., 1996; Vacelet, 2007; Hestetun et al., 2016), which would classify as an important functional significance provided by these sponges. Physical sampling of the observed specimens at the summit of Cadamosto Seamount is needed to achieve a better taxonomic identification and to further investigate the ecological role of these sponges as VME indicators in the study area.

4.2.2. Scleractinian CWC gardens

The CWC *E. rostrata* was found across Cadamosto Seamount, however, the highest densities of the species were located on the NW slopes of the seamount (Community 3, maximum density of 264/100 m²), contributing to the uniqueness criteria of this coral garden habitat in the explored study area. Furthermore, the habitat formed by *E. rostrata* presents a high structural complexity, since, in other regions, such as the seamounts of New Zealand (Tracey et al., 2011) or on the Brazilian margin (Pires et al., 2014), the species is often associated with other reef framework-building corals. On Cadamosto Seamount, one colony of *E. rostrata* was observed entangled in a fishing net in the area where the highest coral density was observed (Fig. 9, B), which shows a potential vulnerability of this indicator species to fishing impacts in the study area. In addition, *E. rostrata* also matches the VME criteria due to its longevity, since it is known to be a long-lived coral (Adkins et al., 2004; Houbrèque et al., 2010). Using the reported growth rates for the species (1.25 ± 0.92 mm/year) based on uranium dating (Houbrèque et al., 2010) and size measurements done for some observed *E. rostrata* colonies (n = 350), it was approximately estimated that 80 % of the measured colonies at Cadamosto Seamount are older than 100 years. The scleractinian coral *E. rostrata* is the only observed CWC species in

Cabo Verde that has some legal protection, since all stony coral species are protected under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) (included in Appendix II since 1990; CITES, 2020).

4.2.3. Octocoral and black CWC gardens with sponge aggregations

Communities dominated by octocorals, with a high density of black corals and sponge aggregations, were present both on the island slopes and on Cadamosto Seamount, including a total of five out of the ten identified communities (Communities 2, 5, 8, 9 and 10), with Community 5 showing the highest associated species diversity. These coral gardens have an important structural role (Bo et al., 2015), typically exhibiting a high number of associated fauna (De Clippele et al., 2015) and being, therefore, true biodiversity oases in the deep sea (Morato et al., 2021). In addition, deep-sea octocorals can exhibit high longevity and slow growth rates (Sherwood et al., 2006; Prouty et al., 2016), and the same has been observed for black corals, with some specimens known to live up to thousands of years (Prouty et al., 2011; Hitt et al., 2020). These observations further support these coral taxa as VME indicators due to their longevity, uniqueness, structural habitat complexity and functional significance. Sponges, as associated taxa of these coral gardens, also present traits to be classified as VME indicators due to their important ecological role as ecosystem engineers in deep-sea carbon and nitrogen cycling processes (Bart et al., 2021; Hanz et al., 2022).

The octocoral gardens documented in our study are very similar to the ones described on Tropic (Ramiro-Sánchez et al., 2019) and on Annan Seamounts (Victorero et al., 2018), both located close to Cabo Verde. Moreover, on the Brava Island slopes, the presence of very large colonies of the bamboo coral *Keratoisis* spp. (Community 10) was observed, comparable to the descriptions and observations of Bridges et al., (2021) for the same taxon on seamounts in the South Atlantic.

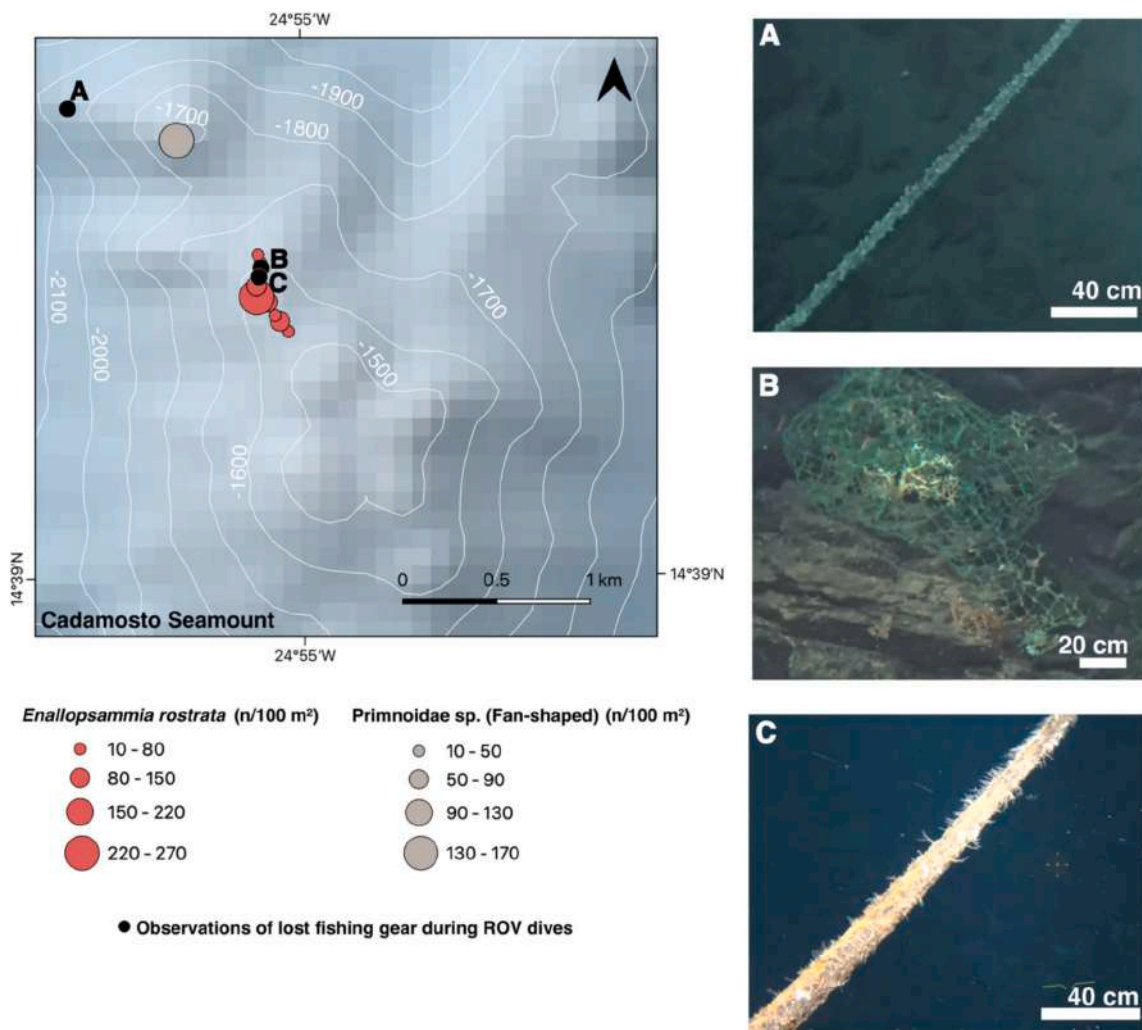


Fig. 9. Map and corresponding pictures of observations of lost fishing gear during ROV dives. Encounters were observed on the north of Cadamosto Seamount, where the communities with the densest populations of CWCs were observed. Pictures A, B and C show remains of the fishing gears encountered in the locations A, B and C depicted on the map, with black dots.

4.2.4. Sea pen fields

Sea pens can be considered VME indicator taxa due to the unique habitat they can form on soft bottoms (Bastari et al., 2018; Miatta and Snelgrove, 2022; Buhl-Mortensen et al., 2023b). In SW Cabo Verde, the presence of sea pens was observed on the soft bottoms of the island slopes, although in lower total abundances when compared to other coral taxa on hard bottoms. As VME indicator taxa, sea pens were present in three communities (Communities 6, 7 and 8), but it was on Community 7 that these taxa were most conspicuous, associated with a higher density of holothurians. A similar community type, with high densities of sea pens and holothurians, was also reported for a protected area in Eastern Canada (Miatta and Snelgrove, 2022); however, the reported densities of sea pens (maximum densities of 6.65/m²) were much higher than the ones observed in our study area (18/100 m² or 0.18/m²). Likewise, in Norway, the density of sea pens can reach over 160/100 m² (or 1.6/m²) (Buhl-Mortensen & Mortensen, 2005), which is also much higher than the total maximum densities of sea pen taxa observed in Cabo Verde. However, these comparisons may be of limited ecological relevance given the different environmental settings (continental shelf vs island slopes) and species compositions of the compared regions, and that most of the surveys in our study focused on rocky substrates. More surveys on soft bottoms should be conducted to investigate the presence

of other sea pen fields in Cabo Verde.

4.3. Vulnerability of benthic communities to fishing impacts and conservation implications

The Republic of Cabo Verde is a member of the Fishery Committee for the Eastern Central Atlantic (CECAF). Most fisheries in Cabo Verde consist of small-scale traditional fisheries in national waters close to shore (González et al. 2020), focusing on tuna, small pelagic, and demersal species (Failler, 2020). However, national and foreign industrial and semi-industrial fishing vessels are also present in the national waters of Cabo Verde, with over 50 % of the fishing fleet consisting of foreign vessels (Aquino, 2023). In addition, overfishing and illegal, unreported and unregulated (IUU) fisheries are dominant fishing problems in the archipelago (Aquino, 2023).

A consultation of the database from Global Fishing Watch (Global Fishing Watch, 2023), based on vessel Automatic Identification System (AIS) data, showed low fishing effort during the past three years, in the region considered in this study. The consultation showed the presence of few fishing vessels in the area, operating with longlines, purse seine and pole and line, under international flags (Supplementary Fig. S10). However, during ROV dives, we recorded three observations of derelict

fishing gear on the NW flank of Cadamosto, near the areas where the highest densities of CWCs were observed (Fig. 9). The impact of long-lines on CWCs is lower than the impact of bottom trawling (Pham et al., 2014); however, CWCs are often by-catch products of long-line fisheries (Sampaio et al., 2012) and lost long lines can entangle with CWCs, causing physical damage (Orejas et al., 2009; Clark et al., 2016).

Currently, Brava is the only island in Cabo Verde without any area-based conservation designation for terrestrial and marine ecosystems (INGT, 2022), and the same applies to Cadamosto Seamount, the nearest seamount to the island. The preliminary analysis presented here suggests that the apparent human pressure on deep-sea benthic communities in SW Cabo Verde is low. However, only a small area of the seafloor was explored, and these observations should be contrasted with a more robust assessment to confirm them. Given the seemingly pristine condition in which most of the investigated deep-sea benthic communities were observed, we recommend the implementation of precautionary measures to protect the area as a reference site, before future human impacts could harm marine communities. For example, deep-sea mining could be a potential future impact for deep-sea benthic communities in the region, given the mineral-rich seafloor of the seamounts of Cabo Verde (Grevemeyer et al., 2010; Wang et al., 2011), even though there are currently no known public plans to explore the area around Cabo Verde for deep-sea minerals. Moreover, in Cabo Verde, three seamounts (Boavista, Cabo Verde and Nola) with suitable habitat for VME indicator taxa (Vinha et al., 2024) are located within a designated Ecologically or Biologically Significant Marine Area (EBSA) (UNEP/CBD/COP/DEC/XII/22, 2014). Similarly, designating Cadamosto Seamount and the area around Fogo and Brava as an EBSA could be an important initial step to incentivize the establishment of conservation measures by local authorities and increase research efforts in the region. To ensure that inclusive national and international collaborations are achieved in the scientific and conservation process, future research should follow the guidelines laid out to avoid parachute science programs and strengthen capacity in deep-sea research in Africa (McQuaid et al., 2024).

5. Conclusions

In this study, we provided a first comprehensive characterization and mapping of the bathyal communities present in SW Cabo Verde. We identified the presence of ten different benthic communities, some of which with taxa that can be considered characteristic of VMEs. Based on the available data, the seamount featured communities with higher CWC and sponge densities, as well as associated species richness, in comparison to the adjacent island slopes. This result could be attributed to terrain geomorphology, but also to underlying hydrodynamic patterns around the seamount, which may be driving a higher delivery of food supply to seamount benthic communities in comparison to the island slopes. Although fishing effort and other human pressures on benthic communities in the study area appear to be low, lost fishing gear was observed in areas with the highest densities of VME indicators. Cadamosto Seamount and the explored areas around Brava and Fogo currently lack any area-based conservation measures. Therefore, if such measures are to be implemented in the future, we recommend applying the precautionary principle to protect benthic communities from future potential damage. Future studies should focus on collecting more data from unexplored areas within the study area and utilizing molecular approaches to improve taxonomical identifications to confirm the “biodiversity hotspot” status of the archipelago. Population dynamics and connectivity across depth and latitudinal gradients should be investigated, not only with other seamounts in Cabo Verde, but also with other Macaronesian islands.

CRedit authorship contribution statement

Beatriz Vinha: Writing – original draft, Software, Methodology,

Formal analysis, Data curation, Conceptualization. **Veerle A.I. Huv-
enne:** Writing – review & editing, Supervision, Resources, Project
administration, Methodology, Conceptualization. **Andrea Gori:** Writing
– review & editing, Methodology, Conceptualization. **Stefano Piraino:**
Writing – review & editing, Supervision, Resources. **Covadonga Orejas:**
Writing – review & editing, Supervision, Resources, Project adminis-
tration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.pocean.2025.103532>.

Data availability

All data and code used in this study are available in FigShare under the following citation: Vinha, B. (2025). Data and code to reproduce the study of Vinha et al., (2025). Characterization and mapping of bathyal benthic communities of Cabo Verde (NW Africa). Progress in Oceanography. figshare. Dataset. <https://doi.org/10.6084/m9.figshare.26780044.v2>.

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