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Holistic approach to restore marine ecosystems: RENOVATE project

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Mediterranean coastal ecosystems are increasingly threatened by multiple anthropogenic pressures and climate change. As a result, these impacts have caused the decline of key endemic habitats such as *Posidonia oceanica* meadows and coralligenous reefs. Due to the slow natural recovery of these habitats after degradation, restoration actions play a key role in accelerating ecosystem recovery, reestablishing ecological structure and functional processes, and preventing further biodiversity and ecosystem service loss. Given the frequent habitat fragmentation and high levels of endemism, effective restoration efforts require a multidisciplinary, ecosystem-based approach that integrates marine science, engineering, socioeconomics, and policy. This study describes the holistic approach adopted in the RENOVATE project, which established an integrated framework to address the combined impacts of climate change and human pressures on vulnerable ecosystems. The framework employs advanced observational technologies, field data, and numerical modeling within an adaptive management loop, enabling site-specific, evidence-based restoration planning and assessment of ecosystem services recovery. Additionally, the study reports results from the northern Tyrrhenian coast (Latium, Italy), where RENOVATE aims to protect EU priority habitats and species from human pressures and climate-related threats. Although project activities are still in early stages, results from active restoration in the northern Latium coast show initial establishment and survival at pilot sites, highlighting the framework's potential to guide effective, replicable interventions in coastal ecosystems. Beyond the regional case study, the proposed framework contributes to global marine restoration efforts by providing a transferable methodology for the management of coastal ecosystems.

KEYWORDS
coralligenous, ecosystem functioning, ecosystem services, marine restoration, *P. oceanica*

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1 Introduction

Coastal marine ecosystems are biologically rich and ecologically dynamic zones that provide essential ecosystem services and support a significant share of global biodiversity. These systems contribute critically to climate regulation, food security, and carbon sequestration, possessing both tangible (e.g., fisheries) and intangible (e.g., cultural) values (Liquete et al., 2013; Trégarot et al., 2024). Among these, *Posidonia oceanica* meadows (priority habitat 1120*; EU Habitats Directive, 1992) are foundational ecosystems in the Mediterranean, offering services such as carbon sequestration, sediment stabilization, shoreline protection, and biodiversity support (Boudouresque et al., 2006, 2012). These meadows face increasing threats from anchoring, illegal trawling, and extreme weather, exacerbated by climate change (Montefalcone, 2009; Telesca et al., 2015). *Posidonia oceanica* is highly sensitive to disturbances, and it is experiencing extensive habitat degradation, with an estimated loss of 124,091 ha, corresponding to 10.1% of its total known extent (Telesca et al., 2015). Similar pressures also affect coralligenous reefs (priority habitat 1170; EU Habitats Directive, 1992), including Mediterranean coralligenous assemblages and infralittoral algae biocenoses dominated by *Cystoseira* spp., which are essential for biodiversity, coastal protection, and carbon sequestration (Ballesteros, 2006; Piazzi et al., 2018). Coralligenous reefs are highly sensitive to physical disturbances, overfishing, and sedimentation, and have experienced significant degradation in the Mediterranean, threatening their structural complexity and the biodiversity they support (Ballesteros, 2006; Piazzi et al., 2012; Gómez-Gras et al., 2021). Coralligenous reefs have been studied mainly in relation to individual stressors such as fishing or thermal anomalies (Piazzi et al., 2011; Tamburello et al., 2012). However, large-scale quantitative assessments examining the combined effects of multiple human pressures are lacking, limiting our understanding of the processes that drive structural and functional changes in these habitats (Deter et al., 2012).

Despite their ecological significance, coastal ecosystems are increasingly exposed to multiple cumulative pressures (Halpern et al., 2015) and typically recover slowly through natural processes (Montefalcone, 2024; Casoli et al., 2025). In this context, restoration actions can play a crucial role in accelerating ecosystem recovery, reestablishing ecological functions, and sustaining the benefits these systems provide to society (Benayas et al., 2009; Bullock et al., 2011; McAfee et al., 2022a; Saunders et al., 2024). Global initiatives, such as the UN Decade on Ecosystem Restoration (UN, 2020; Waltham et al., 2020) and the Nature Restoration Law, NRL, 2024 now mandate large-scale recovery actions demanding scientifically robust, effective, and sustainable approaches (Penca and Tănăsescu, 2025; Santos-Borja et al., 2025).

Traditional restoration approaches for *Posidonia oceanica* meadows, such as shoot or seedling transplantation, and for coralligenous reefs, including fragment transplantation or substrate stabilization (Pergent-Martini et al., 2024; Casoli et al., 2025), face several biological and logistical limitations, including high mortality, slow growth, labor intensity, and limited scalability. Restoration efforts are also constrained by static planning, low predictive capacity, and inadequate long-term monitoring, which together reduce their overall effectiveness and adaptability to future climate scenarios (Bayraktarov et al., 2016; Abelson et al., 2020). Contemporary methods adopt an ecosystem-based perspective, integrating active restoration with monitoring, predictive modeling, and adaptive management to enhance survival, resilience, and replicability (Thom, 2000; Boström-Einarsson et al., 2020; Silliman et al., 2023). Nevertheless, challenges remain due to cumulative stressors and the need for long-term evaluation.

Several integrated restoration frameworks have recently been proposed to provide structured, evidence-based guidance and to address key gaps in global marine ecosystem recovery efforts. For example, Smith et al. (2023) developed a decision-support framework for restoring Mediterranean macroalgal forests, using a stepwise decision tree to guide local site assessments, restoration implementation, success evaluation, and long-term management. Manea et al. (2023) introduced an ecosystem-based marine spatial planning (EB-MSP) approach that integrates both active and passive restoration within a framework aimed at maximizing ocean ecosystem recovery through ecosystem-based management. Meanwhile, Suggett et al. (2023) emphasize the importance of viewing restoration as a social-ecological system, locally tailored but globally relevant, highlighting the need to integrate economic flows and adaptive feedback mechanisms to sustain and adapt restoration financing over time.

Here, we present and apply the holistic approach adopted in RENOVATE project (Ecosystem-based approach to the evaluation and testing of active and passive restoration actions in the marine environment: the case of the Civitavecchia port hub), which has led to the development of an integrated framework designed to mitigate the combined impacts of climate change and human pressures and to guide marine ecosystem restoration interventions. We hypothesize that restoration success is enhanced when interventions are embedded in an iterative loop of observations, functional measurements, numerical simulations and adaptive management.

The manuscript details the application of this integrated framework to the restoration of a complex coastal area in the northern Latium (Italy), a site impacted by significant anthropogenic pressures. Through the case study, we show how the framework allows for a comprehensive assessment of ecosystem services, guides targeted restoration of priority habitats (e.g., *Posidonia oceanica* meadows) and key threatened species (e.g., *Corallium rubrum*, *Pinna nobilis*), and establishes a replicable, technology-driven model for enhancing the efficacy of marine restoration efforts globally.

The manuscript is organized to provide an overview of the framework design and its application. The description of the RENOVATE framework design is followed by a detailed description of the framework's core components contextualized within the case study of the northern Latium coast. Subsequently, the Results section presents findings exclusively from the project activities carried out to date, while planned future activities are detailed in the Discussion section.

2 Materials and methods

2.1 The RENOVATE project framework design

The RENOVATE project's logical framework is grounded in the principle of restoring ecosystem functions and services through both active and passive restoration measures, monitored via an integrated observing system, thereby contributing to biodiversity recovery and ecosystem resilience.

The framework is based on four interdependent pillars forming an iterative feedback loop (Figure 1):

I. An integrated observing system collects data on physical, biological, and ecological pressures, tracks baseline conditions and ecosystem changes, and integrates the assessment of ecosystem services and functionality.
II. Observational data are continuously used to update and validate numerical models that predict key oceanographic and ecological processes (e.g., water circulation, sediment transport, and pollutant dispersion) and support restoration activities.
III. Active and passive restoration activities on vulnerable habitats (e.g., *Posidonia oceanica* meadows and coralligenous reefs) are informed by ecosystem functionality assessment.
IV. The outcomes of ecosystem functionality assessments and restoration activities are continuously monitored, and resulting data are fed back into the observing system and models. This iterative loop enables adaptive management, allowing strategies to be recalibrated to maximize long-term ecological recovery.

Combining observations and models will support the development of a coastal Digital Twin Ocean (DTO) (Chen et al., 2023), a virtual representation that helps forecast scenarios, identify optimal restoration sites, and design effective strategies (Pillai et al., 2022; Li et al., 2025; Shirinov et al., 2025).

2.2 Case study: the northern Latium coast

The coastal stretch between Santa Severa and Tarquinia, along Italy's central Tyrrhenian coast, represents an area where ecological complexity and human activity overlap. This coastal area encompasses diverse marine and coastal environments increasingly subjected to competing demands for conservation and development (Figure 2).

From a geomorphological perspective, the wider area can be divided into two main physiographic units. The northern sector is largely shaped by sediment supply from the Fiora, Marta, and Mignone rivers, forming a wide continental shelf that grades from sandy coastal deposits to offshore silts and clays, with dominant northwestward sediment transport (Scanu et al., 2015). By contrast, the southern sector receives little fluvial input, mainly from ephemeral torrents, and is more fragmented, with seabed stability primarily provided by biogenic formations and *Posidonia oceanica* meadows (Bonamano et al., 2021).

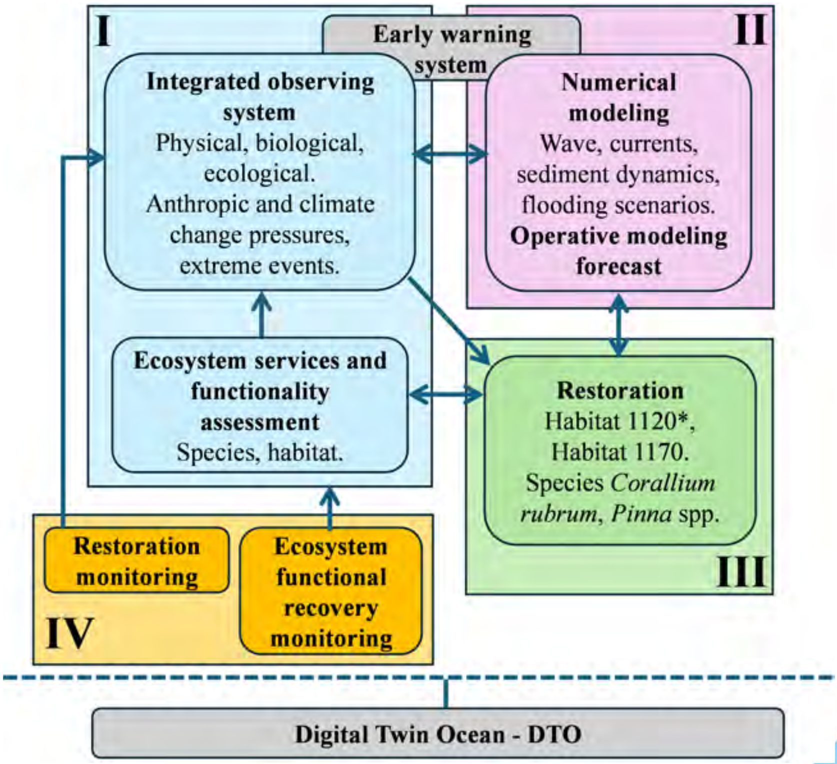

FIGURE 1
Conceptual framework of the RENOVATE integrated approach. The strategy for implementing active and passive restoration interventions follows an integrated approach, in which ecosystem function analysis, fully embedded within the observing system, provides input for numerical models. The outputs of these models, combined with ecological, morphological, and oceanographic data, facilitate the identification of target restoration areas and the determination of suitable restoration methods and scales. The results of restoration activities, together with ongoing observational data, are then used to validate both the numerical models and the algorithms developed to estimate ecosystem services. This iterative feedback loop ensures a continuous improvement process that supports the achievement of its overarching objectives.

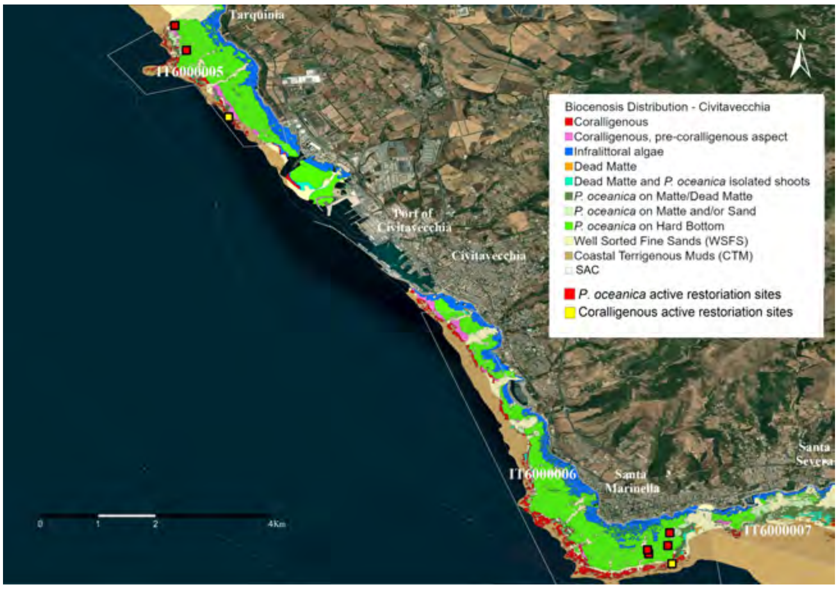

FIGURE 2
Case study area showing the distribution of benthic biocoenoses, bathymetric features, and the special areas of conservation (SACs) designated as IT6000005, IT6000006, and IT6000007. These sites are characterized mainly by the presence of *Posidonia oceanica* meadows and coralligenous biocoenoses. Additionally, the area hosts protected species such as *Pinna nobilis* and *Corallium rubrum*. Red and yellow squares represent coralligenous and *P. oceanica* restoration sites, respectively.

The oceanographic regime is shaped by dominant northwest and southeast winds, seasonal wave climates, and wind-driven currents. Summer stratification and winter mixing significantly influence sediment dispersion and primary productivity. However, climate change is intensifying marine heatwaves, storm surges, and medicanes, thereby disrupting sediment dynamics and morphodynamic stability.

Ecologically, this coastal stretch hosts a mosaic of benthic habitats including rocky substrates, sandy seabeds, soft-bottom communities, *P. oceanica* meadows, and macroalgal assemblages (Ardizzone et al., 2006). Rocky outcrops serve as a refuge for photophilic algal communities and *Corallium rubrum*, which is also protected under the EU Habitats Directive (92/43/EEC Annex 5; Code 1001, Directive, 1992). Infaunal communities in turbid soft-bottom habitats near river mouths have adapted to fluctuating salinity, while transitional estuarine and wetland zones enhance biodiversity through ecotonal species assemblages (Danovaro et al., 2002; Elliott and Whitfield, 2011).

Despite their ecological significance, these habitats face cumulative pressures from coastal urbanization, agricultural runoff, maritime traffic, and illegal fishing practices. Anchoring of recreational vessels and illegal bottom trawling severely damage *P. oceanica* meadows and coralligenous assemblages. Industrial discharges, extreme weather events, and thermal pollution from coastal power plants further compromise habitat integrity (Doney et al., 2012).

Four Special Areas of Conservation (SACs IT6000004 to IT6000007) safeguard vital habitats. However, the combined actions of climate change and human-induced pressures, such as coastal developments and the expansion of the Port of Civitavecchia, threaten adjacent protected areas (SACs IT6000005 and IT6000006), underscoring the need for sustainable planning.

2.2.1 Integrated observing system

To support project implementation, a modern integrated observing system has been established in the study area. This system helps address the typical challenges of coastal ocean observations, which are often too infrequent, sparse, inadequate, or imprecise (Marcelli et al., 2021).

The observing system, which relies on advanced and cost-effective technologies, integrates *in situ* measurements, habitat mapping, and advanced numerical modeling to monitor and anticipate potential impacts associated with climate variability, anthropogenic pressures, and ongoing port construction activities.

The spatial coverage and temporal resolution of the data acquisition strategy were defined according to the spatial and temporal scales of key physical and ecological processes in the region (Martellucci et al, 2018, 2021). These scales were identified based on previous scientific investigations in the area as well as the requirements for model validation and performance optimization (Bonamano et al., 2021).

The observing system integrates autonomous technologies that enhance long-term sustainability and cost-effectiveness, while enabling high-resolution, continuous monitoring across multiple environmental compartments. Habitat mapping activities (Piazzolla et al., 2024), including seabed classification and benthic community characterization, combined with functional ecosystem assessments (Bosch-Belmar et al., 2025; Mancuso et al., 2026), play a central role in identifying priority areas for conservation and restoration, as well as in informing the boundary conditions of numerical models. The placement of monitoring sites and the design of survey strategies have been optimized based on the spatial distribution of active and passive restoration interventions, anthropogenic pressure gradients, and the requirements for calibration and validation of satellite-based remote sensing data.

The integrated observing system will support the project throughout the whole 10-year duration, providing ongoing assessments of marine environmental matrices, including ecosystem services, for which a dedicated monitoring program of the ecosystem functionality of habitats and species has been developed.

Beyond tracking environmental changes, the system plays a crucial role in risk management by supporting Early Warning System (EWS), which delivers timely, actionable information. This is essential for mitigating or preventing the indirect and cumulative impacts of constructing new port facilities, as well as for understanding how these impacts interact with natural phenomena like marine heatwaves (MHWs) and other extreme climate-related events.

Accurate interpretation of these interactions relies on a robust numerical modeling system, continuously refined through a consistent and coherent influx of empirical field data. Such parameterization is crucial to effectively simulating and predicting both coastal and ecological dynamics. Importantly, the integrated observing system also includes areas designated for ecological restoration and mitigation, ensuring that monitoring efforts directly support the success of these interventions.

2.2.2 Assessment of ecosystem functionality

The assessment of ecosystem functionality is based on data regarding the distribution and extent of biocenoses and habitats. From a practical perspective, the distribution of benthic communities can serve as a key spatial unit for analysis (Costanza et al., 2017; Marcelli et al., 2018). The assessment also uses standardized ecosystem service categories derived from seminal and widely cited studies (e.g., Costanza et al., 1997; Daily, 1997; Costanza et al., 2008; Braat and De Groot, 2012; Costanza et al., 2014; Inniss et al., 2016). These categories provide measurable indicators to evaluate restoration effectiveness over time. We focused on carbon sequestration, oxygen fluxes, and biodiversity support, comparing restored and control sites to assess functional recovery trajectories. This evaluation centers on the functional recovery of ecosystems, specifically *Posidonia oceanica* meadows and coralligenous assemblages, starting from predictive models, *in situ* functional measurements, and algorithms calibrated on empirical data (Marcelli et al., 2018; Scanu et al., 2022).

The analysis of ecosystem functional performance considers species and habitats across different benthic biocenoses, allowing the assessment of conservation interventions (both active and passive restoration) while accounting for direct and indirect environmental disturbances.

The adopted methodology follows a dual-level analytical approach. At the broad scale, geospatial algorithms are applied to cartographic products generated through field surveys. At the detailed scale, the analysis is grounded in experimental measurements of key functional traits, including photosynthetic rate, oxygen flux (production and consumption), biodiversity metrics, and a suite of environmental parameters.

In the case of *Posidonia oceanica* meadows, monitoring efforts follow a site-specific strategy as outlined by Marcelli et al. (2018), focusing on oxygen generation, coastal erosion mitigation, primary productivity, bioremediation, and carbon storage.

The initial phase of the ecosystem functionality assessment concentrated on carbon sequestration, with CO_2 uptake identified as a key indicator of restoration success. For this purpose, the InVEST® model (Integrated Valuation of Ecosystem Services and Tradeoffs, version 3.12.0; Natural Capital Alliance, 2026) was parameterized using data derived directly from *in situ* measurements, as reported in Gnisci et al. (2020). These field measurements provided estimates of organic carbon in *Posidonia oceanica* leaves and rhizomes, which were then used as input values in the InVEST Carbon Storage and Sequestration module. Carbon sequestration was expressed in tons per hectare per year, and organized into three classes based on substrate type (*Posidonia oceanica* on rock: average input values of 0.63 leaf organic C and 0.62 rhizome organic C; *Posidonia oceanica* on sand: average input values of 0.37 leaf organic C and 0.39 rhizome organic C; *Posidonia oceanica* on matte: average input values of 0.47 leaf organic C and 0.50 rhizome organic C).

The results of the first application test, covering the entire project area, were used to identify a target carbon sequestration value in the case of restoration carried out on a potential area of 3.6 hectares of sandy gaps within the *Posidonia oceanica* meadow, thus lower than the target of six hectares planned.

The spatial resolution of the analysis was set to 100 × 100 m, corresponding to 1 hectare, so that the output values are numerically equivalent to tons per hectare. A Geographic Information System (GIS) processing was then used to quantify carbon sequestration (in tons per hectare per year; tons/ha/year) of the three different *P. oceanica* substrates. These results were used to establish baseline ecosystem functionality.

For coralligenous assemblages, the monitoring strategy is grounded in the development of habitat-specific algorithms, calibrated using experimental data. Planned field campaigns will include functional measurements in *Cystoseira* and other structurally complex biocoenoses to refine algorithm calibration and validation (Ballesteros, 2006; Garrabou et al., 2009). Measurements consider both intervention and reference (control) sites.

To evaluate ecosystem functioning of *Posidonia oceanica* meadows, *in situ* benthic chambers were deployed at representative sites, including transplant (receiving), donor, and control (pristine) locations. Measurements considered both intervention and reference (control) sites, allowing for a direct comparison of restored and natural conditions. A total of 9 incubations (n = 3 per site) were conducted during the February 2023 field campaign. Benthic chambers were used to quantify metabolic rates and assess structural and environmental variables, establishing a robust functional baseline. Each chamber enclosed a known area of the seabed, allowing simultaneous measurement of oxygen fluxes to estimate gross primary production (GPP), respiration rate (RR), and net community production (NCP). These data were then applied to calibrate ecosystem functional indicators and to track their evolution over time. Environmental parameters such as temperature and salinity were recorded concurrently, and structural traits of the seagrass, biodiversity metrics (macrozoobenthic and vagile fauna), and sediment samples for biochemical and enzymatic analyses were collected. Detailed methods for benthic chamber deployment and oxygen flux measurements follow Roth et al. (2019) and are described in Piazzolla et al. (2024). The Kruskal-Wallis test was used to assess the presence of significant differences among sites.

2.2.3 Numerical modeling and forecast

The experimental framework of the project is based on a robust suite of numerical models addressing wave dynamics, circulation, sediment transport, and deposition using both structured and unstructured high-resolution grids. These modeling systems integrate both design-support and operational forecasting models, including Delft3D-FLOW, SWAN, Delft3D-WAQ, SHYFEM, and WW3 (Lesser et al., 2004; Micaletto et al., 2022; WW3DG, 2019), which have been successfully employed to simulate coastal hydrodynamic processes and the transport of cohesive and non-cohesive sediments within the study area (Bonamano et al., 2021; Shirinov et al., 2025).

To obtain a detailed representation of wave fields and marine currents, the models were forced with a bathymetric dataset combining high-resolution multibeam surveys (depth range 1–40 m) with EMODnet bathymetry (230 × 230 m resolution) in offshore areas, and shoreline data extracted from SkySat satellite imagery. The reliability of numerical simulations was evaluated by assessing the model skill in reproducing variations in salinity, temperature, and current velocity along the water column. Model performance was quantified using the BIAS, widely applied in the literature to evaluate hydrodynamic models in coastal environments (Bonamano et al., 2024; Federico et al., 2017), and validated against observational data from seasonal oceanographic surveys and fixed monitoring stations.

In the first phase of the project, the potential impacts on candidate intervention areas were assessed, allowing the exclusion of zones and depth ranges where restoration actions would have a high probability of failure, and identifying instead the sub-areas most suitable for successful restoration. Design-support models (Delft3D-FLOW, SWAN, Delft3D-WAQ) were specifically applied to optimize restoration site selection, integrating structured-grid simulations of hydrodynamics, waves, and water quality (turbidity and sedimentation). A high-resolution curvilinear grid (up to 50 m) and 15 sigma layers allowed detailed representation of coastal processes, including thermocline dynamics. Models were forced with boundary conditions for currents, sea level, temperature, and salinity from the Mediterranean Forecasting System (MFS) distributed through the Copernicus Marine Service, and meteorological parameters (solar radiation, air temperature, humidity, cloud cover) collected at the Port of Civitavecchia. These simulations evaluated near-bed orbital velocities during extreme events, bottom current velocities, and year-long conditions driven by temporally varying wind and wave fields.

Considering the main meteo-climatic scenarios, the models were further employed to simulate suspended sediment (turbidity) and sedimentation rates from both natural and anthropogenic sources (e.g., dredging). These results were integrated with remote sensing observations.

Operational forecasting models (SHYFEM, WW3) were used to support mitigation and EWS, providing daily support for experimental activities and continuous monitoring of potential impacts from future port infrastructures. These unstructured-grid models simulate fine sediment transport and local coastal processes with variable horizontal resolution from 3,000 m offshore to 50–100 m near SACs, refined to 30 m in the Port of Civitavecchia. Vertical z-coordinate discretization with high surface resolution (1 m) increasing to 50 m at depth, along with tidal constituents (OTPS) and ECMWF atmospheric fields, were applied to accurately simulate surface circulation and air–sea heat fluxes.

Moreover, the hydrodynamic, wave, and circulation models, including extreme-event simulations, proved essential for selecting restoration sites, determining suitable depth ranges, and identifying optimal locations for anti-trawling devices and artificial reefs. The wave and circulation models were also extended to account for the presence of vegetation in dynamic simulations, quantifying its wave-attenuation effects (Shirinov et al., 2025).

The project further included studies at progressively finer spatial scales to analyze the dynamics of fine sediments relative to the distribution and quality of habitats and priority species within the SACs (Sites of Community Importance) involved in the project. Additional analyses, such as hydrocarbon transport, identified potential risk areas associated with the offshore platform north of the port.

A key component was the development of an operational model (see: https://www.cmcc.it/what-we-do/data-services-and-applications/forecasting-systems; or possibly: https://civitavecchia.cmcc.it/), which not only provides daily support to experimental activities but also plays a fundamental role in the EWS, supporting monitoring operations and the spatial analysis of ecosystem service recovery.

2.2.4 Restoration planning and sites selection

The RENOVATE project outlines the criteria, methodologies and operational protocols applied to active and passive restoration activities of *Posidonia oceanica* meadows and Mediterranean coralligenous reefs, as well as to the protected target species *Corallium rubrum* and *Pinna nobilis*.

In this section, all planned restoration activities, scheduled over the next 10 years, are detailed; however, as these interventions are still in an early stage, the evidence reported in the following Results section refers exclusively to the activities implemented during the first year, including active restoration on small areas of *P. oceanica* meadows and the reintroduction of selected coralligenous organisms.

For habitat *Posidonia oceanica* meadows, active restoration involves the transplantation of shoots collected from donor sites and the reintroduction of shoots deposited on the shore by storm events. Restoration targets six hectares using over 112,000

Posidonia cuttings: 76,800 in sandy gaps (≤50 m^2), 19,200 for reinforcement, and 16,000 from storm debris. These actions promote the direct recovery of vegetation cover and substrate stability, with significant improvements expected in the short to medium term. Additionally, seedlings grown from seeds collected during mass flowering events are reintroduced into the sea to enhance genetic diversity and habitat resilience over the medium to long term. These interventions aim to strengthen connectivity with adjacent habitats (e.g., coralligenous reefs) and support *Pinna rudis*, a key benthic species.

Passive restoration actions for *P. oceanica*, on the other hand, focus on reducing the pressures acting on the meadow and include:

I. A network of 100 anti-trawling devices deployed over approximately 957 ha, expected to prevent the annual loss of about 420,000 leaf bundles (approximately 13,000 m^2) (González-Correa et al., 2005; Ardizzone et al., 2018).
II. Sixty mooring buoys installed to limit anchoring damage, preventing another 180,000 bundle losses per year (approximately 6,000 m^2) (Francour et al., 1999; LIFE Sea Forest Project).

Cumulatively, these measures would protect about 6 million leaf bundles, corresponding to roughly 18.8 ha of *P. oceanica* meadow.

Regarding the vulnerable species *Pinna nobilis*, its reintroduction is currently extremely limited due to widespread mass mortality caused by *Haplosporidium pinnae* (Vázquez-Luis et al., 2017). Consequently, RENOVATE is focusing on trialing *Pinna rudis* restoration and aquaculture-based cultivation of *P. nobilis* as alternative approaches to restore ecological functions.

For active restoration of coralligenous reefs, no harvesting takes place at donor sites; instead, a Bycatch Recovery Program collects viable organisms and substrates from legal fisheries, thereby minimizing damage to donor habitats (Garrabou et al., 2017). The recovered organisms are maintained under controlled conditions in laboratory tanks and subsequently reintroduced into the marine environment at the designated restoration sites. This approach reduces impact on natural populations, supporting sustainability and long-term ecosystem health. Active restoration includes the reintroduction of up to 6,000 coralligenous organisms to natural and artificial substrates, including *Corallium rubrum*. Reintroducing these key species promotes habitat complexity and biodiversity recovery, with noticeable improvements expected over the medium term. *Cystoseira amentacea* is restored via colonized clay tiles, aiming to deploy 2,500 tiles (approximately 500 m^2) over 10 years. The deployment of colonized tiles accelerates habitat formation, producing measurable ecological benefits in the medium to long term.

Passive restoration for coralligenous reefs actions include:

I. Fifty-six artificial reef modules (covering 900 m^2 colonization area) deployed to replicate habitat structure (Ponti et al., 2015).
II. Over 3.5 ha of new port surfaces made available for colonization.
III. One hundred anti-trawling deterrents deployed to provide >1,300 m^2 of habitat and reducing illegal fishing (González-Correa et al., 2005).
IV. Thirty-three mooring buoys installed to protect 3.7 ha per year from anchor damage (Francour et al., 1999).

The RENOVATE Project implemented an ecosystem-based protocol to identify suitable restoration sites for *Posidonia oceanica* meadows and Mediterranean coralligenous reefs, integrating ecological, physical, and oceanographic information. The site selection process combined existing knowledge of the study area with new environmental data and spatial analyses. Macro-scale priority areas were first identified based on available information on local ecosystems, then refined through high-resolution morpho-bathymetric mapping and underwater surveys to assess seabed features and substrate suitability. Numerical modeling and GIS-based analyses further helped to assess ocean dynamics, habitat quality, and anthropogenic pressures, guiding the identification of optimal restoration zones, while candidate micro-sites were validated through field observations.

3 Results

3.1 Habitat characterization and ecosystem functionality

The use of *in situ* benthic chambers has allowed for the estimation and monitoring of key metabolic traits representative of ecosystem functioning, as well as their relationships with the associated biodiversity within the *Posidonia oceanica* habitat (Figure 3, panel A). The results indicate that respiration and production levels did not differ significantly among receiving, donor, and control sites. Net community production (NCP) values (average ± Standard Error) were: receiving site 0.58 ± 0.23 mmol O_2 L^{-1} m^{-2} h^{-1} ($n = 3$); donor site 0.48 ± 0.42 ($n = 3$); control site 0.13 ± 0.20 ($n = 3$). Kruskal-Wallis tests revealed no significant differences among sites for NCP ($H = 2.22$, $p = 0.329$), gross primary production (GPP; $H = 2.22$, $p = 0.329$), or respiration rate (RR; $H = 0.61$, $p = 0.739$). While these preliminary findings are consistent with the hypothesis that short-term metabolic compensation may occur following transplantation, the limited sample size ($n = 3$ per site) and single-season sampling preclude definitive conclusions. If confirmed by longer-term monitoring with greater temporal replication, these functional metrics could potentially serve as early indicators of restoration trajectory.

Data from the February 2023 field campaign showed overlapping ranges of metabolic rates among sites (Figure 3, Panel A), allowing for the calculation of net community primary production in *P. oceanica* meadows. These data were also integrated with measurements obtained through Unmanned surface vehicles (USV), enabling the creation of a preliminary *P. oceanica* primary production model (PP-SDM) in the study area (Piazzolla et al., 2024).

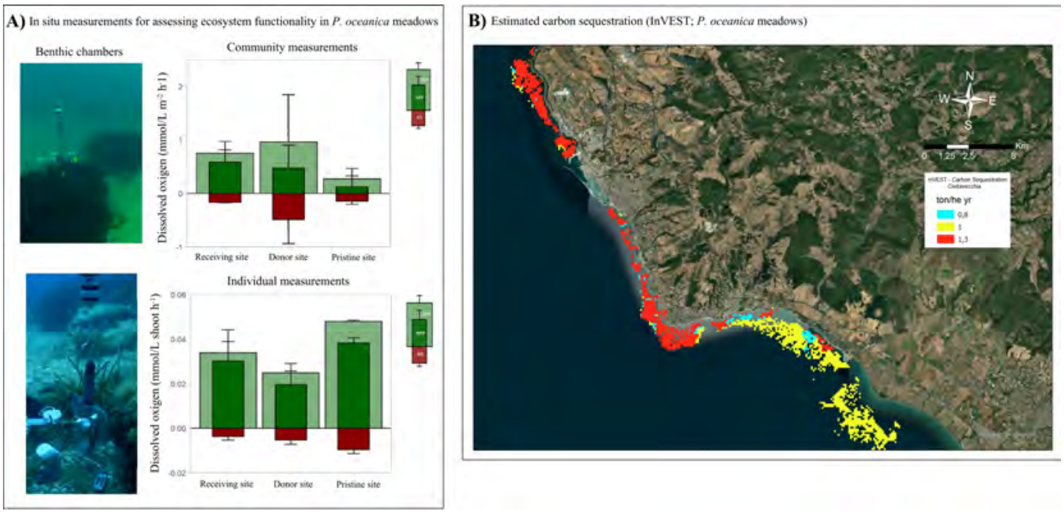

FIGURE 3
Panel **(A)** ecosystem functionality was assessed using benthic chambers at both the individual organism and community levels within *Posidonia oceanica* meadows. Measurements were conducted following the methodology described by Piazzolla et al. (2024). Panel **(B)** outputs of the InVEST model showing estimated carbon sequestration for *P. oceanica* meadows.

Additionally, laboratory experiments were conducted to investigate how *Posidonia oceanica* metabolic traits respond to varying levels of turbidity and temperature. These experiments involved measurements of respiration rate, gross and net primary production, and photosynthetic activity, assessed through chlorophyll-*a* fluorescence analysis (Bosch-Belmar et al., 2025). The results showed that water turbidity caused a marked decline in photosynthetic performance and narrowed the species thermal tolerance by 3 - 4 °C, indicating that sediment resuspension associated with port activities could rapidly impair the functioning and resilience of local *P. oceanica* meadows.

The RENOVATE project has integrated measurements of ecosystem functioning in *Posidonia oceanica* meadows and Mediterranean coralligenous reefs with the quantification of the ecosystem services provided by restored habitats, offering a framework for long-term monitoring of the effects of the restoration activities. Figure 3, panel B, presents model-based estimates of ecosystem functionality under restoration conditions, focusing solely on carbon sequestration. Carbon sequestration in the entire area is estimated to range from a minimum of 0.8 to a maximum of 1.3 tons/ha/year, values consistent with those reported by Marcelli et al. (2018). Considering both the potential active restoration area of the *P. oceanica* meadow (3.6 hectares) and the minimum carbon sequestration value (0.8 tons/ha/year) in the area, a target value achievable through restoration activities was estimated at 1.1 tons/ha/year.

3.2 Validation of numerical models and environmental forecasts

Temperature and salinity outputs were validated against field measurements collected along several cross-shore transects spanning a range of depths. Surface temperature patterns were generally well reproduced by the model (Figure 4, panel A), with temperature biases close to zero in the upper layers. The largest discrepancies occurred in the intermediate part of the water column, around the thermocline (approximately 30–40 m depth), where the temperature BIAS reached values up to about 1.5–1.7 °C. Below the thermocline, the discrepancy gradually decreased, reaching slightly negative values of approximately −0.7 °C near the seabed. Salinity profiles showed a generally good agreement with observations at intermediate and deeper layers, with BIAS values mostly ranging between −0.1 and 0.05 psu. Larger differences were observed near the surface, where the model tended to slightly underestimate salinity (BIAS around −0.15 psu), likely due to underestimated evaporation effects or surface flux uncertainties (Figure 4, panel B). Overall, the model performance in reproducing temperature and salinity vertical structures is consistent with previous findings by Bonamano et al. (2024) and Federico et al. (2017). Vertical current profiles were compared with measurements collected near the northern inlet of the Port of Civitavecchia over two autumn seasons. The model reproduced the latitudinal velocity component (Vy) reasonably well, with BIAS values generally within −0.5 to 0.1 cm s^{-1}, showing only minor underestimations in the deeper layers. Larger discrepancies were observed for the longitudinal component (Vx), particularly in the upper part of the water column where positive BIAS values reached approximately 1.6–1.8 cm s^{-1}. Below about 10–12 m depth, the bias decreased and became slightly negative (around −0.3 to −0.4 cm s^{-1}), indicating a moderate underestimation of current velocities near the seabed (Figure 4, panel C).

Numerical simulations of near-bed hydrodynamic conditions and sediment dynamics were used to support the identification of suitable restoration areas (Figure 5). In particular, the simulations focused on three key parameters controlling the stability and ecological suitability of seabed habitats: bottom orbital velocity generated by extreme wave events, suspended sediment concentration, and sedimentation rates. These variables are critical drivers of the ecological performance of *Posidonia oceanica* meadows, as excessive hydrodynamic stress can cause uprooting of shoots,

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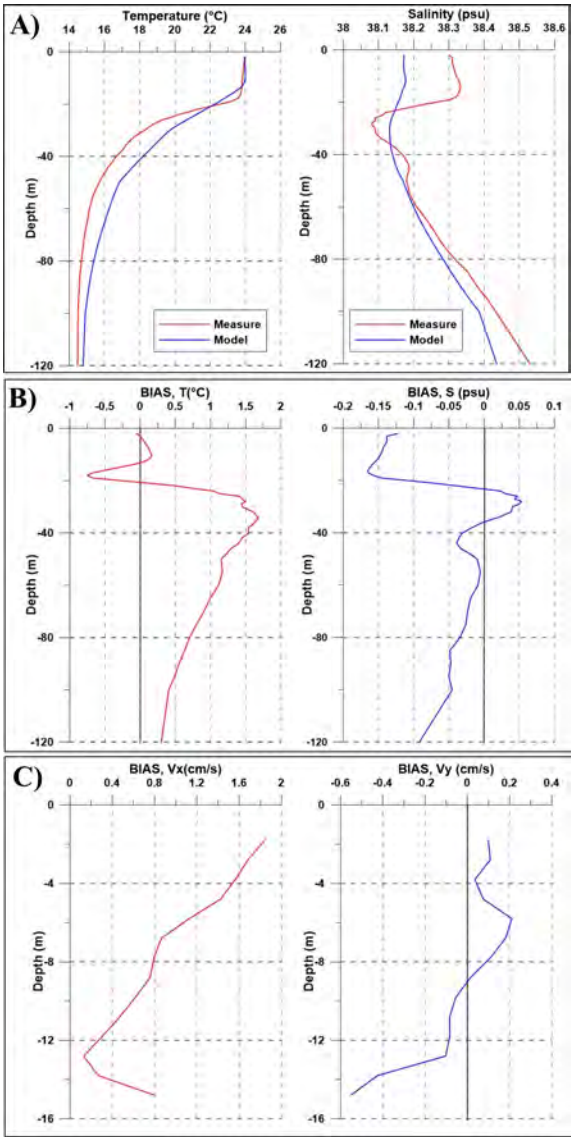

FIGURE 4
Panel **(A)** measured and modeled temperature and salinity profiles across the water column; panel **(B)** bias patterns for temperature and salinity; panel **(C)** bias patterns for the longitudinal (Vx) and latitudinal (Vy) components of current velocity across different water column layers.

while high turbidity and sediment deposition can limit light availability and impair photosynthetic activity.

The upper panels of Figure 6 show the spatial distribution of bottom orbital velocities generated during extreme wave scenarios approaching from the south and from the west. These simulations highlight areas exposed to stronger near-bed hydrodynamic forcing, which may represent potentially unfavorable conditions for restoration activities. Conversely, zones characterized by lower orbital velocities indicate areas where seabed stability is higher and therefore more suitable for transplantation or passive protection measures.

The lower panels of Figure 5 display the modeled patterns of suspended sediment concentration and sedimentation rates under representative wave conditions. These maps provide insights into the spatial variability of turbidity and sediment deposition processes along the coastal sector. Since water transparency and sediment accumulation strongly influence the depth distribution and physiological performance of *P. oceanica*, these parameters were considered essential indicators for evaluating restoration feasibility.

All simulation outputs were integrated within a GIS framework together with high-resolution multibeam bathymetry, benthic habitat distribution, and ecosystem functionality indicators. This multilayer spatial analysis enabled the identification of the most suitable restoration sites by excluding areas characterized by excessive hydrodynamic stress or sediment dynamics potentially detrimental to seagrass establishment and persistence.

3.3 Active restoration interventions of *Posidonia oceanica* meadows and coralligenous reefs

Active restoration activities for *Posidonia oceanica* meadows have started with the selection of pilot sites for transplantation (Figure 2) where specific modules have been positioned for the reintroduction of *P. oceanica* cuttings into the marine environment, covering a total area of 20 m^2 (Figure 6, panel A).

In addition to the standard *P. oceanica* reintroduction activity, an experimental recovery of *P. oceanica* vegetative fragments has been carried out. In detail, the activity focused on the recovery of vegetative fragments dislodged by storm surges and deposited along the seabed and adjacent shorelines for subsequent reintroduction in the restoration sites (Figure 6, panel B). Along 11.5 km of emerged coastline, an average density of 2.6 viable leaf bundles per square meter was recorded. The survey identified a total of 12,000 m^2, encompassing both submerged and emerged beach zones, where cuttings were consistently accumulated. During the first sampling activity, a total of 1,331 viable fragments were recovered.

Posidonia oceanica fruits were collected during a large-scale flowering event in 2024 and have been placed in controlled tanks for seeds germination tests, growth monitoring, and subsequent reintroduction in the marine environment (Figure 6, panel C). During the sampling campaign, a total of 200 fruits were collected from which 98 viable seeds successfully germinated.

Considering passive restoration activities for *P. oceanica* meadows, suitable sites for the deployment of all proposed restoration methodologies have been identified throughout the entire study area.

Figure 7, panel A, shows underwater images of some reintroduced corals within designated coastal restoration sites, previously recovered from fishermen's nets after being accidentally captured as bycatch, and maintained under controlled environmental conditions. During the first year of the project about 400 individuals from various species have been recovered from bycatch, including *Eunicella cavolini*, *Cladocora caespitosa*, *Paramuricea clavate*, and *Corallium rubrum*. The reintroduction process follows species-specific protocols, which include the reintroduction of either individual organisms or fragments of larger colonies. The reintroduction density of organisms recovered from bycatch, intended to restore natural habitats, is maintained between 15 and 20 individuals per square meter, to approximately replicate the natural population densities naturally observed at selected restoration sites.

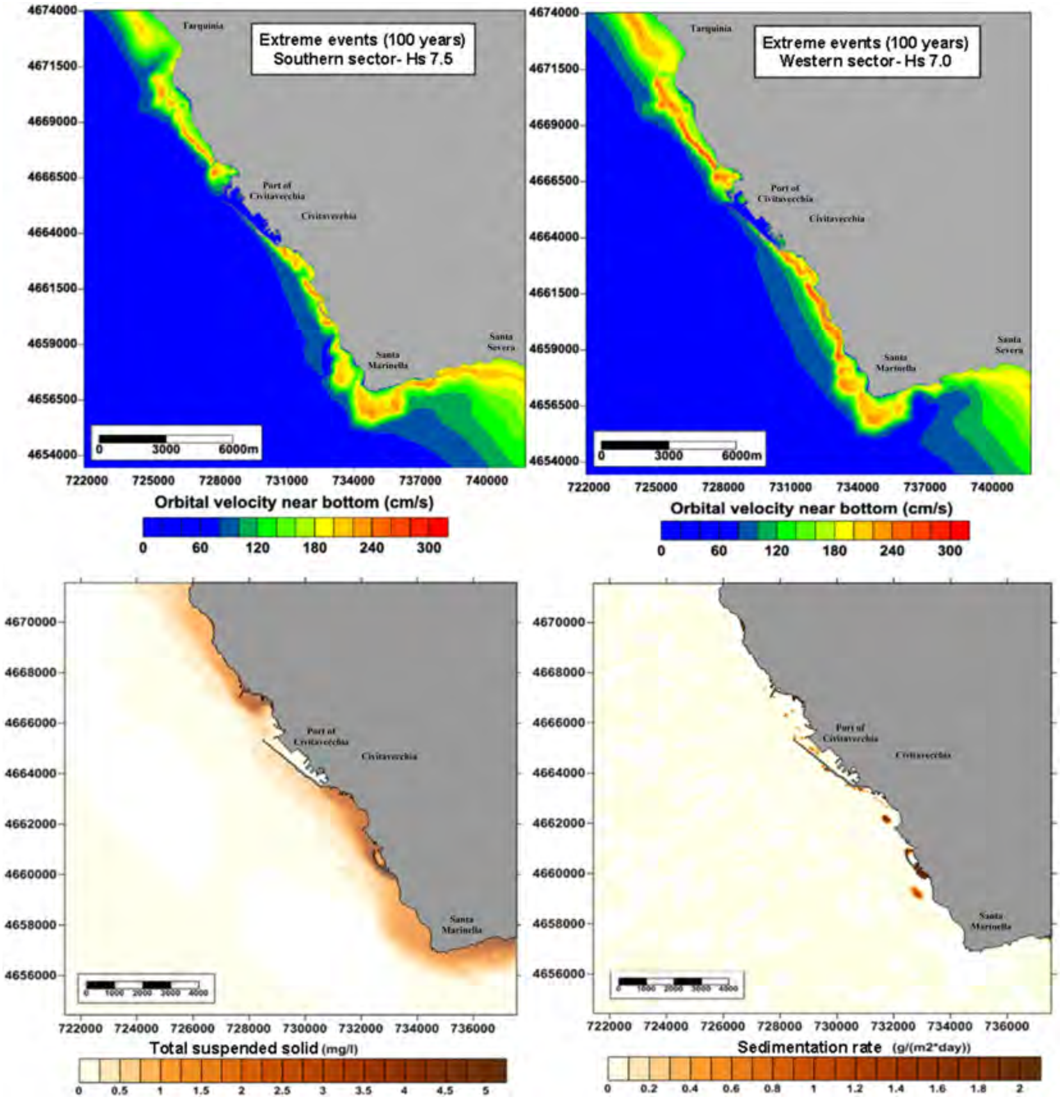

FIGURE 5
Results of numerical simulations used to support restoration site selection. The upper panels show the spatial distribution of bottom orbital velocity generated by extreme wave events approaching from the south (left) and from the west (right), simulated using Delft3D and WW3 models. These maps identify areas subjected to stronger near-bed hydrodynamic forcing, which may negatively affect seabed stability and the establishment of benthic habitats such as *Posidonia oceanica*. The lower panels show modeled suspended sediment concentration (left) and sedimentation rates (right) under the southerly wave scenario (Delft3D). These variables provide an indication of turbidity and sediment deposition patterns that can influence light availability and seagrass performance.

A total of 196 organisms have been successfully reintroduced into the marine environment to date.

A dedicated activity has focused on the recovery and reintroduction of the macroalgae *Cystoseira* spp. plantlets, also sourced from bycatch, into more coastal areas (Figure 7, panel B). After an acclimatization and cultivation phase in mesocosm systems, the substrates bearing *Cystoseira* plantlets were transported to reintroduction sites as rapidly as possible and affixed to rocky substrates by specialized scientific divers (see Figure 6, panel B, n.3). To date, 340 tiles have been placed in the upper infralittoral, covering a surface of about 50 m^2 over 70 m of length.

4 Discussion

Through an integrated framework that combines an observing system with functional trait assessment, ecosystem services evaluation, and high-resolution numerical modeling within an adaptive management loop, the RENOVATE project provides a structured approach to marine restoration that is transferable and globally applicable. The framework supports the planning and implementation of restoration activities at the northern Latium study site, addressing both ecological functions and ecosystem services associated with *Posidonia oceanica* meadows and Mediterranean

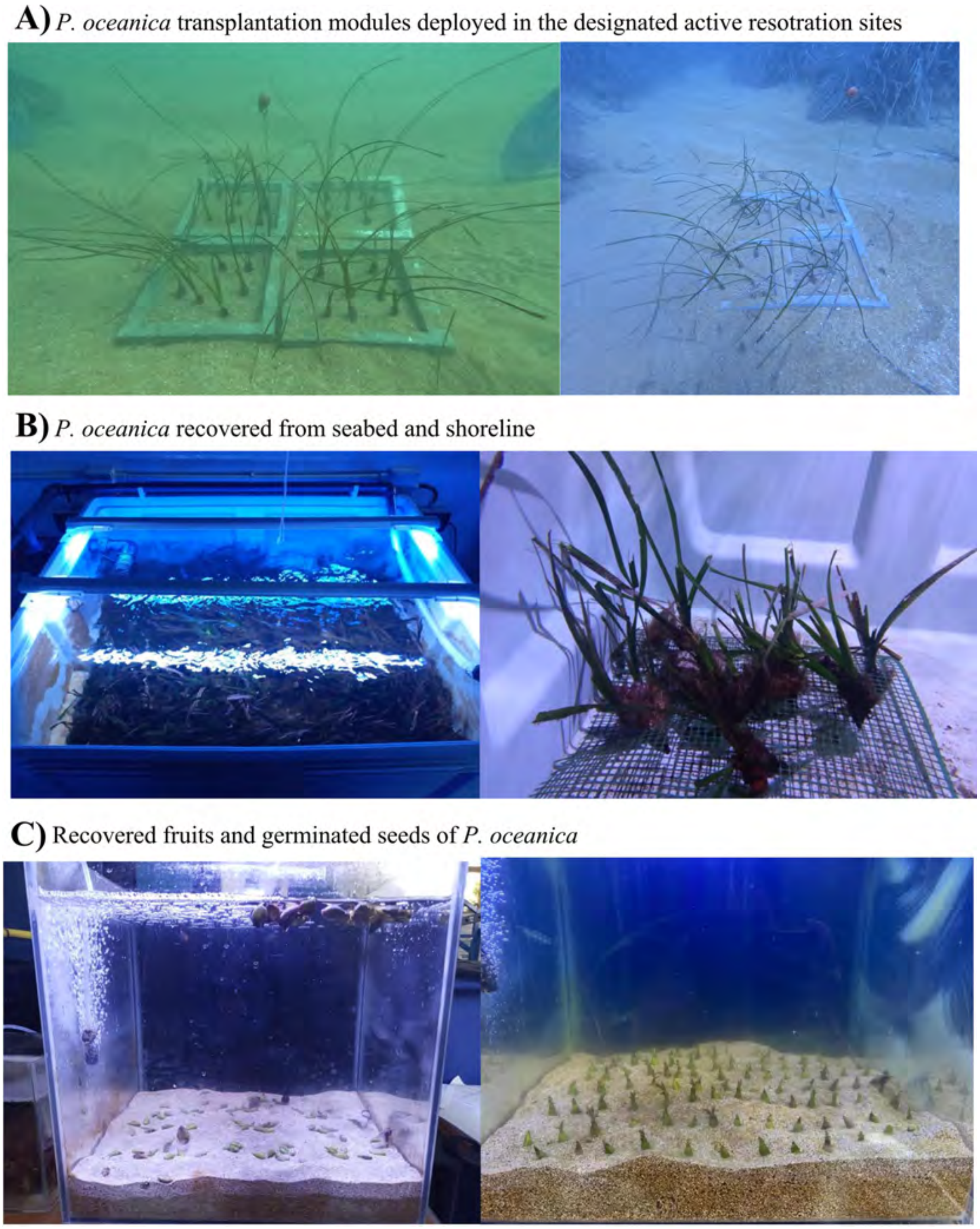

FIGURE 6
Panel **(A)** pilot *P. oceanica* transplant modules in the selected areas designated for the *P. oceanica* restoration operations; panel **(B)** some recovered *P. oceanica* vegetative cuttings from both the seabed and beaches following storm surges in the study area; panel **(C)** *P. oceanica* fruits and germinated seeds ready to be reintroduced in restoration sites.

coralligenous reefs. The integration of diverse monitoring and modeling tools is crucial for capturing the complex spatial and temporal dynamics of coastal ecosystems, ensuring that restoration efforts are ecologically sound, site-specific, and resilient to ongoing environmental pressures. Such a framework provides a robust scientific basis for adaptive management and long-term assessment of restoration outcomes.

The RENOVATE active and passive restoration activities for *Posidonia oceanica* meadows and coralligenous assemblages are designed to be site-specific and coordinated with regional coastal zone management and conservation strategies promoted by the Latium Region. The feasibility of these measures is supported by successful examples from other Italian Marine Protected Areas (MPAs), demonstrating the practicality and replicability of the proposed methodologies in similar ecological contexts.

From a methodological perspective, the active and passive restoration actions at small scale already implemented within the RENOVATE project, and those planned for the coming years, are consistent with approaches adopted worldwide. Restoration interventions planned at small spatial scales, and capable of considering

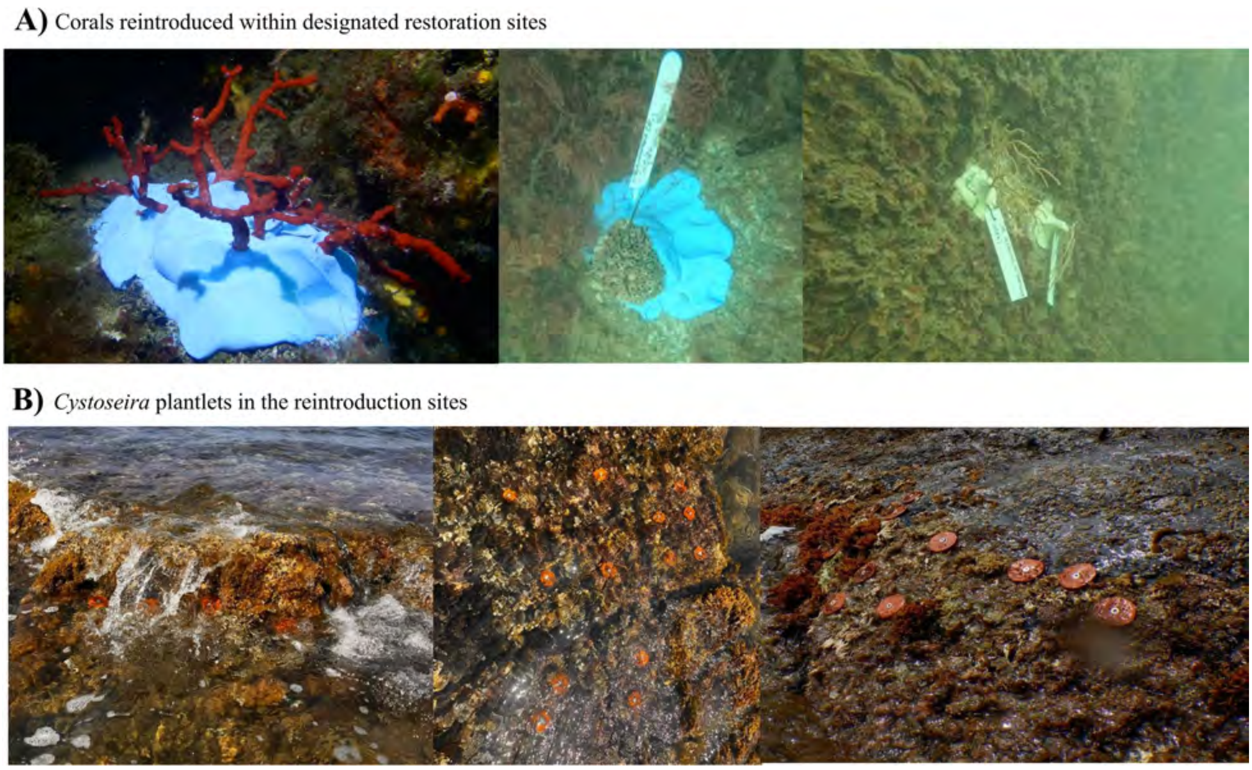

FIGURE 7
Panel **(A)** some coralligenous species recovered from bycatch and reintroduced into the marine environment. Panel **(B)** *Cystoseira s.l.* outplanting activities; the replanted supports are visible in orange.

local ecological variability, have proven not only to be effective in recovering biodiversity and ecosystem functions, but also contribute significantly to broader-scale regeneration (Danovaro et al., 2025). Small-scale interventions, when well-designed and maintained, can achieve high average success rates and serve as strategic tools to initiate gradual yet robust ecological recovery processes. Their modular and replicable nature makes them particularly suitable for complex or fragmented environments, enabling the progressive expansion of positive ecological outcomes through a mosaic-based approach (Danovaro et al., 2025). Such interventions are generally more feasible from both economic and operational standpoints, facilitating the involvement of local stakeholders and supporting adaptive monitoring. These characteristics make them highly functional tools, especially when embedded within a broader ecosystem-based management framework and underpinned by policies for conservation and sustainable use. Furthermore, restoration actions implemented within the RENOVATE framework may enhance habitat connectivity. Restoring fragmented *Posidonia oceanica* meadows and structurally complex coralligenous assemblages can reduce habitat discontinuities and facilitate the ecological processes among adjacent habitats. By strengthening linkages between meadows, reefs, and nearby coastal areas, these interventions may improve ecosystem resilience, support biodiversity, and increase the long-term effectiveness of restoration (McAfee et al., 2022b).

The initial activities of the RENOVATE project carried out at the northern Latium study site have led to the dissemination of results through several scientific publications (Piazzolla et al., 2024, 2025; Varghese et al., 2024; Bosch-Belmar et al., 2025; Burchio et al., 2025; Mancuso et al., 2026). These contributions help to improve understanding and inform best practices for marine ecosystem restoration in the Mediterranean region.

It is nonetheless important to acknowledge that the results obtained so far have some limitations. Restoration is still in its early stages, so the effects of recovery actions are only partially developed, making it challenging to attribute observed changes to specific interventions within this highly dynamic coastal system. Nevertheless, early outcomes from the first year of active restoration in the northern Latium study area show successful initial establishment and survival at pilot sites, offering preliminary evidence of the framework's potential to guide effective and replicable interventions. These data provide valuable insights to inform the continuation of project activities. They also highlight how the integration of observational data, functional trait assessments, and predictive modeling can support the ongoing restoration of *Posidonia oceanica* meadows and coralligenous assemblages. While still limited, these results may be useful for planning similar interventions in other Mediterranean and temperate coastal areas.

In the coming years, work at the northern Latium study site will focus on comprehensive monitoring of ecosystem functions alongside active restoration efforts, to assess the long-term recovery trajectories of coastal habitats. Continuous data collection and complementary analyses will be employed to further elucidate ecosystem dynamics and validate numerical model predictions.

Future planned activities will focus on the continued measurement of ecosystem functionality, with particular attention to coralligenous reefs, where *in situ* measurements will be conducted using methodologies analogous to those applied for *Posidonia oceanica* meadows. The project will maintain sustained monitoring of metabolic traits and biodiversity across all reintroduction sites, enabling the assessment of restoration trajectories over both medium and long-term periods. Large-scale active restoration of *Posidonia oceanica* remains a priority, aiming to restore a total of six hectares at designated sites. Alongside this, recovery of vegetative *P. oceanica* fragments along the shoreline will continue, with an estimated annual recovery potential of approximately 89,000 viable leaf bundles from storm surges, substantially exceeding the 16,000 bundles required to meet restoration objectives. Furthermore, seeds collected during flowering events will be regularly reintroduced to selected marine areas, with repeated introductions scheduled as new seeds become available. Active restoration of coralligenous reefs will proceed throughout the project duration, focusing on the recovery of organisms from bycatch, their maintenance under controlled conditions, and subsequent reintroduction into the marine environment, with the goal of reintroducing up to 6,000 coralligenous organisms. Concurrently, outplanting of *Cystoseira* spp. will continue, aiming to restore approximately 500 m^2 of habitat. All planned passive restoration activities, for both *Posidonia oceanica* meadows and coralligenous reefs, are still in the planning phase and will be implemented in the coming years.

Looking forward, DTO development could provide an integrative platform to further support restoration. By combining real-time monitoring with predictive hydrodynamic and ecological models, the DTO could forecast the evolution of restored habitats under varying environmental conditions. Thresholds based on ecosystem indicators could trigger adaptive management actions to optimize restoration outcomes. This approach would establish a closed-loop system where observations, predictions, and management actions are continuously synchronized, offering a prospective tool for evidence-based, adaptive ecosystem restoration.

By actively involving local stakeholders (e.g., underwater associations, recreational and professional divers, and representatives of the small-scale fisheries sector) the project fosters social legitimacy, encourages stewardship, and strengthens the integration of restoration practices within broader marine conservation and sustainability frameworks. This inclusive approach not only improves local acceptance and compliance but also enhances the ecological effectiveness and resilience of the interventions by anchoring them in the socio-ecological context of the area.

5 Conclusions

The RENOVATE project establishes a comprehensive and interdisciplinary framework for marine ecosystem restoration, addressing the complex interplay of ecological, climatic, and anthropogenic pressures along the northern Tyrrhenian coast. By combining an integrated observing system, high-resolution numerical modeling, *in situ* ecosystem functionality assessments, and adaptive management strategies, the project demonstrates how scientifically grounded, site-specific interventions can effectively restore priority habitats and endangered species. The results of implementing the RENOVATE framework at the northern Latium study site highlight the utility of the framework and its potential to support the restoration of ecosystems, ecological functions, biodiversity, and related ecosystem services. This holistic approach provides a replicable model for integrating conservation, sustainable resource use, and resilience building, with broad applicability for supporting the goals of the EU Nature Restoration Law and the UN Decade on Ecosystem Restoration.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

MM: Methodology, Supervision, Writing – original draft, Investigation, Funding acquisition, Conceptualization. SS: Methodology, Formal analysis, Investigation, Writing – original draft, Software. DP: Data curation, Software, Writing – original draft, Formal analysis, Investigation. SB: Software, Writing – original draft, Formal analysis, Validation. AM: Resources, Data curation, Writing – original draft, Investigation. GF: Writing – original draft, Project administration. VP: Funding acquisition, Formal analysis, Methodology, Conceptualization, Writing – original draft, Investigation. MB-B: Data curation, Writing – original draft, Investigation, Formal analysis. FM: Data curation, Formal analysis, Investigation, Writing – original draft. GCe: Methodology, Formal analysis, Investigation, Writing – original draft. AF: Investigation, Methodology, Formal analysis, Writing – original draft. PN: Writing – original draft, Investigation, Methodology, Formal analysis. AS: Investigation, Writing – original draft, Formal analysis. IF: Validation, Formal analysis, Writing – original draft, Software. GCo: Conceptualization, Writing – original draft, Methodology, Software, Formal analysis, Validation. NP: Formal analysis, Writing – original draft, Software, Conceptualization, Methodology, Validation. GS: Methodology, Writing – original draft, Conceptualization, Supervision.

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