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PERSPECTIVE

From habitat mapping to deep-sea ecosystems restoration: Conceptual and operational tools for recovering cold-water coral habitats in two Mediterranean canyons

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Abstract

1. The recent implementation of the European Union Nature Restoration Regulation (2024/1991) highlights the urgent need for innovative strategies to counter biodiversity loss in degraded marine ecosystems, such as those formed by stony cold-water corals (CWCs) *Madrepora oculata* and *Desmophyllum pertusum*, increasingly degraded by anthropogenic activities and climate change.
2. We developed a multidisciplinary framework that integrates high-resolution geophysical mapping and oceanographic data with ecological surveys to identify areas suitable for deploying 3D-printed artificial structures (EcoReefs) and transplanting coral fragments to support restoration of degraded CWC habitats in the Bari and Dohrn canyons.
3. Restoration sites were selected within the Levantine Intermediate Water depth range, targeting areas impacted by marine litter and abandoned fishing gears. Seabed slope ≤15° was identified as a critical threshold for EcoReefs stability. To evaluate material-specific effects on species recruitment, iron and steel plates were attached to the EcoReefs.

Giorgio Castellan, Paolo Montagna and Marco Taviani equally contributed as first authors.

4. The operational phase involved the deployment of 28 EcoReefs and 6 autonomous monitoring units using sub-meter positioning accuracy. The monitoring units included cameras and ADCP (Acoustic Doppler Current Profiler) sensors, enabling long-term tracking of coral survival, recruitment and local hydrodynamic conditions.
5. *Policy implications*. Our study provides evidence that active restoration of deep-sea CWC habitats is technically feasible when guided by a rigorous, multidisciplinary approach integrating habitat mapping, ecological aspects and long-term monitoring. The methodological framework presented here is intended to provide an operational template for designing and scaling restoration interventions in the deep-sea, thereby supporting the implementation of the EU Nature Restoration Regulation (2024/1991).

KEYWORDS
artificial structures, cold-water corals, coral recruitment, deep sea, Mediterranean Sea, monitoring, restoration

1 | INTRODUCTION

Anthropogenic climate change and direct human impacts, such as fishing, resource extraction and pollution, are degrading marine ecosystems across the globe, from coastlines to remote deep-sea environments (e.g. Claudet & Fraschetti, 2010; Garrabou et al., 2022; Ramirez-Llodra et al., 2011). Conservation and management efforts play an essential role in mitigating the impacts of human activities and preserving the structure and functions of marine ecosystems (Danovaro et al., 2020). However, weak enforcement, fragmented governance and current challenges in policy implementation have often rendered these efforts insufficient to recover ecosystems and biodiversity (e.g. Ban et al., 2014; Bett et al., 2025; Castellan et al., 2022; Fanelli et al., 2021; Gjerde, 2012; Manea et al., 2020; Micheli et al., 2013). Consequently, many vulnerable marine ecosystems are still subjected to anthropogenic pressures and still lack adequate measures for their protection, with the actual risk of irreversible harm. Marine conservation alone may no longer be enough to ensure the good environmental status of all marine habitats, and restoration actions are becoming increasingly needed, if not strictly necessary, to slow down the loss of biodiversity and ecosystem functions (Danovaro et al., 2021; Duarte et al., 2020). In this context, the Nature Restoration Regulation (2024/1991) of the European Union has recently come into force as an attempt to halt and reverse biodiversity loss across terrestrial and marine ecosystems by setting legally binding restoration targets (Hering et al., 2023).

Successful restoration requires a systematic approach. This includes stakeholders involvement to ensure mutual benefits for nature and society, the implementation of measures to reduce and prevent further impacts on the target habitat, the census of degraded habitats and the definition of clear restoration targets that should be properly monitored to track success rates (Da Ros et al., 2019; Danovaro et al., 2025; Gann et al., 2019). From an operational perspective, the identification of intervention sites relies on the analysis of available data to detect degraded areas, identify the causes and delineate zones suitable for restoration. Restoring deep-sea ecosystems is particularly challenging due to their remoteness and the scarcity of high-resolution spatial information on ecosystems distribution (Aguzzi et al., 2024). In the selection of optimal restoration sites, integrating geophysical, ecological and oceanographic insights is essential to pinpoint suitable restoration areas, together with high-resolution habitat mapping, which provides detailed information on habitat features, distribution and degradation (Fraschetti et al., 2021).

The habitats formed by stony cold-water corals (CWCs) are among the most suitable candidates for active restoration interventions in the deep-sea. In this work, the term 'cold-water corals (CWCs)' refers exclusively to the scleractinian species *Desmophyllum pertusum* and *Madrepora oculata*. These species, included in Annex I of the Habitats Directive (92/43/EEC) and listed as Vulnerable Marine Ecosystems (VMEs) of global conservation priority (FAO, 2009), build intricate three-dimensional structures (reefs) that serve as biodiversity hotspots, nurseries, refugia, spawning and feeding grounds for a wide array of fishes and invertebrates and contribute substantially to carbon cycling and sequestration, and to nutrient cycling (Armstrong et al., 2014; Buhl-Mortensen et al., 2017; Capezzuto et al., 2018; Cordes et al., 2023; D'Onghia, 2019; D'Onghia et al., 2016; Edinger et al., 2025; Greiffenhagen et al., 2025; Mastrototaro et al., 2010; Rueda et al., 2019; Soetaert et al., 2016; Titschack et al., 2016; Van Oevelen et al., 2009). CWCs face significant threats due to climate change and human activities (e.g., Roberts et al., 2009; Roberts & Cairns, 2014; Morato et al., 2020; Portilho-Ramos et al., 2022), particularly deep-sea fisheries that physically destroy reefs through bottom-contact fishing (e.g., Gianni, 2004; Otero & Marin, 2019; Rogers, 1999; Williams et al., 2010), and marine litter (e.g., Angiolillo & Fortibuoni, 2020; Appah et al., 2022; D'Onghia et al., 2017; Kühn et al., 2015; Ragnarsson et al., 2016; UNEP, 2017; Weinnig et al., 2020).

In response to these challenges, a joint initiative launched in 2024 explored the feasibility of active restoration in the Bari Canyon (southern Adriatic Sea) and the Dohrn Canyon (southern Tyrrhenian Sea). Here, we illustrate our conceptual and technical approach for identifying intervention sites and deploying artificial structures and monitoring systems for the restoration of CWCs in the Dohrn and Bari canyons. Our methodology integrates site selection criteria, deployment strategies and post-restoration monitoring to assess effectiveness over time. The aim is to contribute to the definition of best practices for active restoration actions in the deep sea and facilitate the replication and adaptation of these methods in diverse ecological settings, ultimately contributing to the broader restoration of vulnerable deep-sea ecosystems.

2 | IDENTIFYING ACTIVE RESTORATION SITES

2.1 | Geological setting

The 10 km-wide Bari Canyon system breaches the Apulian shelf edge at ~200 m depth and extends ~30 km downslope (Figure 1). It consists of two main E–W branches reaching 800 m depth, with steep flanks and minor scarps, influenced by strong cascading currents that transport sediments and nutrients downslope, shaping southwestern Adriatic deep-sea sediment dynamics (Foglini et al., 2016; Minisini et al., 2006; Trincardi et al., 2007).

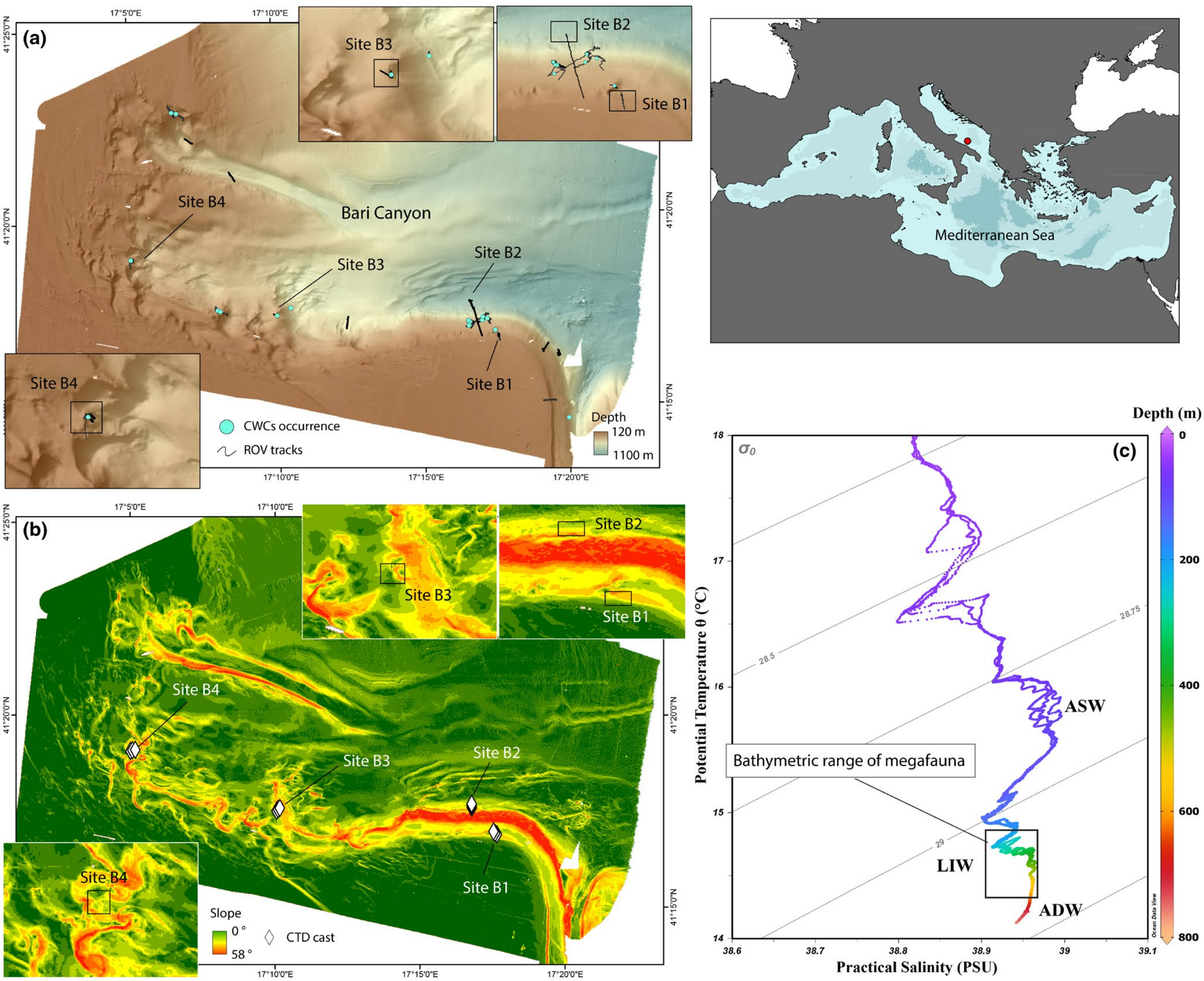

FIGURE 1 Map of the Bari Canyon (Southern Adriatic Sea). (a) Location of the visual surveys with CWCs occurrences and proposed sites for active restoration actions over a bathymetric map; (b) CTD cast collected in the Canyon area and the proposed sites over terrain slope; (c) T-S plot of 12 different depth profiles, with isopycnals calculated at 0 m (σ0). Water masses identified include ADW, Adriatic Deep Water; ASW, Adriatic Surface Water; LIW, Levantine Intermediate Water.

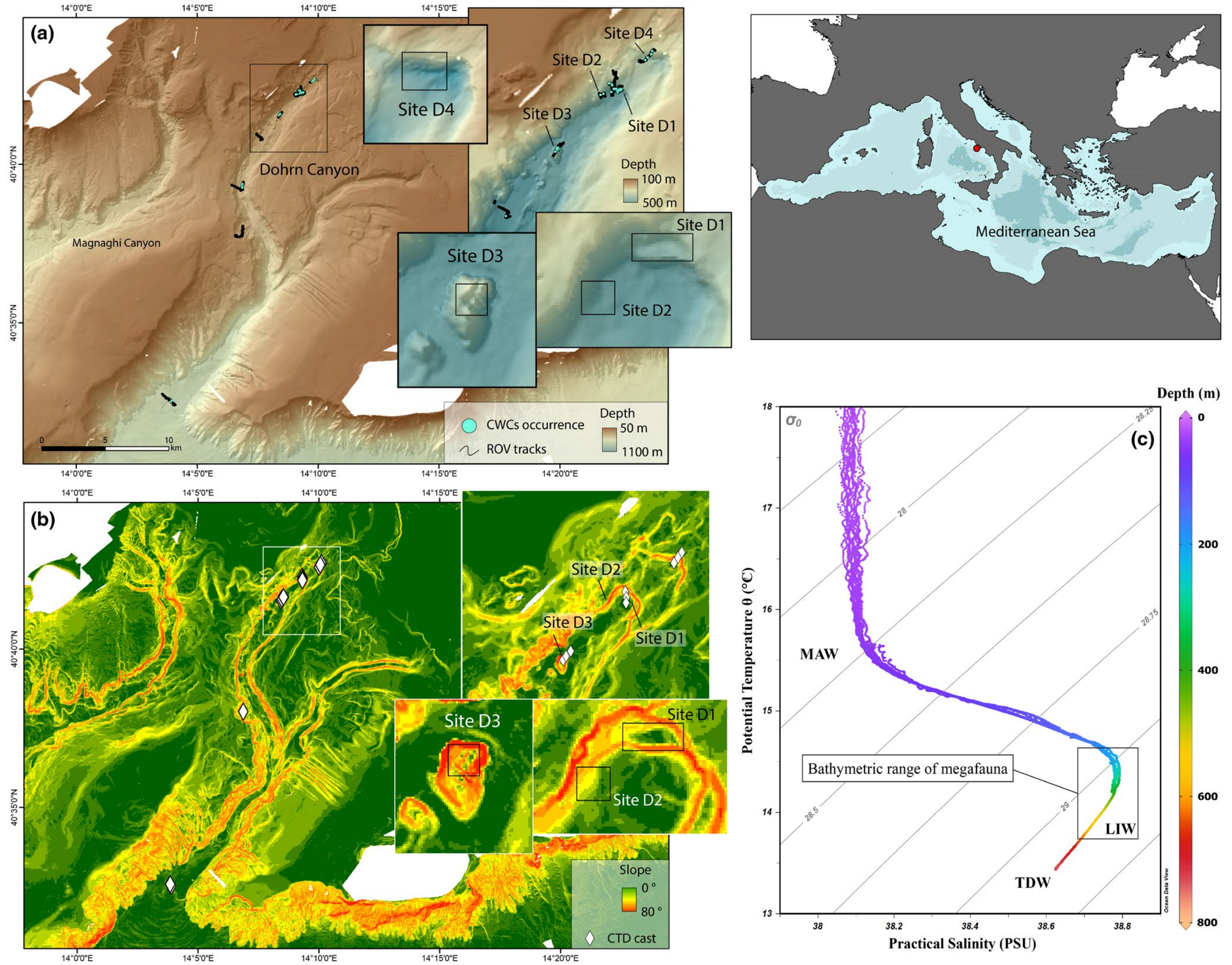

FIGURE 2 Map of the Dohrn Canyon (Southern Tyrrhenian Sea). (a) Distribution of visual surveys documenting CWCs occurrences, along with designated sites for active restoration, over a bathymetric map. (b) CTD casts conducted within the canyon, displaying proposed restoration sites over a terrain slope map. (c) Temperature-salinity (T-S) diagram based on 15 depth profiles, with isopycnals computed at 0 m (σ0). Water masses identified include LIW, Levantine Intermediate Water; MAW, Modified Atlantic Water; TDW, Tyrrhenian Deep Water.

In the Dohrn Canyon, the morphology is likely influenced by extensional faults and volcanic activity (Aiello & Sacchi, 2022; Foglini et al., 2025). The two branches of the canyon, about 500 m wide, display a V-shaped profile in the upper part and a U-shaped profile in the lower part, indicating uniform sediment fill (Figure 2).

2.2 | Benthic megafauna, anthropogenic impacts and conservation measures

Multiple surveys have been conducted in the Bari Canyon in the last decades (see Supplementary Materials) that documented the presence of CWCs habitats between 200 and 1000 m along canyon slopes and flanks (Angeletti et al., 2014, 2019; Bargain et al., 2018; Foglini et al., 2019; Freiwald et al., 2009; Taviani et al., 2016, Figure 1). In 2024, extensive ROV surveys were conducted onboard the RV Gaia Blu and analyzed following the methodology described in Castellan et al. (2020). The results confirmed that CWC habitats are mainly on steep slopes and vertical flanks, with patchy distribution at greater depths, colonizing exposed hard substrates protruding from muddy sediments and providing structural complexity and settlement surfaces in an environment otherwise dominated by sediments (Figure 3). The scleractinian *M. oculata* dominates the reef-building community while colonial *D. pertusum*, *D. cornigera* and solitary *Stenocyathus vermiformis* and *D. dianthus* are less frequent, often settling on dead *M. oculata* structures (Figure 3 a,b). The community functions as an Essential Fish Habitat EFH (Angeletti et al., 2014, 2021; Capezzuto et al., 2018; Carluccio et al., 2024, 2025; D'Onghia et al., 2016; D'onghia, Capezzuto, Cardone, et al., 2015; D'Onghia, Capezzuto, Carluccio, et al., 2015; Sion et al., 2019).

Reports document marine litter on the seafloor entangling sessile organisms along with the presence of abandoned, lost or discarded fishing gear ALDFG (Angeletti et al., 2021). In 2024,

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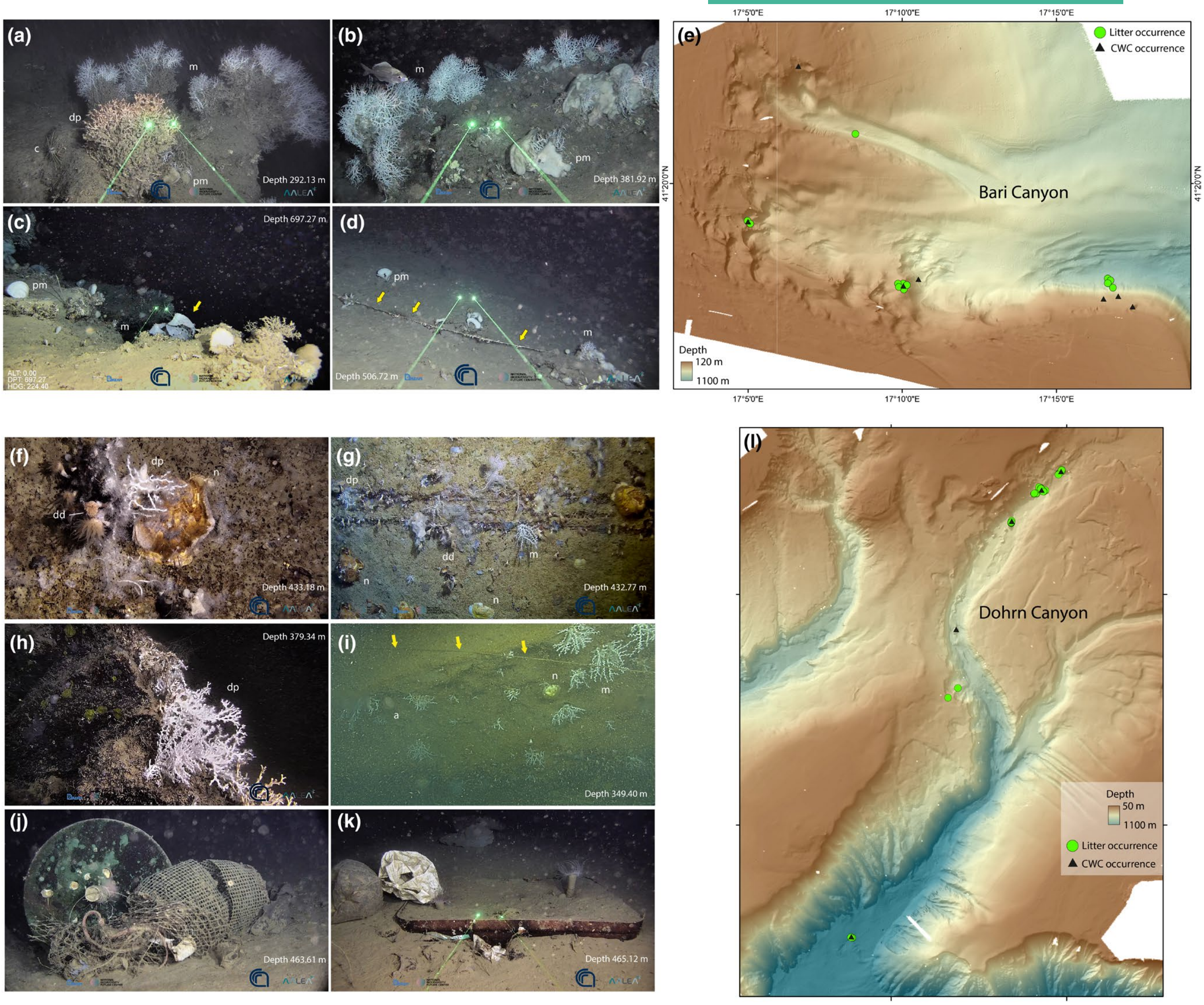

FIGURE 3 Scleractinian cold-water coral habitats and marine litter in the study sites. (a, b) Morphology and diversity of CWCs habitats in the Bari Canyon Location; m: *Madrepora oculata*, dp: *Desmophyllum pertusum*, pm: *Pachastrella monilifera*; (c, d) examples of observed benthic marine macrolitter in the Bari Canyon (yellow arrows); (e) distribution of marine litter and CWCs based on surveys. (f–h) Association among CWCs (mo: *M. oculata*, dp: *D. pertusum*, dd: *D. dianthus*), the large bivalve *Acesta excavata* (ae) and the deep-water oyster *Neopycnodonte zibrowii* (nz) in the Dohrn Canyon; (i–k) Benthic marine macrolitter and ALDFG (yellow arrows) in the Canyon with (l) the distribution of marine litter and CWCs based on surveys.

ROV surveys recorded longlines entangled around coral-colonized substrates (Figure 3 c,d), along with plastic bags, miscellaneous plastic items, glass bottles and aluminium cans, likely from fishing, maritime traffic or downslope transport from shallower areas. A Fishery Restricted Area (FRA) has been established in Bari Canyon to mitigate fishery impacts on CWCs (Angeletti et al., 2021), and, more recently, the area has been proposed as a Natura 2000 site (Grande et al., 2024).

In the Dohrn Canyon, a unique deep-sea benthic community characterized by an association between CWCs, the large bivalve *Acesta excavata* and the giant deep-water oyster *Neopycnodonte zibrowii*, populates the slopes and flanks of the Dohrn Canyon between 300 and 600 m, with sporadic occurrences observed below 600 m (Figure 2a). The CWC habitats are concentrated on vertical cliffs (Figure 3 f–h), with *D. pertusum* prevailing and *M. oculata* subordinate, particularly on the canyon head and northwestern flank, associated with solitary corals (*Javania cailleti*, *D. dianthus*).

The first evidence of ALDFG and marine litter was documented in 2016 (Taviani et al., 2019), while in 2024, ROV surveys documented a large number of longlines entangled among corals and bivalves (Figure 3 i–k), with the highest litter accumulation at the canyon head, including areas largely covered by discarded waste bags likely transported from coastal or surface waters.

No conservation measures are in force in the Dohrn Canyon, and the areas surrounding the canyon head was recently proposed as Natura 2000 site (Grande et al., 2024).

2.3 | Oceanographic setting

The Temperature-Salinity (T-S) profiles generated from CTD-Rosette casts (see Supporting Information) performed in the Bari Canyon revealed distinct vertical stratification in line with the literature (Turchetto et al., 2007), with potential temperature ranging 14–21°C and salinity 37.47–39 PSU (Figure 1c). The upper layer (down to 100–150 m) is dominated by the Adriatic Surface Water (ASW), the intermediate layer by the Modified Levantine Intermediate Water (MLIW), and deeper values are indicative of the Adriatic Deep Water (ADW) (Guglielmo et al., 2019). Since CWCs in the Bari Canyon occur within the LIW depth range (Chimienti et al., 2019; Freiwald et al., 2009), deployment sites were selected accordingly.

In the Dohrn Canyon, T-S plots show the hydrological signatures of southern Tyrrhenian water masses (Figure 2c): the Modified Atlantic Water (MAW) at 0–150 m, the LIW at 200–700 m and the Tyrrhenian Deep Water (TDW) below 700 m (Carrada et al., 1980; Taviani et al., 2019). Deployment sites were identified within the LIW depth range (~300–700 m), consistent with the vertical distribution of CWC habitats.

3 | DEPLOYING ARTIFICIAL REEFS

3.1 | EcoReefs

The 3D-printed artificial structure, EcoReefs, consisted of a stack of layers of quarry aggregates held together by pozzolanic cement (CEM IV/B 32.5R) that was manufactured using 3D printing techniques (Sreekanth et al., 2019). The weight of the structures ranged from 550 to 1020 kg per structure. EcoReefs were designed to achieve two main restoration objectives: (i) the recovery of structural complexity in degraded areas through the addition of hard substrate; and (ii) the promotion of recruitment and persistence of *M. oculata* and *D. pertusum*. These objectives address both habitat structure and biological function, aiming to re-establish the ecological roles typical of CWC habitats.

To test colonization on materials other than concrete, small plates (30 × 20 cm) of stainless steel and iron were attached to the structures. Additionally, several fragments of living *D. pertusum* and *M. oculata* were transplanted into two structures deployed at two sites (D1 and D3) in the Dohrn Canyon using plastic ties and iron wire to investigate their potential survival after transplantation. The CWCs fragments were obtained from pre-deployment ROV surveys and maintained in aquaria onboard prior to transplantation. Corals were exposed to air for up to 60 min before EcoReefs deployment.

All activities at sea were permitted by the Italian Navy General Staff (Prot. 191100Z/24), the Hydrographic Institute of the Italian Navy (Prot. 145/24; 0078293/24), the Port Authority of Naples (Prot. 0060559) and the Marine Protected Area of 'Regno di Nettuno' (AMP 2876). No ethical approval was requested for this study.

3.2 | Conceptual framework for the implementation of restoration actions and selection of intervention sites

A structured decision-making framework guided restoration actions using EcoReefs in the Bari and Dohrn canyons (Figure 4). Deployment site selection was based on specific goals and measurable indicators: seabed morphology, substrate type, water-mass characteristics, proximity to existing CWC habitats and anthropogenic disturbance. The process began by assessing baseline data, habitat degradation and existing conservation measures. High-resolution mapping and oceanographic data helped identify abiotic drivers and prioritize restoration sites suitable for CWCs survival and artificial reef deployment (Figure 5). Once the sites were deemed suitable, EcoReefs, both bare and with transplanted CWCs, were deployed, followed by cameras for monitoring. Optimal sites featured soft sediments, slopes <15°, and water masses able to sustain CWCs, with sufficient space for 2–3 EcoReefs spaced ≥10 m apart.

In situ ROV surveys validated local conditions, including nearby living CWCs and potential threats such as marine litter. Pre-deployment surveys refined slope estimates and identified obstacles undetectable through remote mapping using ROV sonar and Motion Reference Unit.

In the Bari Canyon, candidate sites were located on the upper northern canyon flank (B1, Figure 1), at the base of the canyon flank with gentler gradients (B2, B3), and at the rim of the canyon head (B4), close to existing CWCs to ensure access to donor colonies and target impacted areas. The persistence of CWCs indicated suitable environmental conditions.

In the Dohrn Canyon, the steep canyon walls limited deployment options. Candidate sites included a northern flank plateau offering a stable area (D1, Figure 2), a base site with a gentler slope further southwest (D2), a summit of a large structure rising several hundred meters from the seafloor (D3) where flattened topography and favorable hydrodynamics could prevent sediment accumulation, and a flat area at the base of the canyon's head (D4).

Operations in both canyons comprised 23 survey days, deployment of 28 EcoReefs, 6 monitoring units and a total investment of €874,000 (Figure 4). Future maintenance of monitoring cameras and sensors (mainly for data retrieval and battery replacement) is estimated at three offshore days per area at €30,000 per day.

3.3 | Deployment of EcoReefs and cameras, and post-deployment positioning assessment

The EcoReefs were deployed from the vessel's stern A-frame through a 12.8 mm steel winch cable (Figure 6). The 3D structure was attached to the hook of an Oceanographic Release Transponder (ORT) using hemp ropes. A weight of ca. 200 kg was used to ensure proper cable tension. A Kongsberg cNODE MiniS 31–180 Beacon USBL positioning system, equipped with a pressure sensor, was also affixed to the winch cable to ensure the precise positioning (within 1 m) of the structures on the seabed. The structures were

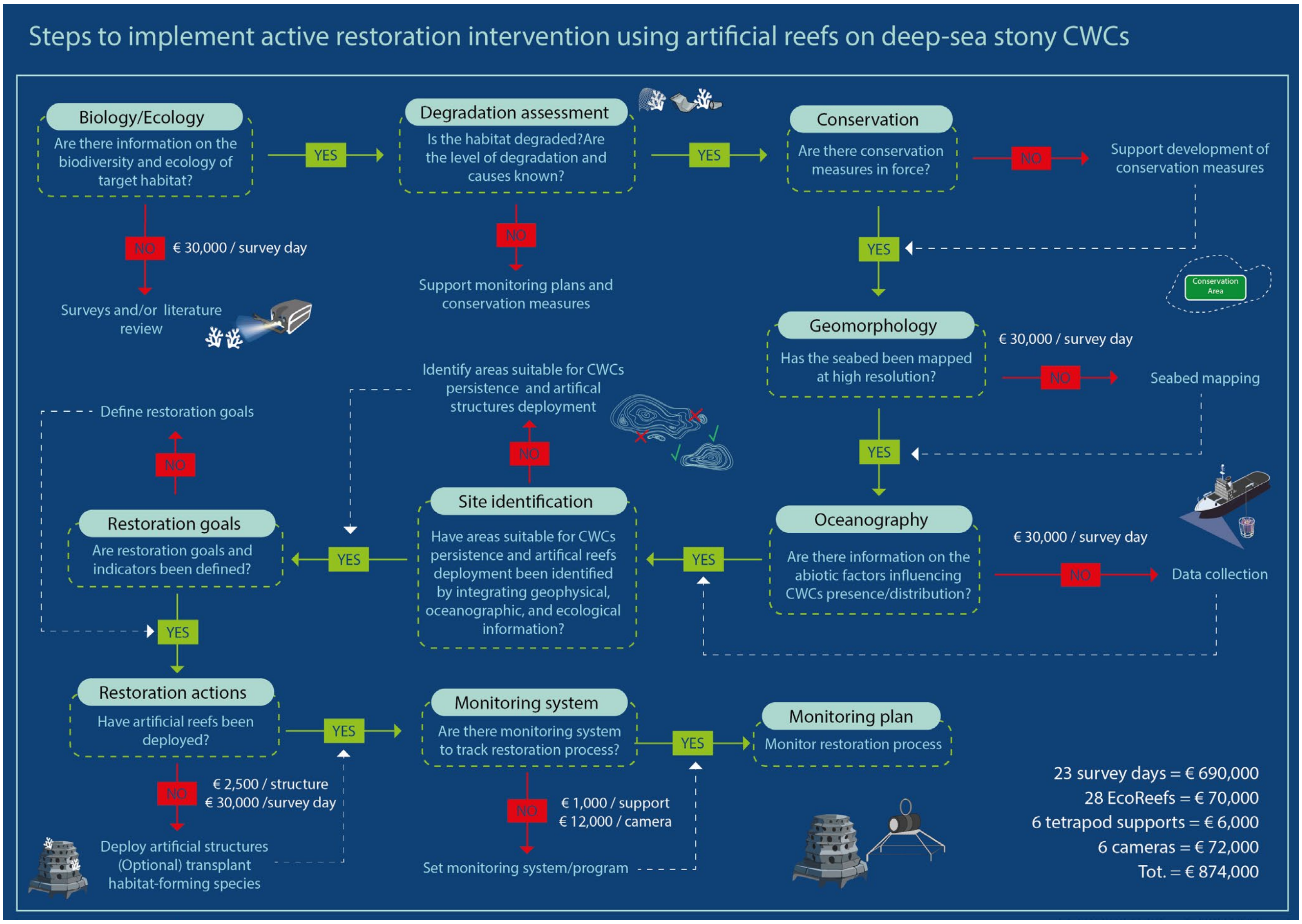

FIGURE 4 Decision-making workflow applied to implement active restoration interventions using artificial reefs for CWC habitats in the Bari and Dohrn canyons. The flowchart reports the sequential assessment of ecological, geomorphological and oceanographic factors to determine site suitability for restoration. Estimated costs are indicated for each step.

gently lowered to the seafloor to ensure a controlled placement and minimize disturbance on contact. Once the EcoReefs reached the seabed and the cable tension measurement system showed a drop in load, the acoustic releaser was triggered to free the structure from the deployment frame and ensure settlement into position. Post-deployment ROV surveys verified the stability and the correct positioning of the EcoReefs in situ, obtained high-accuracy georeferencing and recorded initial conditions for long-term monitoring.

In the Bari Canyon, 12 EcoReefs were deployed and surveys confirmed all structures were correctly positioned (Figure 7) and provided precise coordinates to support long-term monitoring and future assessments of restoration effectiveness.

In the Dohrn Canyon, 16 EcoReefs were deployed and most of them were correctly positioned. However, two EcoReefs at the site D2 had moved downslope, ending at greater depths than initially intended. This displacement likely resulted from the steep slope rather than human intervention. Although the site was chosen for proximity to CWCs impacted by ALDFG, the pronounced slope proved unsuitable for structural stability. This underscored the importance of selecting deployment sites with an inclinations ≤15° to minimize post-deployment displacement.

4 | MONITORING RESTORATION PROCESS

The GUARD-1 Underwater Autonomous Smart Cameras (European patent EP2863257 by the National Research Council and OnAir S.R.L., Italy) were positioned at a distance of approximately 1 m from the EcoReefs with the ROV for long-term visual monitoring of the restoration process (Figure S1). The camera is a high-resolution, autonomous system cable of collecting images with a programmable frequency, equipped with automatic LED lighting and zoom. The cameras were anchored on stainless-steel tetrapod supports and positioned at about 1 m from the EcoReefs to ensure optimal image capture even under conditions of water turbidity. Sites hosting the cameras are B2, B3, and B4 for the Bari Canyon, and D1, D3, and D4 for the Dohrn Canyon. One image every hour will be collected, with a battery life lasting up to 1 year. One support per area is also equipped with an Acoustic Doppler Current Profiler (ADCP) Nortek Aquadopp Profiler 400 kHz, for the purpose of collecting data on current velocity and direction for 1 min every 60 min in a 90 m depth range above the EcoReefs with a vertical resolution of 1 m. The sensor also collects temperature and backscatter data along the water column, providing information on sedimentation processes.

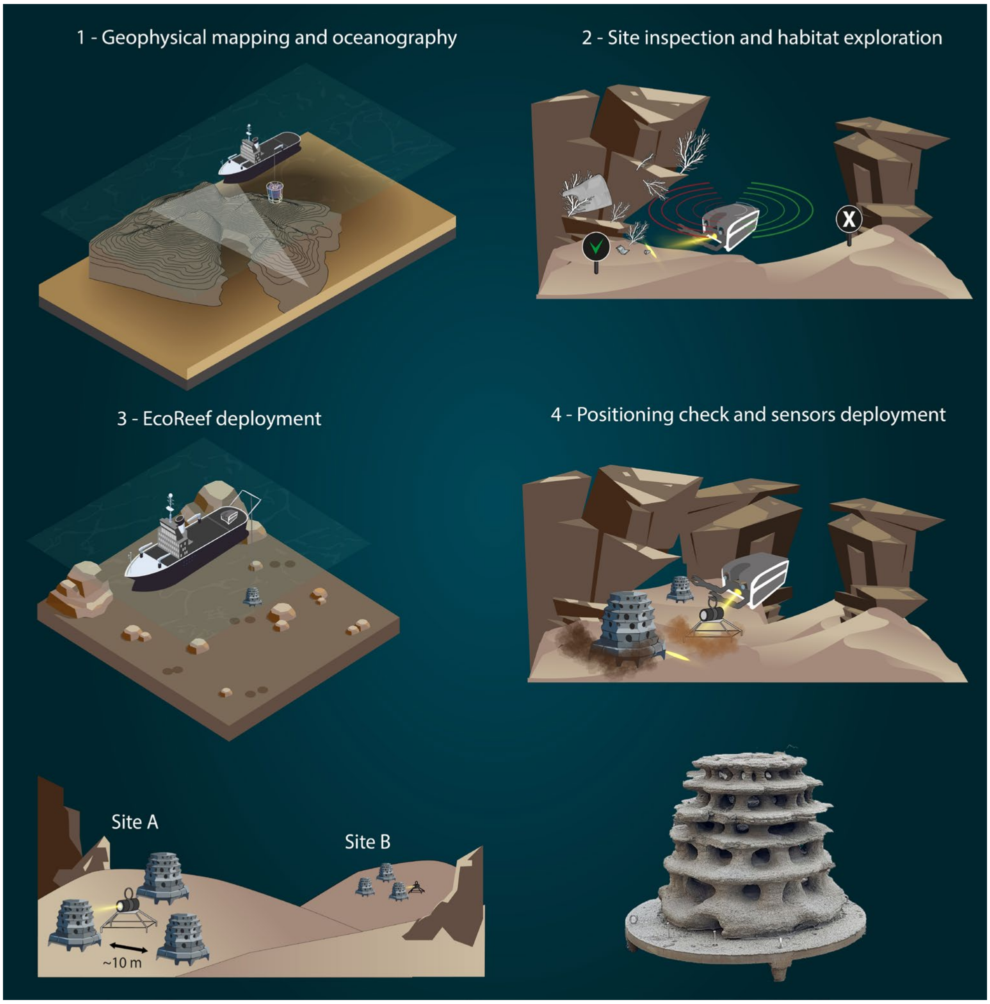

FIGURE 5 Scheme of the conceptual framework adopted for the selection of sites for active restoration efforts, and the deployment of both EcoReefs and monitoring cameras in the Bari and Dohrn canyons. (Bottom-right) Example of a 3D-printed EcoReef.

During yearly maintenance, camera supports will be recovered by means of ROV to replace batteries and download data to monitor coral settlement and growth, and explore current velocity and direction data from the ADCP. After maintenance, supports will be repositioned close to the EcoReefs, maintaining as much as possible the same point of view and will monitor coral recruitment (number of colonies per m^2) and growth (mm/year) on EcoReefs for a total monitoring period of 8 years. These metrics are based on existing evidence from ex situ studies showing that reef-building corals can settle and grow on artificial substrates (Larcom et al., 2014; Lartaud et al., 2017).

5 | CONCLUSION AND FUTURE PERSPECTIVES

Restoration of deep-sea ecosystems is inherently challenging due to the complexity and limited understanding of these environments (Da Ros et al., 2019; Van Dover et al., 2014). This knowledge gap complicates the identification of suitable sites, which requires integrating geophysical, oceanographic and ecological information, together with the definition of the most appropriate restoration methods (Danovaro et al., 2025). The deployment of high-relief artificial substrates has been recognized as one of the most effective and cost-efficient approaches to promote CWC restoration (Strong et al., 2023). Since ours constitutes the first attempt to use artificial structures for the restoration of deep-sea scleractinian CWCs in the Mediterranean, we identified key criteria to select deployment sites that may favour maximizing the potential for success of restoration actions. However, unforeseen events might prevent the success of restoration interventions. For example, during deployment in the Dohrn Canyon, some EcoReefs experienced displacement along the canyon flanks. This not only underscores the importance of selecting proper deployment sites but also highlights the necessity of adopting an adaptive approach that can adjust dynamically to changing conditions during implementation.

The selection of materials for the EcoReefs is critical for the success of restoration, influencing both the rate and success of CWC colonization. Studies on artificial substrates for shallow-water coral restoration show that surface texture, porosity, and biofilm formation affect colonization likelihood (Matus et al., 2024). However, evidence regarding material preferences for scleractinian CWCs remains limited (Larsson et al., 2014; Strömberg et al., 2025),

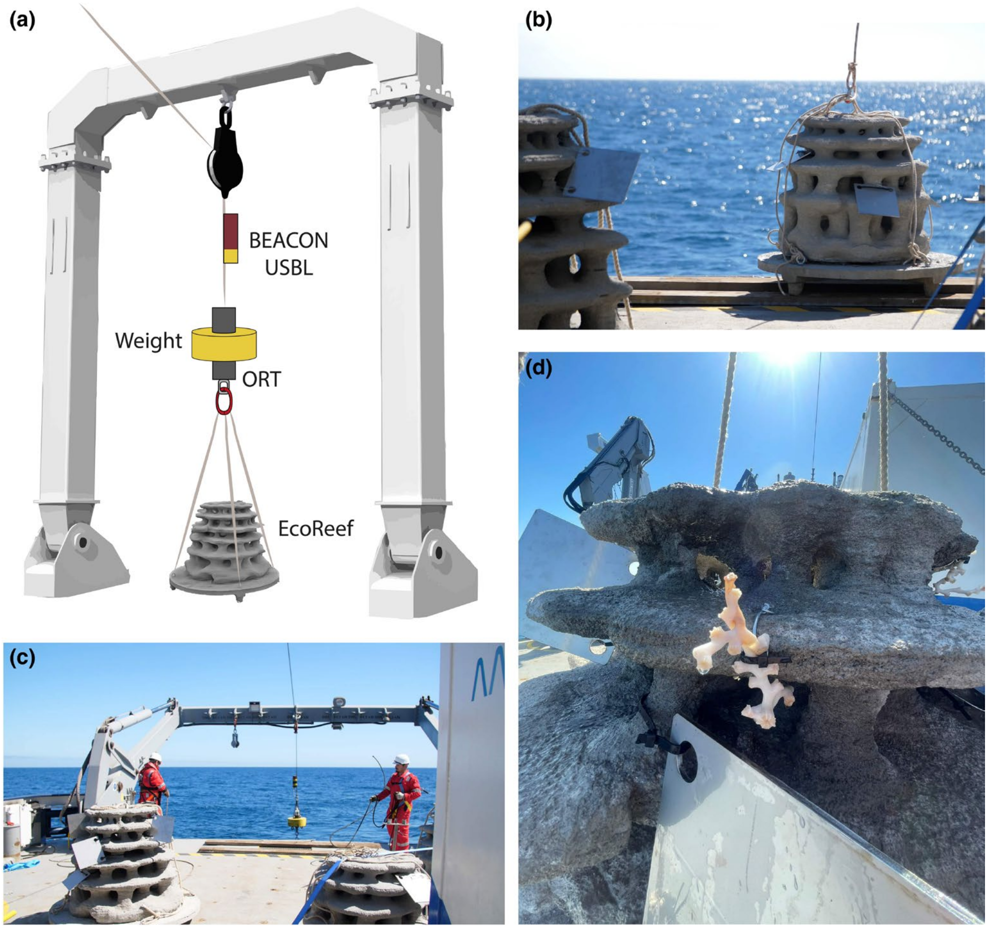

FIGURE 6 Deployment system and EcoReefs. (a) The onboard setup for deploying the structures at the selected sites, including an Oceanographic Release Transponder (ORT) with a weight and an acoustic USBL beacon to ensure precise positioning. (b, c) EcoReef structures positioned on the main deck of the R/V Gaia Blu, with a close-up view (d) showing of a fragment of *Desmophyllum pertusum* attached to the structure just before the deployment.

highlighting the need for experiments with different materials and designs. We used metallic plates (stainless-steel and iron) to gather information on their suitability, allowing us to test the efficiency of different materials under comparable environmental conditions and across geographic locations, informing future restoration strategies.

Long-term monitoring will be crucial not only to understand the development of restoration actions but also to link their evolution with local environmental dynamics. ADCPs integrated into the camera-supporting structures will provide near-bottom temperature and current velocity and direction, allowing us to relate physical conditions such as sedimentation, temperature changes, and flow patterns to the restoration process. We will track the growth of corals, the main target of our interventions, while simultaneously observing associated fauna that may influence larval settlement; for example, post-deployment surveys have revealed the presence of sea urchins of the genus *Cidaris*, a deep-sea echinoid feeding on corals (McClanahan, 1988; Stevenson & Mitchell, 2016), on some structures just a few days after their deployment (Figure S1). Cameras will also enable us to monitor the survival of transplanted CWC colonies, providing insight into both their persistence and the effectiveness of our transplantation approach.

The restoration actions undertaken in the Bari and Dohrn canyons are experimental in nature and embedded within a long-term perspective. Scaling up restoration efforts in deep-sea ecosystems involves substantial ecological, economic and logistical complexities. Ecologically, interventions must be informed by data on larval dispersal, hydrodynamic flow patterns and biogeochemical gradients that affect coral recruitment and growth, in order to be effective at large spatial scales. Even small habitat restoration requires numerous EcoReefs (3.2 – 6.6 m^2 each) at a unit cost of €2,000 – 3,000. Additionally, sea time and ROV operations for deployment and monitoring remain costly (around €30,000 per day) and logistically complex. The upkeep of monitoring devices, including data download and power replacement, typically requires three-day offshore missions for each intervention area, corresponding to roughly €90,000 in ship time.

Although the ecological success of our intervention is yet to be fully determined, our results suggest that active restoration of deep-sea CWCs can be enhanced when guided by comprehensive data and implemented with flexibility and long-term commitment. The approach described here is inherently scalable: 3D printing allows for mass production, the structures can be customized to suit

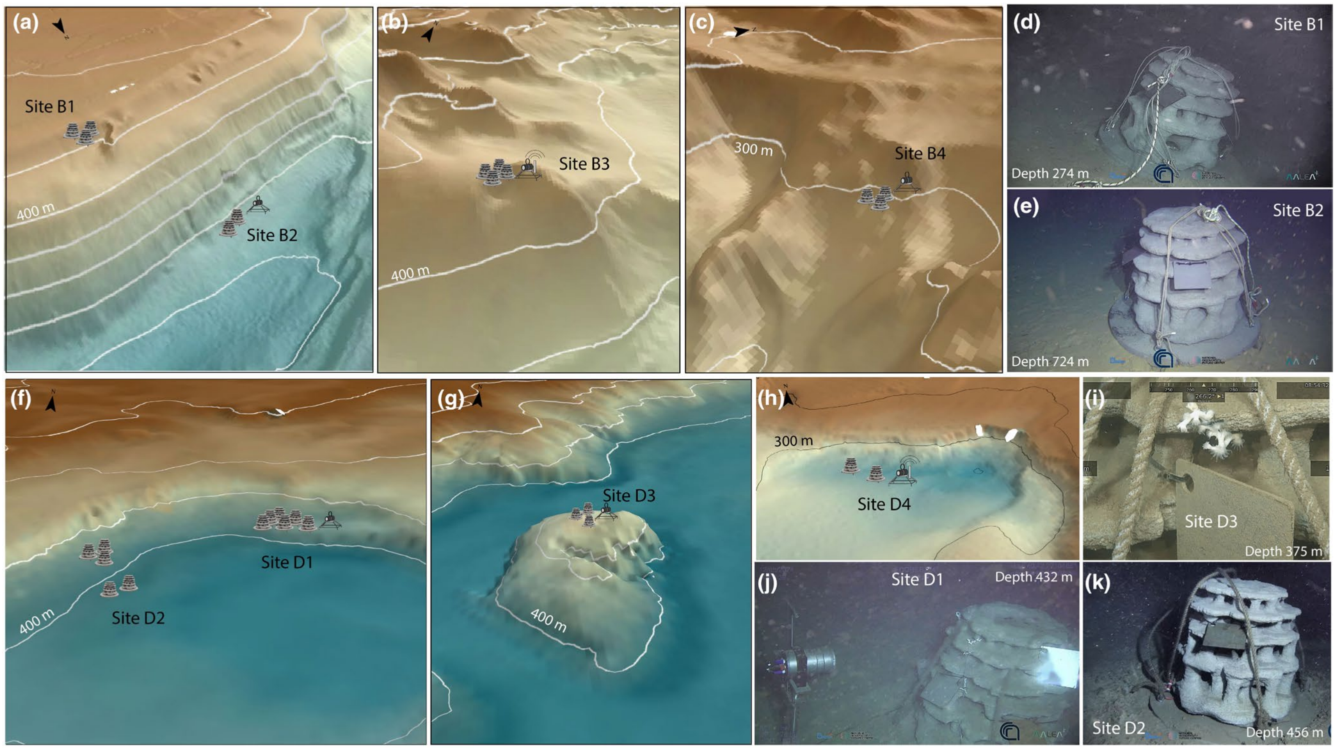

FIGURE 7 Bathymetric location of the deployment sites and ROV images of the EcoReefs. (a–c) 3D bathymetric models of the selected restoration sites in the Bari Canyon within a depth range of 306–727 m. (d, e) ROV images of EcoReefs positioned on the seafloor in site B1 and B2, respectively; Contour lines spacing: 100 m. (f–h) 3D bathymetric models illustrating the deployment locations in the Dohrn Canyon in a bathymetric range of 366–450 m; (i–k) ROV photographs documenting the correct in situ positioning of the EcoReefs, with a close-up view of a transplanted branch of *Desmophyllum pertusum* with coral polyps extended beyond their calyx 2 days after the deployment (I). Contour lines spacing: 50 m.

different environmental conditions, and monitoring technologies (e.g. autonomous cameras) reduce the need for repeated ROV expeditions, primarily for battery maintenance and data download with a frequency depending on settings of the instruments.

While the restoration of CWCs habitats can significantly mitigate biodiversity loss and enhance ecosystem services, it represents only one element of a broader strategy for deep-sea biodiversity recovery, integrating habitat protection, sustainable management and policy initiatives to reduce anthropogenic impacts under climate change. Restoration may be most effective in areas less affected by future climate shifts; submarine canyons, such as those studied here, have been proposed as potential refugia for CWCs, offering greater resilience and functioning as supra-regional larval sources (Wienberg et al., 2018). Through innovation and a sustained commitment to monitoring and adaptive management, active restoration can play a pivotal role in safeguarding the biodiversity and functionality of these unique and vulnerable ecosystems.

AUTHOR CONTRIBUTIONS

Giorgio Castellan: Writing—review and editing, writing—original draft, validation, methodology, investigation, conceptualization; Paolo Montagna: Writing—review and editing, writing—original draft, validation, methodology, investigation, conceptualization; Marco Taviani: Writing—review and editing, writing—original draft, validation, methodology, investigation, conceptualization; Mariacristina Prampolini, Valentina Grande, Giovanni Chimienti; Giorgio Simone, Fabio Di Giovanna, Alessandra Mercorella, Giacomo Dalla Valle, Alessandro Remia, Taha Lahami, Frine Cardone, Simonepietro Canese, Francesco Stenico, Augusto Passarelli, Marie-Claire Fabri, Anthony Grehan, Oisín Callery, Alberto Colletti: Writing—review and editing, investigation; Zaira Da Ros, Roberto Danovaro, Gianfranco D'Onghia, Simonetta Fraschetti: Writing—review and editing, conceptualization; Federica Foglini, Emanuela Fanelli: Writing—review and editing, investigation, conceptualization.

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CONFLICT OF INTEREST STATEMENT

The contact author has declared that none of the authors have any competing interests.

DATA AVAILABILITY STATEMENT

Data available from the CNR-ISMAR GeoNetwork metadata catalogue (http://seamap-catalog.data.ismar.cnr.it:8080/geonetwork; Foglini & Grande, 2023) and from the Geoportal of Marine Biodiversity in Italy (http://seamap-explorer.data.ismar.cnr.it:8080/mokaApp/apps/pnrrb/index.html).

STATEMENT OF INCLUSION

Our study brings together authors from a number of different countries, including scientists based in the country where the study was carried out. All authors were engaged early on with the research and study design to ensure that the diverse sets of perspectives they represent were considered from the onset. Whenever relevant, literature published by scientists from the region was cited; efforts were made to consider relevant work published in the local language.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Figure S1. Visual monitoring system and macrofauna associated with EcoReefs. (A) Photo collected by the Guard-1 camera deployed in the Dohrn Canyon (site D1), imaging the EcoReef with *M. oculata* and *D. pertusum* fragments. (B, C) Specimens of deep-sea urchins in the genus *Cidaris* on the deployed EcoReef imaged during post-deployment surveys.

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