



Habitat suitability model for predicting the occurrence of scleractinian cold-water corals in the Gulf of Naples (Tyrrhenian Sea): A tool for restoration planning and governance of deep-sea ecosystems

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ABSTRACT

Cold-water corals (CWCs) are key ecosystem engineers in deep-sea habitats, yet their distribution in the Gulf of Naples remains poorly known. Here, we applied a Maximum Entropy (MaxEnt) model with high-resolution environmental predictors to investigate the fine-scale suitability of scleractinian CWCs within the Gulf of Naples and adjacent areas. Presence records were derived from Remotely Operated Vehicles (ROV) video analyses, while predictors included bottom current velocity from a Regional Ocean Modeling System (ROMS) simulation and geomorphological variables from multibeam bathymetry (bathymetric position index, slope, roughness, aspect, and backscatter).

The model predicted $\sim 0.43 \text{ km}^2$ of suitable habitat (suitability index > 0.6) corresponding to 0.09 % of the entire study area, mainly along canyon walls and elevated seabed features of the Dohrn Canyon. Additional suitable areas were identified in the deeper canyon sectors and south of Ischia Island. Current velocity at the bottom influenced the most our model, with high suitability values obtained from 0.10 to 0.18 m/s, suggesting these as favorable conditions for sediment removal and food supply. The variable response curves documented that Bathymetric position index and roughness contributed to the model, with preferences for elevated seabed features and heterogeneous seafloor topography.

These findings highlight the role of bottom current velocity and topographic complexity in shaping CWCs habitats in the study region and reveal unexplored areas with high potential for coral occurrence. Model outputs provide a scientific basis for Natura 2000 site designation and support conservation and restoration strategies for vulnerable deep-sea ecosystems in the area.

1. Introduction

The increasing availability of underwater technologies, particularly remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) has revolutionized our understanding of the distribution and

abundance of cold-water corals (CWCs) communities (e.g., Angeletti et al., 2020; Bo et al., 2014; Freiwald et al., 2004, 2009; Orejas et al., 2009; Rossi et al., 2017; Trotter et al., 2022; Cordes et al., 2023). The occurrence of CWCs has been increasingly documented over the past two decades, particularly in the western and central Mediterranean basins,

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highlighting that the region provides suitable environmental conditions for the persistence of diverse CWCs assemblages, including scleractinians, gorgonians, and antipatharians, which thrive on both hard and soft substrates (Freiwald, 2002; Orejas and Jiménez, 2019; Taviani et al., 2017).

The most common and widely distributed scleractinian CWCs, also known as “stony corals”, in the modern Mediterranean Sea include the white colonial species *Madrepora oculata* (Linnaeus, 1758) and *Desmophyllum pertusum* (Linnaeus, 1758) (Addamo et al., 2016), alongside the yellow branching coral *Dendrophyllia cornigera* (Lamarck, 1816), the solitary *Desmophyllum dianthus* (Esper, 1794), and other species in the Family Caryophyllidae (e.g., Altuna and Polisenio, 2019; Angeletti et al., 2014; Freiwald et al., 2009; Prampolini et al., 2020; Taviani et al., 2005).

Due to their sensitivity to anthropogenic stressors such as bottom-contact fisheries, marine litter, and seabed resource exploitation, CWCs habitats are recognized as Vulnerable Marine Ecosystems (VMEs) (Angiolillo et al., 2023; Carbonara et al., 2020; Danovaro et al., 2020; FAO, 2009; ICES, 2016). They fall under habitat type “1170 – Reefs” of the EU Habitats Directive (92/43/EEC), and habitat-forming species are listed in Annex II of the Barcelona Convention (UNEP/MAP-SPA/RAC, 2013). CWCs habitats act as biodiversity hotspots, providing refuges, feeding, spawning, and nursery areas, as well as substrates for larval settlement and juvenile growth (Angiolillo et al., 2021, 2023; Cordes et al., 2023; Lo Iacono et al., 2018; Roberts et al., 2009). However, large portions of the deep-sea, such as submarine canyons, remain unexplored, resulting in significant knowledge gaps regarding the spatial distribution of these habitats (Fraschetti et al., 2024).

In the Gulf of Naples (Tyrrhenian Sea, Mediterranean Sea), CWCs communities populating the Dohrn Canyon were first documented by Taviani et al. (2019), and further investigated in recent surveys (Angiolillo et al., 2023; Castellan et al., 2025a,b). These findings uncovered a unique Mediterranean biotope characterized by framework-forming scleractinian corals, including *M. oculata*, *D. pertusum* and *D. dianthus* in association with the giant oyster *Neopynodonte zibrowii* (Gofas, Salas & Taviani, 2009), and the bivalve *Acesta excavata* (Fabricius, 1779). These vulnerable habitats coexist in the area alongside clear evidence of anthropogenic impacts, such as illegal dumping and destructive fishing practices (Angiolillo et al., 2023; Taviani et al., 2019).

As CWCs are increasingly recognized as a conservation priority, the designation of a new Site of Community Interest (SCI) under the Natura 2000 network started in 2024, covering sectors of the Dohrn Canyon (Grande et al., 2024). The proposed site is particularly focused on habitats formed by the association between CWCs and deep oyster reefs, and aims to raise awareness of this exceptional biotope and foster its protection against the growing anthropogenic pressures that currently threaten the area.

In this scenario, identifying the factors influencing the distribution of CWCs is essential to developing effective spatial planning and management measures (Castellan et al., 2022; Danovaro et al., 2020; Fanelli et al., 2021). Habitat suitability models (HSMs) represent a valuable tool to support conservation planning, as they relate the environmental conditions of known species occurrences to those of a broader study area, allowing the identification of areas with high habitat suitability (Anderson et al., 2016a,b; Bargain et al., 2017, 2018; Davies and Guinotte, 2011; Di Giovanna et al., 2025; Georgian et al., 2014, 2020; Lauria et al., 2021; Palummo et al., 2023).

In recent years, several habitat suitability models have been developed in the Mediterranean Sea to predict the potential distribution of CWCs communities, focusing on specific taxonomic groups, such as black corals and gorgonians (e.g., Figuerola-Ferrando et al., 2025; Georges et al., 2024; Innangi et al., 2024; Lauria et al., 2021; Standaert et al., 2023) or scleractinian coral species including *M. oculata*, *D. pertusum*, and *D. cornigera* (Bargain et al., 2017, 2018; Cordes et al., 2023; Fabri et al., 2017; Gori et al., 2023; Lastras et al., 2016; Matos

et al., 2021).

However, among the main limitations of HSMs is the coarse horizontal resolution of environmental predictors that are often derived from global-scale models: ~450 m horizontal resolution for bathymetry (GEBCO, www.gebco.net) and from ~8 km for physical variables (Copernicus, www.copernicus.eu) (Cordes et al., 2023; Davies and Guinotte, 2011). Recent work has therefore increasingly focused on developing finer-scale (up to 5 m horizontal resolution) applications (Bargain et al., 2017, 2018; Lo Iacono et al., 2018). This requires higher-quality environmental data at finer resolution, along with updated species occurrence datasets that combine new findings with existing records to ensure continuous improvement in data quality.

Here, we apply a HSM in the Gulf of Naples to identify areas suitable for scleractinian CWCs. By integrating oceanographic variables and terrain attributes at high horizontal resolution with habitat occurrence data across the study area, we identify sites that exhibit conditions favorable for the potential presence of scleractinian CWCs. Our effort aims at orienting future exploration, supporting conservation strategies, and informing maritime spatial planning frameworks.

2. Materials and methods

2.1. Study area

Recent high-resolution (20 m) bathymetric survey conducted in the Gulf of Naples and Salerno has provided new geomorphological insights into the Dohrn and Magnaghi canyons, two submarine canyons incising the continental shelf and slope (Fig. 1) (Foglini et al., 2025; Somma et al., 2016). These canyons are shaped by the interaction of extensional tectonic structures and volcanic activity, which primarily control their morphology (Aiello and Caccavale, 2021; Loreto et al., 2021; Ruberti et al., 2022; Miramontes et al., 2023). According to previous geological interpretations, both canyons also acted as major sediment drainage systems during the late Quaternary (Aiello and Caccavale, 2021). The Dohrn Canyon, with two main branches ~500 m wide and distinct V- and U-shaped profiles, shows features such as terrace rims, hanging gullies, slide scars, and a radial bedform field, indicative of complex sedimentary processes. In contrast, the Magnaghi Canyon is shorter, less deeply incised, and not gullied on its flanks, possibly reflecting its lack of connection to a major source of sediment-laden flows (Foglini et al., 2025). Its right-hand slope displays short, straight incisions with distinct bedforms typical of high-energy sediment transport processes (Kostic, 2011; Sloomman and Cartigny, 2020). Recognized as sediment conduits and potential biodiversity hotspots, these canyons represent key features of the Tyrrhenian margin (Taviani et al., 2019).

2.2. Geophysical data

In September and October 2022, high-resolution bathymetric data were acquired during the JammeGaia22 oceanographic cruise aboard the CNR R/V *Gaia Blu*, using three hull-mounted Kongsberg multibeam echosounders (EM2040, EM712, and EM304). Data acquisition was supported by a Seapath 380 positioning system and continuously corrected using sound velocity profiles. Bathymetric and backscatter data were processed onboard using Qimera and Fledermaus FMGT software, applying standard corrections (e.g., sound speed, offsets, outlier removal). This study used a Digital Elevation Model (DEM) and the backscatter mosaic at a resolution of 20 m. For more details regarding the processing methodology, refer to Foglini et al. (2025).

2.3. ROV data

A total of 22 ROV video transects (Table 1) were selected and analyzed in this study: one from the *ANOMCITY16* cruise (June–July 2016), one from the *MS16-TIRRENO* cruise (July–August 2016), and one from the *MSFD-IT-1-2017-Tirreno* cruise (June–July 2017), all

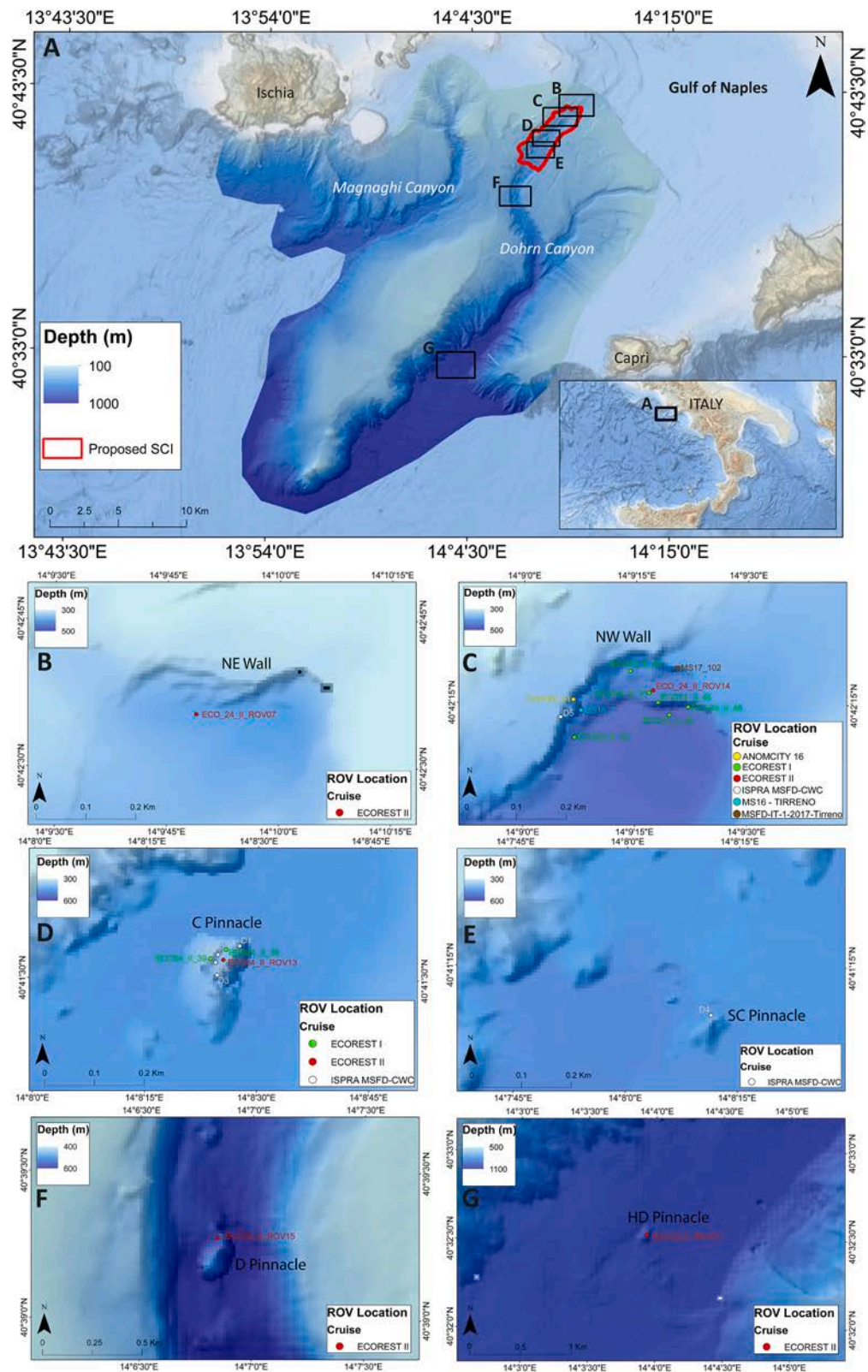


Fig. 1. A) Overview of the study areas located in the Gulf of Naples and the extension of the proposed Site of Community Importance (SCI); B-G) details of the explored areas by ROV dives during oceanographic cruises. NE wall: North-eastern wall; NW wall: North-western wall; C pinnacle: Central pinnacle; SC pinnacle: South-center pinnacle; D pinnacle: deep pinnacle, located in the central sector of the canyon; HD pinnacle: pinnacle located in the deeper sector of the canyon. Maps are projected in WGS84 Zone 33N datum.

Table 1

Metadata of ROV dives including date, depth, location, and corresponding cruises. Coordinates refer to the centroid of each ROV transect. NE wall: North-eastern wall; NW wall: North-western wall; C pinnacle: Central pinnacle; SC pinnacle: South-center pinnacle; D pinnacle: deep pinnacle, located in the central sector of the canyon; HD pinnacle: pinnacle located in the deeper sector of the canyon.

Dive	Date	Location	Depth (m)	Latitude (ddeg)	Longitude (ddeg)	Cruise
ECO24_II_31	09/05/2024	NW wall	392–433	40.704483	14.154697	ECOREST I
ECO24_II_32	09/05/2024	NW wall	444–467	40.703861	14.155461	ECOREST I
ECO24_II_35	10/05/2024	NW wall	392–418	40.703200	14.151934	ECOREST I
ECO24_II_38	11/05/2024	C pinnacle	394–469	40.692507	14.140518	ECOREST I
ECO24_II_39	11/05/2024	C pinnacle	370–387	40.692241	14.139940	ECOREST I
ECO24_II_43	11/05/2024	NW wall	358–425	40.705087	14.153997	ECOREST I
ECO24_II_44	12/05/2024	NW wall	432–458	40.704205	14.155036	ECOREST I
ECO24_II_48	12/05/2024	NW wall	431–462	40.704089	14.156157	ECOREST I
ECO_24_II_ROV06	15/07/2024	HD pinnacle	1030–1049	40.542120	14.065572	ECOREST II
ECO_24_II_ROV07	17/07/2024	NE wall	328–378	40.709826	14.163600	ECOREST II
ECO_24_II_ROV13	21/07/2024	C pinnacle	376–463	40.692211	14.140418	ECOREST II
ECO_24_II_ROV14	21/07/2024	NW wall	438–473	40.704549	14.154844	ECOREST II
ECO_24_II_ROV15	21/07/2024	D pinnacle	605–576	40.654603	14.114122	ECOREST II
D1	27/08/2020	C pinnacle	375–387	40.692611	14.141027	ISPRA MSFD-CWC
D3	28/08/2020	C pinnacle	382–392	40.691778	14.140194	ISPRA MSFD-CWC
D4	28/08/2020	SC pinnacle	414–438	40.686139	14.136528	ISPRA MSFD-CWC
D5	29/08/2020	NW wall	353–382	40.703778	14.151417	ISPRA MSFD-CWC
D9	01/09/2020	C pinnacle	364–374	40.692139	14.140139	ISPRA MSFD-CWC
D15	03/09/2020	C pinnacle	358–394	40.692362	14.140222	ISPRA MSFD-CWC
DOHRN_01	02/06/2016	NW wall	375–455	40.704274	14.151880	ANOMCITY16
MS16_7	17/07/2016	NW wall	375–455	40.703970	14.152168	MS16 - TIRRENO
MS17_102	13/07/2017	NW wall	345–470	40.705178	14.155732	MSFD-IT-1-2017 - Tirreno

conducted aboard the R/V *Minerva Uno* in the Dohrn Canyon using the ROV Pollux III; six from the *ISPRA MSFD-CWC* campaign aboard the R/V *Astrea* (August–September 2020) with the ROV Perseo; eight from the *ECOREST I* cruise (May 2024) using a sub-Atlantic Tomahawk ROV, and five from the *ECOREST II* cruise (July 2024) with the ROV Perseo GTV, both aboard the R/V *Gaia Blu*. All ROVs were equipped with HD or 4K UHD cameras, allowing high-resolution video documentation of deep-sea habitats. This analysis considers only the videos specifically aimed at exploring the canyon seafloor, while those dedicated to system tests or unrelated activities were excluded. High-resolution video footage was acquired continuously along each transect, providing detailed visual documentation of the benthic communities inhabiting both the canyon environments and the adjacent shelf areas.

2.4. Occurrence data

The modeling framework included occurrences of *D. pertusum*, *M. oculata*, and solitary corals classified as Caryophylliidae spp. (Fig. 2). A finer taxonomic resolution for solitary corals was not applied because the video footage did not always allow for reliable species-level identification. Since these species concur in forming the target habitat, they often occur in similar environmental settings (Arnaud-Haond et al., 2017; Mastrototaro et al., 2010), we modeled them collectively following the approach used in previous modeling studies (Anderson et al., 2016a,b; Barbosa et al., 2020; Bargain et al., 2017, 2018).

Species occurrences were extracted from ROV video transects by extracting a frame every 10 s that was then analyzed for taxonomic identification, following the method described in Castellan et al. (2020). In cases of uncertainty, extracted frames were cross-validated with the corresponding high-definition video sequences to improve identification accuracy. Image extraction for videos collected during the *ANOMCITY16*, *MS16 – TIRRENO*, and *MSFD-IT-1-2017 - Tirreno* cruises was performed using Adelie Video 3 and the Adelie GIS (©Ifremer) extension for ArcGIS. ROV navigation data were used to georeference the video tracks, which were smoothed with a Gaussian filter to better represent the actual path, and then converted to line format using the ‘points to line’ tool in Adelie GIS (Foglini et al., 2019).

For ROV videos from the *ECOREST I* and *II* cruises, images were extracted using a custom R software-based workflow. Video tracks were georeferenced using ROV navigation data acquired during the dives,

allowing for the spatial integration of biological observations extracted from the videos and their association with the corresponding navigation data.

For videos from the *ISPRA MSFD-CWC* cruise, images were extracted following the protocol described by Angiolillo et al. (2023). Georeferenced ROV transect plots were imported into ArcGIS v10.3.1. Video footage was processed using VLC media player to identify all visible megafaunal taxa to the lowest possible taxonomic level.

The presence of scleractinian corals was quantified by recording their occurrence within each frame, resulting in 50 observations from the *ANOMCITY16* cruise, 20 from the *MS16–TIRRENO* cruise, 2 from the *MSFD–IT–1–2017–Tirreno* cruise, 547 records from the analysis of video material from the *ISPRA MSFD–CWC* campaign (Angiolillo et al., 2023), and 289 observations derived from the *ECOREST I* and *II* campaigns (Table S1). A total of 908 occurrences were identified, georeferenced, and converted into spatial points. Due to the spatial clustering typical of ROV-based observations, multiple detections frequently fell within the same raster cell of the environmental background. To prevent sampling bias from duplicated environmental information, we applied a spatial thinning procedure retaining only one presence per raster cell, resulting in a final dataset of 76 unique presence cells at 20 × 20 m of resolution.

2.5. Oceanographic variables and terrain attributes

The set of oceanographic variables and terrain attributes used for modeling is summarized in Table 2. Temperature and current velocity were obtained from the Gulf of Naples Advanced Model (GNAM), with a high-resolution Regional Ocean Modeling System (ROMS) specifically downscaled for the Campania coastal sector (Kokoszka et al., 2022). The data were provided as daily NetCDF files for the period 2001–2010, with a native spatial resolution of 500 m.

Data processing was carried out in R software. For each oceanographic variable, the deepest valid layer per grid cell representing near-bottom conditions was extracted daily, producing a time series of bottom-layer raster. To obtain a more coherent description of near-bottom hydrodynamics, we applied a bottom boundary layer (BBL) harmonization procedure to the ROMS outputs, averaging the current velocity components (u and v) within the lower 100 m of the water column. Daily BBL-averaged values were then averaged at the annual

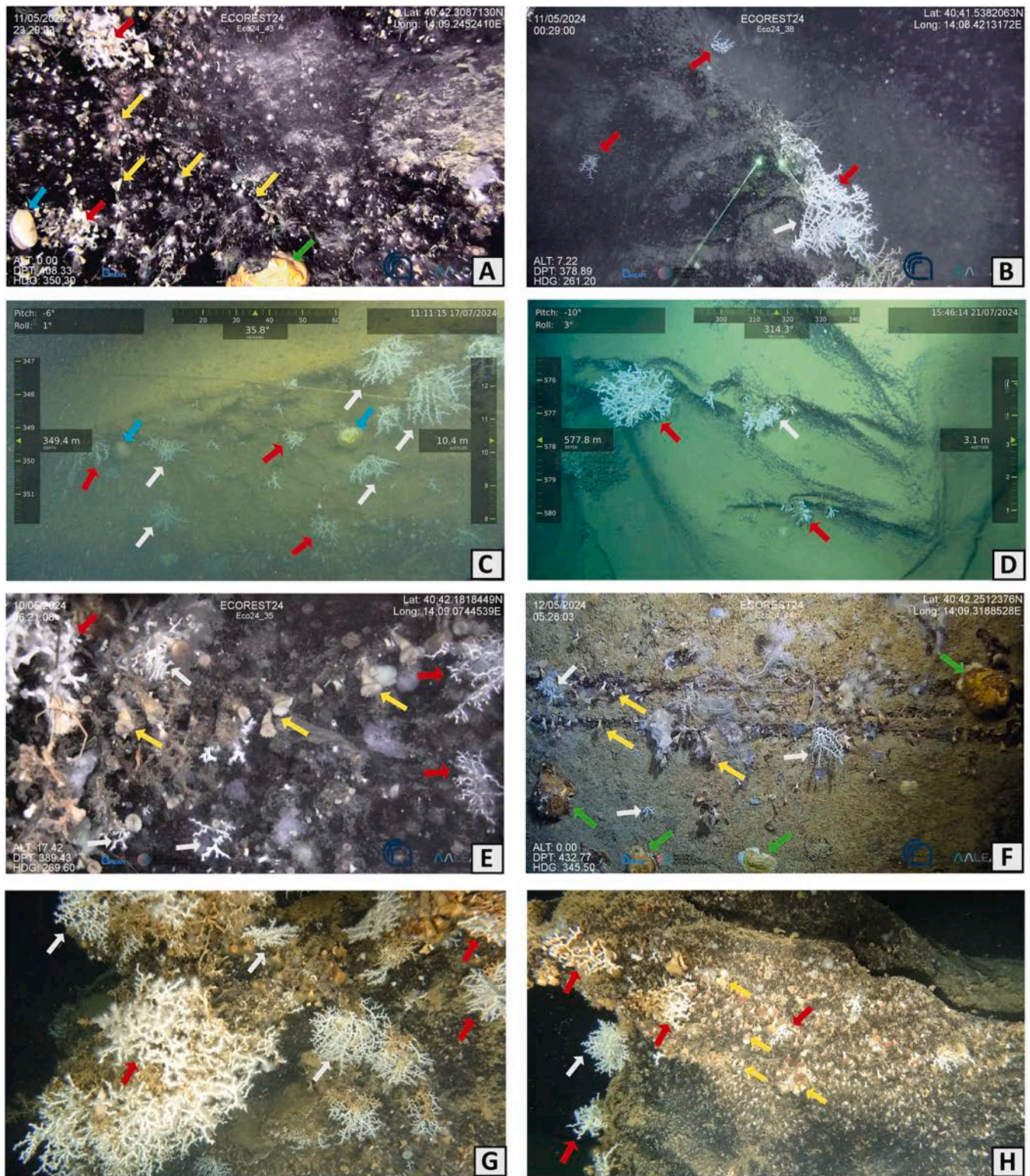


Fig. 2. Frames from ROV surveys showing scleractinian cold-water corals (CWCs) in the Dohrn Canyon. Red arrows indicate *Desmophyllum pertusum* colonies; white arrows indicate *Madrepora oculata*; yellow arrows show solitary Caryophylliidae spp.; green arrows highlight the giant oyster *Neopercnodonte zibrowii*; blue arrows mark the bivalve *Acesta excavata*. A) Dive ECO24_II_43 performed along the NW wall; B) dive ECO24_II_38 on C pinnacle showing a rocky seabed colonized by large *D. pertusum* and smaller *M. oculata* colonies; C) dive ECO24_II_ROV07 conducted on the NE wall displaying *D. pertusum*, *M. oculata*, and *A. excavata* with longline entangling coral colonies; D) image from ECO24_II_ROV13 performed along the eastern-facing vertical wall of C pinnacle; E) frame from dive ECO24_II_35 conducted on the NW wall showing close-up of living solitary Caryophylliidae spp. and *M. oculata* colonies; F) vertical wall of the NW flank imaged by ECO24_II_44 showing *M. oculata* and Caryophylliidae spp. associated with *N. zibrowii*; G) image showing colonies of *D. pertusum* and *M. oculata* modified from Angiolillo et al. (2023); H) association of *D. pertusum*, Caryophylliidae spp. and *M. oculata* colonizing hard substrate in C pinnacle. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 2

Set of environmental variables used as predictors in modeling efforts. The table reports units, native spatial resolution, temporal coverage (for oceanographic variables), and data sources. Terrain attributes were derived from multibeam bathymetry at 20 m resolution. Oceanographic predictors (bottom temperature and bottom current velocities) representing long-term decadal averages (2001–2010) were obtained from high-resolution ROMS simulations.

Variable	Unit	Original resolution	Historical run	Source
Bottom temperature	°C	500m	2001–2010	Kokoszka et al. (2022)
Bottom current velocity (mean and max)	m/s	500 m	2001–2010	Kokoszka et al. (2022)
Depth	m	20 m	\\	Acquired bathymetry (Foglini et al., 2025)
Backscatter	dB	20 m	\\	Acquired backscatter (Foglini et al., 2025)
BPIs (1:3, 1:9, 1:17, 1:25, 1:33, 1:65)	–	20 m	\\	Derived from bathymetry
Roughness	0–120	20 m	\\	Derived from bathymetry
Slope	0°–90°	20 m	\\	Derived from bathymetry
Curvature	–	20 m	\\	Derived from bathymetry
General aspect	0–360°	20 m	\\	Derived from bathymetry

scale and subsequently across the entire 2001–2010 period, producing the decadal mean bottom current rasters. For maximum current velocity, daily bottom-current values were first used to identify, for each pixel, the maximum value recorded within each month. Monthly maxima were then averaged to obtain one annual value per pixel. Finally, annual values from 2001 to 2010 were averaged to generate a decadal raster representing the typical intensity of recurrent extreme bottom-current events, rather than a single exceptional peak.

For temperature, daily bottom values were averaged to generate annual means, which were then combined into a decadal average raster.

All resulting rasters were resampled (bilinear interpolation) to match the spatial resolution of the bathymetric grid, ensuring full alignment across all environmental and geomorphological predictors used in the HSM (Kinlan et al., 2020).

High-resolution bathymetry was processed to derive morphometric indices such as Bathymetric Position Index (BPI), slope, curvature, roughness, and general aspect, using the Benthic Terrain Modeler (BTM version 3.0) within the ArcGIS environment, as outlined in Walbridge et al. (2018). The BPI compares the elevation of a cell to the average elevation of surrounding cells within defined inner and outer radii, identifying ridges (positive values), depressions (negative values), and flat areas (values near zero) (Weiss, 2001). BPI is derived through neighborhood analysis, with its scale factor determined by multiplying the analysis radius (in cells) by cell resolution (Lundblad et al., 2006). In this study, we used BPI grids with radii of 1:3, 1:9, 1:17, 1:25, 1:33, and 1:65 to capture both fine and broad-scale bathymetric features. These ranges were selected following a Fibonacci sequence as suggested by Wilson et al. (2007) that can describe topographic variations, such as minor mounds or depressions, as well as larger geomorphological structures of the seafloor. Slope describes the steepness of the seafloor and serves as a proxy to distinguish different large-scale habitats, such as continental margins, canyons, or abyssal plains. Low slope values are typically associated with flat depositional areas, whereas higher values indicate potential rocky outcrops or ledges (Georges et al., 2024). Terrain roughness is an index of seafloor complexity, and high values are

often associated with the presence of hard substrates, which represent favorable habitats for CWCs (Masclé et al., 2015). Terrain curvature was measured using the general curvature index, which indicates concave (negative) or convex (positive) surfaces and can reflect how water flows interact with the seafloor (Vierod et al., 2014). General aspect identifies the orientation of the steepest downhill slope, indicating the compass direction faced by each grid cell. Calculations were performed using planar methods to account for surface orientation (Lo Iacono et al., 2018). Finally, acoustic backscatter refers to the acoustic reflectivity of the seafloor: it measures the amount of acoustic energy backscattered from the seafloor and recorded by sonar sensors. It provides insights into seabed composition and texture (Lurton et al., 2015). Backscatter data were used as additional predictors to characterize seafloor complexity.

2.6. Modeling

Species distribution model was performed using the MaxEnt algorithm (Phillips and Dudík, 2008, version 3.4.4), a presence-background points (Sillero and Barbosa, 2021) method widely used for modeling ecological niches based on occurrence data together with environmental predictors.

A total of three models were performed. Firstly, a MaxEnt model for BPIs selection (*MaxEnt BPIs*) was carried out to identify the most representative BPI resolution among the different BPIs calculated, and the one showing the highest contribution was subsequently retained and included in the following models. Since inclusion of highly correlated variables negatively impacts model performance and complicates the interpretation of individual predictor contributions (Georgian et al., 2020, 2021; Huang et al., 2011), a second model (*MaxEnt Selection*) was applied to obtain a more parsimonious set of predictors. Variables were retained by jointly considering their percent contribution to the model runs and the pairwise correlations. When two or more predictors showed Pearson's $|r| > 0.75$, their percent contribution to the model was compared to select the variables to be retained. In cases where this contribution-based approach would have led to the exclusion of variables known to be ecologically important for CWCs distribution, the final selection was guided by expert opinion. Finally, a third model (*MaxEnt Final*) was performed using the set of variables selected from the previous runs to generate the final prediction. All three models runs were performed with 10 bootstrap replicates using default parameters (convergence threshold = 10^{-5} , maximum iteration = 500, and 10,000 background points as suggested by Elith et al. (2006) and Tong et al. (2023) except for the regularization multiplier (β) and default prevalence, which were set to 0.5 and 0.7, respectively, to better capture suitability in known occurrence zones and reduce over-fitting (Bargain et al., 2017, 2018).

The final prediction map was produced using an ensemble approach by averaging the suitability predictions across all replicates obtained from *MaxEnt Final* models, resulting in a suitability map ranging from 0 (low suitability) to 1 (high suitability) at 20 m of horizontal resolution. We considered 0.2 to 0.4 suitability index as “low suitability”, 0.4 to 0.6 as “low-mid suitability”, 0.6 to 0.8 as “medium suitability”, and 0.8 to 1 as “high suitability”.

2.7. Model evaluation

Scleractinian coral occurrences data, together with background points, were randomly partitioned into training (70 %) and testing (30 %) datasets to assess model fit and predictive performance. Evaluation was carried out using the Area Under the Curve (AUC) and the True Skill Statistic (TSS), both frequently used for model accuracy and discrimination ability in species distribution modelling (e.g. Bargain et al., 2017; Davies and Guinotte, 2011; Georgian et al., 2021; Shabani et al., 2018; Stephenson et al., 2021; Vitelletti et al., 2023).

The AUC value, which ranges from 0 to 1, measures the model's ability to discriminate between presence and background points. A value

below 0.5 indicates a performance no better than random, and 1 represents perfect discrimination. Values above 0.7 are generally considered indicators of good model performance (Elith et al., 2006; Lauria et al., 2021). The True Skill Statistic (TSS) accounts for both omission errors (false negatives) and commission errors (false positives), providing a balanced measure of model performance. It is independent of prevalence and the size of the validation set. TSS values range from -1 to $+1$, where $+1$ indicates perfect agreement between predicted and observed occurrences, and values of 0 or below reflect a performance equivalent to or worse than random chance (Allouche et al., 2006; Liu et al., 2016). To assess model stability and quantify spatial uncertainty between runs, all models were replicated using a bootstrap procedure with 10 replicates. The mean and standard deviation (SD) of model performance metrics (AUC and TSS) were calculated across all replicates. Model uncertainty was further quantified using the coefficient of variation (CV), calculated as the ratio between the standard deviation and the mean habitat suitability values across replicates (Figueroa-Ferrando et al., 2025; Standaert et al., 2023). Lower CV values indicate higher agreement among model predictions and, thus, greater confidence in the estimated suitability, whereas higher CV values reflect increased variability and lower confidence in model estimates.

3. Results

3.1. Model evaluation and variables contribution

The *Maxent* BPIs outputs indicate that BPI 1:9 contributed the most to the model, with a percentage of approximately 36.3 % (Tables S2 and S3). Consequently, BPI 1:9 was included in the subsequent modeling process.

The *MaxEnt* Selection model (Tables S4 and S5 and Fig. S1) indicated the bottom temperature as the most influential variable, accounting for 35.5 % of model contribution. However, bottom temperature showed a very strong positive correlation with depth, maximum, and mean bottom current velocity ($r = 0.90$ with depth, and $r = 0.75$ and 0.73 with both current velocity metrics). Because GNAM reported that bottom temperature is relatively uniform across these canyons and because depth can be considered as a robust proxy for several ecological gradients such as temperature, dissolved oxygen, and aragonite and calcite saturation states (Davies and Guinotte, 2011; Tittensor et al., 2009; Yesson et al., 2012, 2017), we therefore decided to retain depth in the final model despite the higher contribution of temperature in the earlier model.

The correlation analysis showed that maximum bottom current velocity (~ 15.4 % contribution) and mean bottom current velocity (0.46 %) were highly collinear ($r \approx 0.94$). Since the higher contribution of maximum current velocity and ROV observations showed CWCs presence in high-flow areas, we retained maximum current velocity.

Roughness and slope resulted correlated, and the first was kept due to its higher contribution to the model (16.7 % vs. 1.4 %). The performance metrics (AUC, TSS, sensitivity, and specificity) of the *MaxEnt* Selection model are summarized in Table S5.

Finally, *Maxent* Final predictors set comprises depth, maximum bottom current velocity, BPI 1:9, curvature, backscatter, and roughness. This selection allowed us to reduce multicollinearity, preserve explanatory power, and align the model with field evidence of scleractinian CWCs habitat preferences.

Response curves for the environmental predictors and their percentage contributions in the *MaxEnt* Final model are shown in Fig. 3. The results of *MaxEnt* Final show that the 10-year maximum current velocity contributed the most to the prediction (~ 35.3 %), with the highest suitability values between 0.10 and 0.18 m/s of maximum current velocity. BPI 1:9 represented the second most important predictor (31 %), with increasing suitability values associated with positive BPI values, indicating a preference for elevated seabed features. Roughness variable

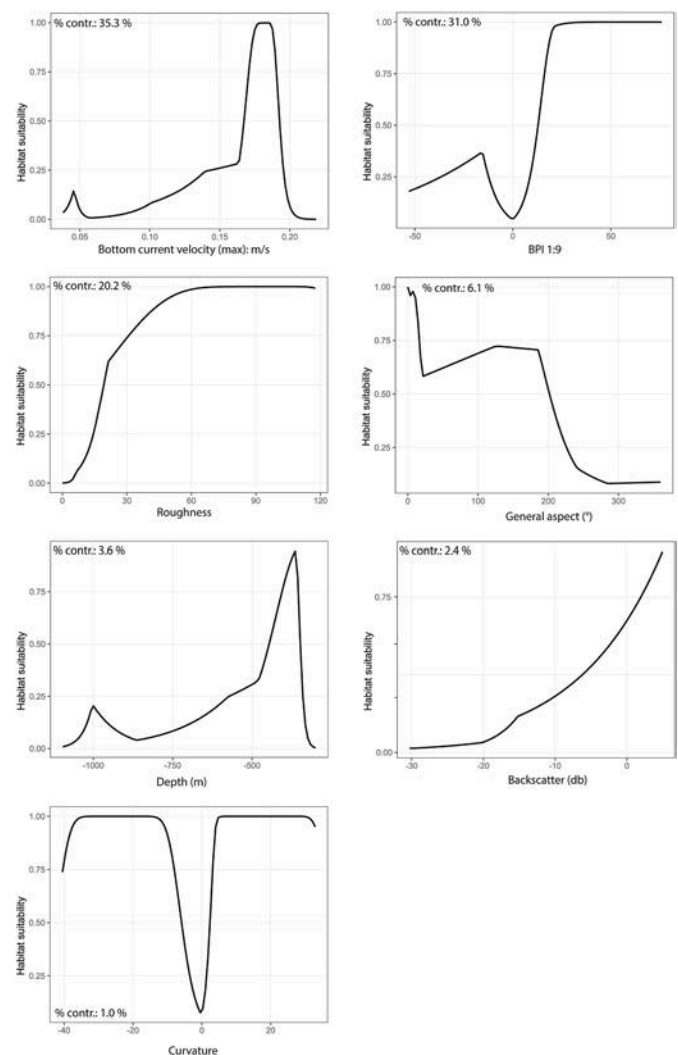


Fig. 3. Predictor response curves obtained from the final *MaxEnt* model using the “cloglog” transformation. The curves, shown in order of decreasing percentage contribution, depict the relationship between the habitat suitability index and the predictors. % contr.: percentage contribution of the predictor in final model.

contributed 20.2 % to the *MaxEnt* Final model, with high suitability values reached in areas with rugged and heterogeneous substrate.

General aspect response curve (6.1 %) showed higher suitability for seabed facing approximately from north (0°) to south-southwest (100° – 200°). Despite its low contribution to the model (3.6 %), depth showed high suitability between 200 and 700 m, and a minimal peak around 1000 m depth. Backscatter showed a low contribution to the model (2.4 %); however, suitability tended to increase with higher backscatter values, consistent with the presence of rocky substrates. Finally, curvature contributed minimally (1 %) to the final prediction.

Metrics for *MaxEnt* Final are reported in Table S6 and were remarkably high, with AUC values of 0.9963 (SD = 0.0028) for the training set and 0.9846 (SD = 0.0078) for the test set, indicating excellent discriminatory ability. The TSS was also high, with a value of 0.900 (SD = 0.044), suggesting strong model accuracy and balanced performance. The maps of predictors used in the *MaxEnt* Final are reported in Fig. S2.

3.2. Distribution of suitable areas

Regions investigated through ROV surveys, as well as their

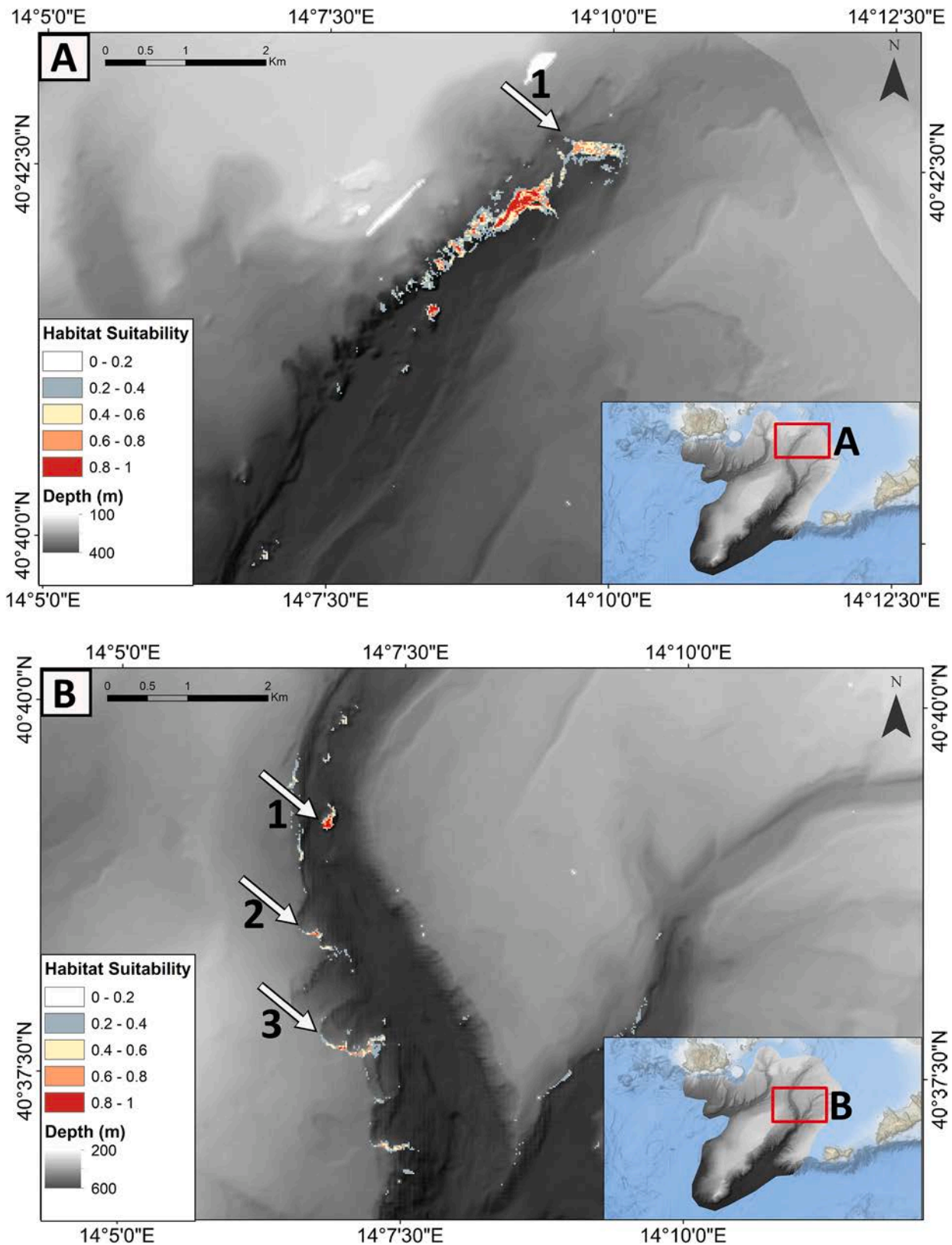


Fig. 4. Habitat suitability maps for the northern and central sectors of the Dohrn Canyon. Arrows highlight areas predicted as suitable by the MaxEnt model despite the absence of known coral records. A) Habitat suitability in the northwestern sector of the Dohrn Canyon. Warm colors (orange-red) denote high suitability for scleractinian CWCs. Arrow 1 indicates a highly suitable sector along the northeastern canyon wall. B) Habitat suitability in the central sector of the Dohrn Canyon. High-suitability zones are highlighted by arrows 1, 2, and 3 within the main canyon axis, particularly around the 500-m depth pinnacle and on the western steep flanks. Insets show the location of each detailed map within the Gulf of Naples. Coordinate reference system: WGS84/UTMZone 33N. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

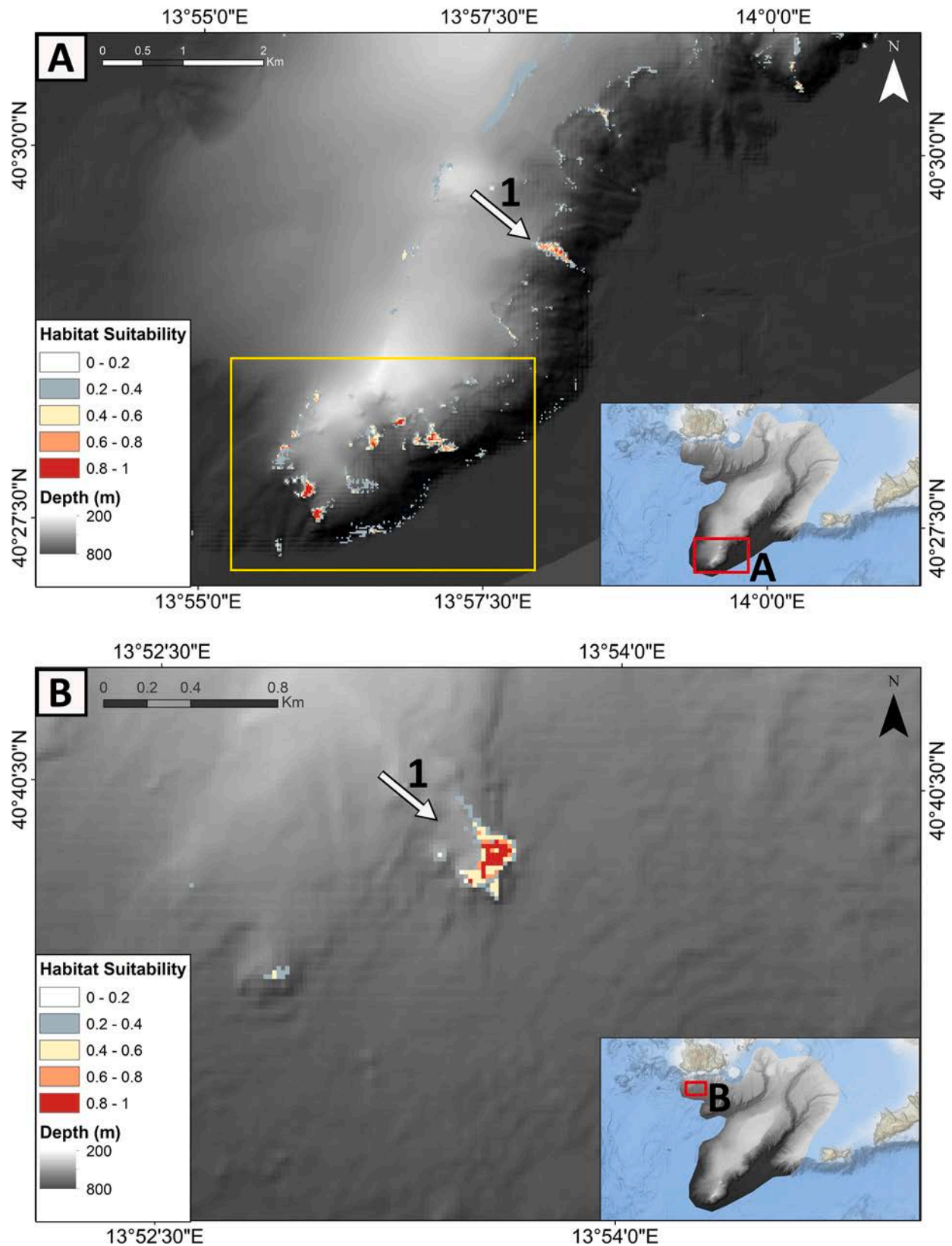


Fig. 5. A) Habitat suitability in the southernmost sector of the Dohrn Canyon. The yellow polygon and arrow 1 indicate unsampled areas where *MaxEnt Final* model predicts high suitability values (>0.8), mostly occurring between 500 and 700 m depth along steep southwestern canyon flanks. B) Areas of favorable environmental conditions predicted by the MaxEnt model on an elevated morphological feature south of Ischia. Arrow 1 marks unsampled locations showing moderate-to-high suitability. Insets show the position of the enlarged areas within the regional context. Coordinate reference system: WGS84/UTM Zone 33N. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

immediate surroundings, consistently exhibited high suitability, particularly along steep and topographically complex seafloor (Figs. 4–5).

Areas characterized by favorable environmental conditions suitable for the presence of scleractinian CWCs (suitability index >0.6) were detected along a south-east facing slope located at the Dohrn Canyon head, where steep walls range from 50° to 70° (Fig. 4A).

Additionally, elevated seabed features along the central axis of the canyon exhibited high suitability values, which gradually decreased to lower suitability values (ranging between 0.2 and 0.4) with increasing distance from the canyon slope.

In the central sector of the canyon (Fig. 4B), high habitat suitability values (suitability index 0.8–0.1) were obtained in correspondence with a prominent elevated structure at 500 m depth and a narrow area on the western canyon flank.

In the southernmost sector of the Dohrn Canyon (Fig. 5A), the model identified scattered patches of high habitat suitability index, mostly concentrated between 500 and 700 m depth, along slopes ranging from 30° to 60° with roughness and backscatter values indicative of hard bottom substrate. Indeed, these areas were located along the south-western canyon flank, characterized by steep morphologies and complex terrain.

In the south of Ischia Island (Fig. 5B), outside the morphological boundaries of the Dohrn Canyon, the model identified a high habitat suitability value (>0.8) in an area with an elevated feature at approximately 400 m depth, rising ~ 150 m from the seafloor. Additional areas along the adjacent slope exhibited low suitability values, ranging from 0.2 to 0.4.

Finally, within the Magnaghi Canyon, the model did not predict any significant suitable areas, with only a few scattered pixels showing low suitability values.

Model uncertainty, expressed as % CV, was generally low in the final spatial prediction (Fig. 6). Higher uncertainty values (>0.6) were primarily concentrated in the Dohrn and Magnaghi canyons floors and in areas located between canyons ridges, where bottom current velocities were low. These zones largely correspond to flat seabed sectors that, based on backscatter values, are predominantly characterized by mobile substrates. Overall, higher uncertainty was observed in areas distant from steep canyon walls and highly rugged seabed features. In contrast, regions predicted as highly suitable consistently exhibited low uncertainty.

4. Discussion

The use of high-resolution environmental predictors in this study enabled the identification of fine-scale patterns of environmental suitability for scleractinian CWCs in the Gulf of Naples, highlighting areas that have not been previously investigated and that may represent suitable habitats for their occurrence.

According to model outputs, the total area identified as suitable (suitability index >0.6) for scleractinian corals corresponds to approximately 0.43 km^2 of the study region. Suitable conditions were mainly predicted within the Dohrn Canyon, particularly in correspondence of canyon head and along the flanks, as well as in correspondence of elevated seabed features along the canyon central axis. These spatial patterns were consistent with previous ROV observations collected during multiple research expeditions (Angiolillo et al., 2023; Taviani et al., 2019; Castellan et al., 2025a,b). Outside the canyon, further suitable areas were detected south of Ischia Island.

Although these suitable areas represent only a small fraction of the region (0.09 %), the model also highlighted potentially suitable locations that have not yet been explored. This result suggests that the distribution of CWCs in the area may extend beyond currently known occurrences, in agreement with patterns reported in the literature (Gori et al., 2023, with references therein). Despite their limited spatial extent, the predicted suitable zones are well delineated, spatially coherent, and

consistent with known habitat preferences of scleractinian CWCs. The low uncertainty observed in highly suitable areas likely reflects the presence of ecologically relevant environmental conditions that are consistently associated with scleractinian CWCs occurrence, indicating a robust combination of key predictors. Conversely, higher uncertainty was mainly confined to areas that are considered ecologically unsuitable for CWCs, such as canyon floors and flat seabed areas. Although these environments have received limited attention during survey campaigns, potentially contributing to model uncertainty through uneven data distribution, the primary factor underlying their low suitability appears to be the persistent presence of soft sediments. As documented by backscatter data, these substrates represent unfavorable conditions for coral settlement and growth (Gori et al., 2023; Roberts et al., 2009), thereby accounting for the high uncertainty and low predicted suitability for CWC occurrence in these areas.

In our model outputs, hydrodynamics appeared to be crucial in defining areas suitable for the presence of CWCs. Maximum near-bottom current velocity emerged as the most influential predictor in our model, highlighting its role in sediment removal and food delivery (Angeletti et al., 2020a,b; Bargain et al., 2017; Fabri et al., 2017; Georgian et al., 2015; Lauria et al., 2021; Sanna et al., 2023). Highest suitability values were observed in areas characterized by current velocity from 0.10 to 0.18 m/s, but the response curve showed a decline in suitability at higher values, suggesting that excessively strong current velocities may limit settlement and successful attachment of larvae to the substrate (Strömberg and Larsson, 2017).

Seabed morphology was also of primary importance in our modelling efforts. Bathymetric position index (BPI 1:9) was the second most important variable in the model, indicating the role of complex topographic settings in creating suitable conditions for CWCs (Georgian et al., 2014, 2020; Kinlan et al., 2020). Suitability was highest at positive BPI values, suggesting a clear preference for elevated seabed features. Indeed, elevated geomorphological features, such as pinnacles or seamounts, are typically exposed to locally accelerated bottom currents, which can enhance food delivery and larval supply (Canals et al., 2009; Roberts et al., 2009; Rogers, 1994; Thiem et al., 2006). Roughness was among the most informative variables, showing a clear positive relationship with habitat suitability. The most favorable conditions for CWCs were observed in areas with terrain complexity and slope above 30° , such as canyon walls, confirming the known preference of CWCs for heterogeneous seabed that may present hard exposed substrate (Buhl-Mortensen et al., 2015; Guinan et al., 2009; Sundahl et al., 2020; Wilson et al., 2007).

Depth contributed modestly to the model, with the highest suitability values between 200 and 700 m, matching the depth range of the Levantine Intermediate Water (LIW) known to support CWCs in the Mediterranean (Angeletti et al., 2020a,b; Taviani et al., 2019). The depth response curve shows medium-high suitability values also around 1000 m, likely driven by the presence of solitary coral (Caryophylliidae spp.) specimens that were observed at this depth during the ECO24_II ROV06 dive. No colonial scleractinian CWCs were recorded at these depths, suggesting that conditions at these depths may be more favorable for solitary coral specimens. The shape of its response curve, however, suggests partial overfitting, probably influenced by the spatial clustering of ROV data. Although depth had a limited contribution to the final prediction, this constraint may have biased some response patterns and should therefore be taken into account when interpreting the results.

General aspect contributed minimally to the model, and the response curve showed high suitability for portions of seabed oriented north to northeast and south to southwest. The north-facing portions of some elevated features along the central canyon axis were predicted as characterized by medium-high suitability values, whilst canyon head and surrounding flanks, where CWCs were largely documented, showed south-southwest orientation. No suitable areas were identified in the Magnaghi Canyon, where ROV exploration was limited to a single and

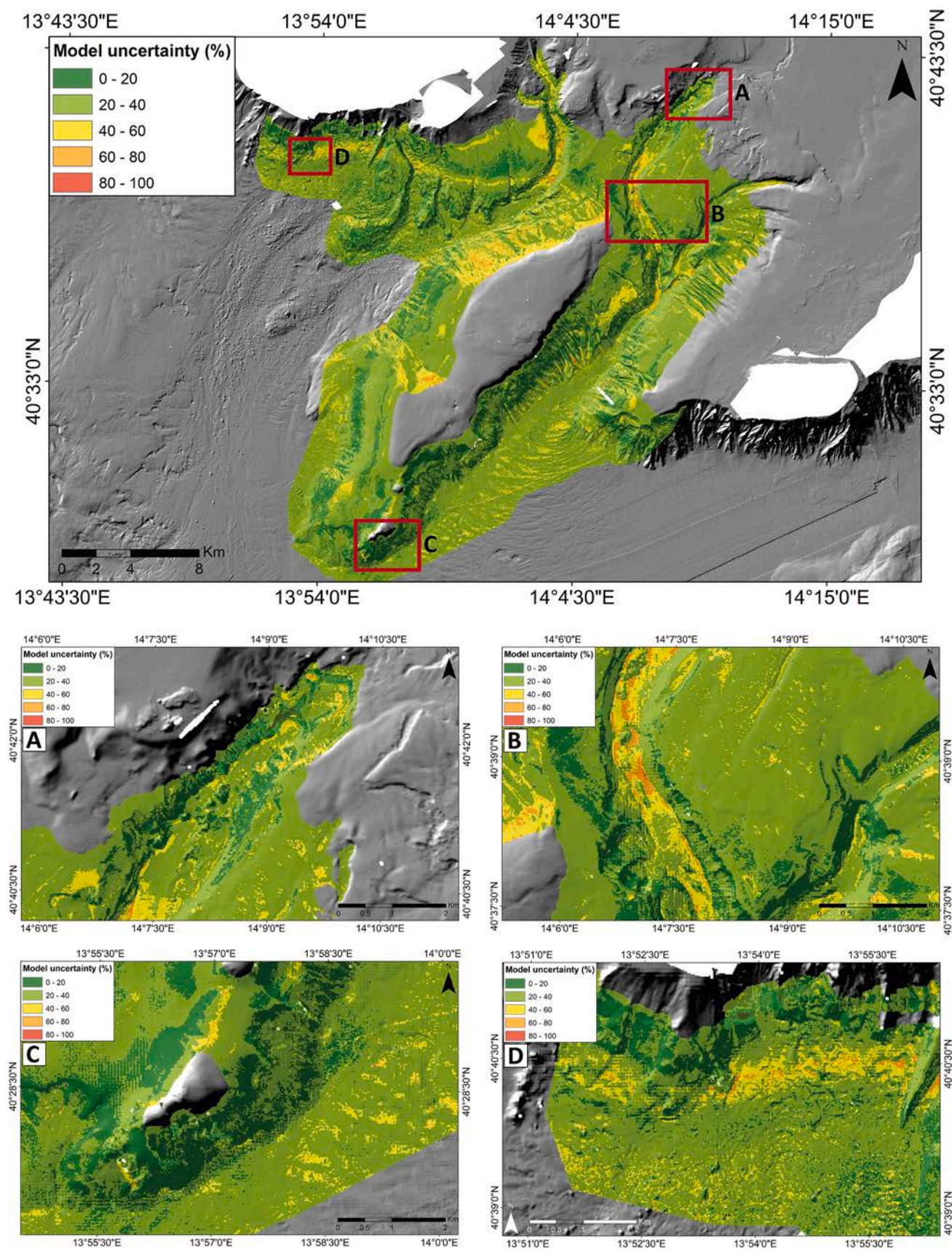


Fig. 6. Model uncertainty, estimated using the coefficient of variation (standard deviation divided by the mean of predicted suitability values across model replicates), is represented by a color scale ranging from green (lower uncertainty) to red (higher uncertainty). Red polygons named from A to D delineate areas predicted with suitable conditions by modeling efforts. Coordinate reference system: WGS84/UTM Zone 33N. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

incomplete dive, due to the high presence of fishing nets that posed a risk to the vehicle. This lack of data may have influenced the model outcomes. However, preliminary observations from ROV dives conducted during the subsequent DEMETRA25 cruise (Castellan et al., 2025a,b) documented the absence of scleractinian CWCs in Magnaghi Canyon. Conversely, exploratory dives carried out during the same cruise on the top of the D pinnacle, following model-derived coordinates within an area predicted as highly suitable (>0.8), revealed a previously unknown scleractinian CWCs site. The reef, primarily composed of both live and dead colonies of *D. pertusum* and *M. oculata*, identifies this area as a site of high ecological value and a strong candidate for targeted conservation and protection measures.

Overall, the results of this study provide a useful first step toward refining our understanding of the environmental conditions that support scleractinian CWCs in the Gulf of Naples. Although some response patterns may reflect the spatial structure of the available data and the inherent constraints of using ROV-derived occurrences for modelling, the main suitability patterns are consistent with current ecological knowledge and were partly supported by preliminary results of exploratory dives performed after the modelling effort. These elements suggest that, despite its limitations, the model represents a valuable spatial representation of the distribution of suitable conditions for scleractinian CWCs within the study area.

The predicted suitability patterns may help prioritize future ROV surveys and high-resolution mapping efforts in areas where conditions appear most favorable, such as less explored canyon flanks and branches, and elevated morphological features.

5. Conclusions

Our modelling effort provided maps of the distribution of areas with conditions suitable for the presence of scleractinian CWCs, also identifying new, unexplored sectors that may be characterized by environmental settings able to support their habitats. The predictions suggest that about 0.43 km² (0.09 % of the area) of the Gulf of Naples may present suitable conditions for scleractinian CWCs. Highly suitable areas were primarily located along the head, flanks, and elevated seabed features in the central axis of the Dohrn Canyon, together with sporadic areas south of Ischia Island.

Our results suggest that maximum near-bottom current velocity emerged as a key driver in shaping the distribution of conditions suitable for scleractinian CWCs, followed by the bathymetric position index, indicating preference for elevated features, and roughness confirming the association with complex terrain. Despite some response patterns potentially reflecting spatial clustering of ROV-derived occurrences, the main suitability patterns are consistent with current ecological knowledge and were preliminarily validated by exploratory dives conducted in the area after our modelling efforts.

These results provide strategic guidance for future surveys, prioritizing less-explored canyon areas. The spatial predictions provided here can contribute to enforce conservation processes in the Gulf of Naples (Grande et al., 2024), and may help inform ongoing and future restoration initiatives in the region. Continued monitoring and complementary high-resolution mapping will be essential to validate predictions and ensure that management and restoration actions are grounded in robust ecological information.

CRediT authorship contribution statement

Fabio Di Giovanna: Writing – original draft, Methodology, Data curation, Conceptualization. **Giorgio Castellan:** Writing – original draft, Supervision, Data curation, Conceptualization. **Michela Angiolillo:** Writing – review & editing, Investigation, Data curation. **Vincenzo Botte:** Formal analysis, Data curation. **Simonetta Frascchetti:** Writing – review & editing. **Valentina Grande:** Writing – review & editing, Supervision, Data curation. **Daniele Iudicone:** Methodology, Data

curation. **Florian Kokoszka:** Writing – review & editing, Validation, Methodology, Data curation. **Paolo Montagna:** Writing – review & editing, Data curation. **Mariacristina Prampolini:** Writing – review & editing, Data curation. **Giorgio Simone:** Writing – review & editing, Data curation. **Marco Taviani:** Writing – review & editing, Investigation. **Maria Letizia Vitelletti:** Writing – review & editing, Validation. **Federica Foglini:** Writing – review & editing, Data curation.

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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.marenvres.2026.107879>.

Data availability

The habitat suitability map is findable and accessible in the Seamap metadata catalogue at the link: <http://seamap-catalog.data.ismar.cnr>.

it:8080/geonetwork. The bathymetric surface and the scleractinians occurrences are described in the same catalogue and integrated in the Geoportal for Marine Biodiversity in Italy available through the Italian Biodiversity Gateway (<https://www.biodiversitygateway.it>).

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