

FRAMEWORK TECHNICAL - SCIENTIFIC REPORT OF THE IMPLEMENTING ENTITY



Funded by the
European Union
NextGenerationEU



Ministero
dell'Università
e della Ricerca



Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA

NATIONAL RECOVERY AND RESILIENCE PLAN (NRRP) – MISSION 4 COMPONENT 2 INVESTMENT 1.1 – “Fund for the National Research Program and for Projects of National Interest (NRP)”

INTRODUCTION

The Technical-Scientific Report is produced by the *Principal Investigator*, on the basis of a discussion with each local manager for the purposes of collecting data and documenting the progress of each operational unit. It is then submitted according to deadlines envisaged in the related notification.

The Report is composed of the following sections:

SECTION 1 – GENERAL TRENDS OF THE PROJECT, where information on the general trends of the projects are included by making reference to the achievement of intermediate and long-term goals, to the compliance with the project activities, to the *DNSH* and *Open Access* principles as per the approved project.

SECTION 2 – PROGRESS OF ACTIVITIES, which entails the description of carried out activities based on the details provided by the operational units involved in the implementation of the project during the collaboration period. It also includes the description of future activities, potential publications and challenges encountered as well as actions for improvement. This, in order to guarantee the achievement of goals that have been established when the financed project was presented.

SECTION 3 – COMMON INDICATORS, where EU common indicators connected to the specific investment should be enhanced.

SECTION 4 – PREDICTIVE ANALYSIS AND FINAL COMMENTS, regards the forecast scenario on the development of the project and final comments.

The hereby provided scheme will also be used when presenting the final results of the implemented activities within the project financed by the Ministry.

SECTION 1 – GENERAL TRENDS OF THE PROJECT

With regard to the activities completed during the project's duration, it is below provided:

a) a brief summary of the project;

The project was aimed at an integrated assessment of blue carbon dynamics in *Posidonia oceanica* meadows along the Italian coasts and it was carried out through the complementary activities of the different research units (UniRoma2, UniTuscia, UniParthenope), combining ecological modelling, carbon sequestration estimates, ecosystem accounting, and spatial risk analysis.

Before the scenario-based modelling and ecosystem accounting analyses, a key component of the project consisted in the development of spatially explicit mathematical models describing the main biophysical attributes of *Posidonia oceanica* meadows in all the Italian seas. Through the application of machine learning techniques and the integration of field observations, literature data, and environmental predictors, spatially explicit estimates of shoot density and rhizome primary production were produced at national scale (UniRoma2). These modelling outputs provided the core ecological inputs for the subsequent analyses carried out within the project, supporting both the assessment of blue carbon dynamics under future environmental change scenarios and the implementation of ecosystem accounting and ecosystem service assessments.

In detail, a quantitative and spatially explicit assessment of blue carbon sequestration by *Posidonia oceanica* meadows along the Italian coasts was carried out, integrating ecological modelling, analysis of cumulative anthropogenic pressures, and economic valuation. Ecological modelling was aimed at estimating density and primary production of *Posidonia oceanica* meadows within their known boundaries. Estimates have been provided by neural networks trained on existing field data and on data collected by other projects, then validated on other existing field data. Through the application of the InVEST Coastal Blue Carbon model, supported by national data on meadow distribution and biophysical parameters related to above- and below-ground biomass and soil (matte), the CO₂ balance was estimated for the period 2025–2050 under three plausible future scenarios: Business-as-Usual (BAU), Sustainable (SS), and Non-Sustainable (NSS). The results indicated that under the BAU scenario, Italian *P. oceanica* meadows would lead to a cumulative emission of approximately 5 Mt CO₂e over the considered period, whereas under the NSS scenario emissions could increase up to about 40 Mt CO₂e. Conversely, the implementation of effective management and conservation measures (SS scenario) would result in a net sequestration of approximately 28 Mt CO₂e between 2025 and 2050. The analysis also highlighted marked regional variability, with the most significant impacts occurring in regions characterized by extensive meadow coverage, while local pressure intensity strongly influenced the overall carbon balance. Finally, changes in carbon stocks were translated into economic terms through the application of the Social Cost of Carbon, demonstrating that sustainable management of *Posidonia oceanica* meadows not only contributes to climate change mitigation but also generates significant socio-economic benefits. Overall, the project provides a robust scientific basis for integrating marine seagrass ecosystems into national climate neutrality strategies and coastal planning frameworks.

Complementary to the modelling and scenario-based assessment, the project also implemented the System of Environmental Economic Accounting-Ecosystem Accounting (SEEA-EA) framework to develop integrated ecosystem accounts for *Posidonia oceanica* meadows along the Italian coasts, with particular reference to their role as blue carbon

ecosystems. The analysis integrated ecosystem extent and condition indicators with the biophysical and economic evaluation of the carbon sequestration service, and further considered ecosystem exposure to anthropogenic pressures, the potential loss of ecosystem services, and the related restoration costs of the service.

Within this accounting framework, the asset extent account was derived from national habitat distribution data describing the spatial coverage of *Posidonia oceanica* meadows. Spatial distribution layers provided within the project by the partner University of Rome “Tor Vergata” (UniRoma2) were used to map the extent of *Posidonia oceanica* meadows along the Italian coasts. A national raster layer representing meadow distribution was subsequently produced and used as the spatial reference for the ecosystem accounting analyses. The asset condition account was assessed using spatial indicators of shoot density and rhizome primary production generated within the project through the machine-learning modelling component developed by the partner University of Rome “Tor Vergata” (UniRoma2). These raster layers were used as proxies of structural and functional ecosystem attributes and were combined into an aggregate index describing the ecological status and productive capacity of *Posidonia oceanica* meadows at regional scale.

The service account quantified carbon sequestration at the national scale by integrating the spatial extent of *Posidonia oceanica* meadows with estimates of rhizome primary production. Spatially explicit estimates of rhizome productivity, provided by the machine-learning model developed by UniRoma2, were used as the main ecological input. Rhizome productivity values were converted into carbon content assuming a fixed carbon fraction of seagrass dry biomass and subsequently expressed as CO₂ equivalents using the appropriate stoichiometric conversion factor. Pixel-level calculations produced a national raster map of carbon sequestration capacity. Results were expressed using both intensive metrics (per unit area) and extensive metrics (total sequestration), ensuring comparability across coastal regions and consistency at the national level. The resulting estimates indicated a total sequestration capacity of approximately 630,000 t CO₂ yr⁻¹ across Italian *Posidonia oceanica* meadows. These national estimates were subsequently disaggregated to quantify the relative contribution of different coastal regions to the overall carbon sequestration service.

The benefits account translated biophysical estimates into monetary values through two complementary valuation approaches: a market-based assessment based on carbon credit prices and a damage-based assessment based on the social cost of carbon. The carbon credit valuation, using a market-based carbon price (€67.28 t⁻¹ CO₂ [European Union Emissions Trading System]), reflected the potential exchange value of sequestered carbon in carbon markets and resulted in an estimated annual economic value of approximately 42 M€ yr⁻¹. The Social Cost of Carbon approach (€148 t⁻¹ CO₂; 2.5% discount rate [Dynamic Integrated Climate-Economy model]), resulted in an estimated avoided damage value associated with carbon removal of approximately 93 M€ yr⁻¹.

In the final phase of the project, a cumulative spatial risk assessment was carried out to evaluate the exposure of *Posidonia oceanica* meadows to anthropogenic pressures. Multiple spatial proxies were integrated, including proximity to commercial and recreational ports, river inputs representing potential sediment and nutrient sources, pollution sources derived from environmental monitoring datasets, and anchoring pressure proxy obtained from EMODnet Human Activities datasets. All pressure layers were rasterized, normalized, and combined into a cumulative risk index. This phase was essential for identifying spatial hotspots of elevated anthropogenic pressure and for assessing areas where the carbon sequestration service provided by *Posidonia oceanica* meadows may be most vulnerable. By overlaying the cumulative risk index with the condition map, areas characterized by high

pressure levels and low ecosystem condition were identified and used to estimate the potential ecosystem service loss. Subsequently, the potential loss was translated into economic terms by applying a replacement cost approach, estimating the investment required to compensate for the lost climate regulation service. Replacement costs were approximated using reforestation-based carbon offset interventions, representing the economic effort necessary to restore an equivalent amount of CO₂ sequestration capacity.

Overall, the project delivered an integrated system of ecosystem accounts and spatial indicators linking ecosystem extent and condition, service provision, economic valuation, and exposure to anthropogenic pressures across the Italian coastal zone, providing quantitative support for conservation planning and marine spatial management.

b) names of the operational units involved in the implementation of the project;

The operational units involved in the implementation of the project are listed below:

- University of Rome “Tor Vergata” (UniRoma2) – Department of Biology (Coordinating Unit);
- University of Tuscia (UniTuscia) – Department of Ecological and Biological Sciences, Laboratory of Experimental Oceanology and Marine Ecology;
- University of Naples “Parthenope” (UniParthenope) – Department of Science and Technology, Laboratory of Ecodynamics and Sustainable Development.

The three operational units worked in close scientific and methodological integration, contributing in a complementary manner to data collection, ecological modelling, blue carbon quantification, and the implementation of the ecosystem accounting framework.

c) description of the achievement of the objectives connected to the project and related outcomes;

The objectives of the project were achieved through the coordinated activities of the different research units, which contributed complementary methodological components ranging from ecological modelling and carbon balance assessment to ecosystem accounting, economic valuation, and spatial risk analysis.

The modelled attributes of *Posidonia oceanica* which are only indirectly related to carbon sequestration, as estimated shoot density or primary production, are of paramount importance to other ecological analyses and they were not available at the Italian national scale before this project.

The project achieved its objective of providing an integrated and spatially explicit assessment of the role of *Posidonia oceanica* meadows in the national carbon balance along the Italian coasts, with particular emphasis on their future dynamics and related climatic and economic implications. One of the main outcomes of the project was the development and application of three future scenarios up to 2050 (Business-as-Usual, Sustainable and Non-Sustainable) constructed on the basis of cumulative anthropogenic pressures. The analysis showed that under the BAU scenario, Italian *P. oceanica* meadows would result in a cumulative emission of approximately 5 Mt CO₂e over the period 2025–2050. Under the NSS scenario, characterized by increasing anthropogenic pressures, emissions could rise to about 40 Mt CO₂e, reflecting a substantial loss of sink capacity and the potential release of

previously stored carbon. Conversely, under the Sustainable scenario (SS), which assumes effective management measures and reduced pressures, a net sequestration of approximately 28 Mt CO_{2e} is projected over the same time frame. The spatially explicit analysis also highlighted marked regional heterogeneity, with the most significant impacts occurring in regions characterized by extensive meadow coverage (e.g., Sardinia and Sicily), although strongly modulated by local pressure intensity. Changes in carbon stocks associated with the different scenarios were further translated into economic terms through the application of the Social Cost of Carbon. The results indicate that non-sustainable trajectories would entail significant socio-economic losses, whereas sustainable management strategies would generate measurable economic benefits. Overall, the project provides robust quantitative evidence of the potential contribution of *Posidonia oceanica* meadows to climate change mitigation, demonstrating how management choices implemented in the coming decades may lead to substantial differences in the national CO₂ balance and associated socio-economic outcomes.

Complementary to the scenario-based modelling activities described above, additional project tasks focused on the implementation of an ecosystem accounting framework and the spatial assessment of ecosystem service provision and associated pressures.

The project activities were implemented in accordance with the approved work plan, ensuring coherence with the defined work packages and the achievement of both intermediate and long-term objectives. The intermediate goals related to data harmonization, spatial modelling outputs, and the development of ecosystem accounting components were successfully completed within the planned timeframe, enabling the implementation of the SEEA - Ecosystem Accounting (SEEA-EA) framework at national scale.

Within this framework, spatial predictions of *Posidonia oceanica* rhizome primary production generated within the project were integrated with habitat distribution data to quantify CO₂ sequestration along the Italian coastline. Carbon sequestration was estimated using both intensive (per unit area) and extensive (aggregated total) metrics, ensuring spatial comparability and consistency at national level. These results enabled the development of ecosystem service and benefits accounts, translating biophysical estimates into economic values through two complementary approaches: a market-based valuation based on carbon credit prices and a damage-based valuation based on the Social Cost of Carbon.

In line with the long-term objective of supporting conservation planning and climate mitigation strategies, a cumulative spatial risk assessment was conducted to evaluate the exposure of *Posidonia oceanica* meadows to anthropogenic pressures potentially affecting service provision. Multiple spatial proxies, including proximity to ports, river inputs, pollution sources, and anchoring pressure derived from vessel density indicators, were integrated into a composite risk index. The resulting analysis enabled the identification of spatial hotspots of elevated pressure and supported the estimation of potential ecosystem service losses. These losses were quantified both in biophysical terms, as reductions in carbon sequestration capacity, and in economic terms through the application of a replacement cost approach, estimating the investment required to restore an equivalent level of climate regulation service through reforestation-based carbon offset interventions.

Overall, the project produced harmonized geospatial datasets, ecosystem accounting tables, spatial risk indicators, and economic valuation results that support marine spatial planning and conservation prioritization at national scale.

- d) description of the carried out activities which are in compliance with the *DNSH*, *Open Access* principles as well as with *gender*, *generational* principles and with those of *Equal opportunities*

Project activities were carried out in full compliance with the DNSH (Do No Significant Harm) principle, ensuring that the methodologies adopted and the actions undertaken did not generate significant environmental impacts, either direct or indirect. In particular, the project was primarily based on ecological modelling, data analysis, and spatially explicit assessments, thereby with no direct environmental footprint of the research activities. While this project were planned to carry out field campaigns aimed at acquiring density and primary production data at a set of sampling stations, the opportunity to get data collected from other projects in the same time span allowed to avoid further sampling (which would have involved the collection of more shoots and rhizomes). This allowed to reduce to zero the impact of this project on the marine ecosystems under investigation. In line with the principles of Open Science and Open Access, the scientific results produced within the framework of the project will be submitted to peer-reviewed international open-access journals or made available through channels that ensure free and unrestricted access, in compliance with publishers' policies. Geospatial datasets, cartographic products, and modelling outputs were organized in interoperable formats and published on the dedicated project website (www.posidoniacarbon.it), which was developed using project funding. The project was also implemented in full adherence to the principles of gender equality, generational inclusion, and equal opportunities, ensuring an inclusive and non-discriminatory working environment.

- e) description of the actions aimed at informing and disseminating knowledge

Project results were presented in high-level international scientific contexts. In particular, key findings on future blue carbon sequestration scenarios were presented at the European Geosciences Union (EGU) General Assembly 2025 through a contribution entitled “Future Scenarios of Blue Carbon Sequestration in Italian *Posidonia oceanica* Meadows” (<https://meetingorganizer.copernicus.org/EGU25/EGU25-10978.html>). The presentation highlighted the methodological framework and main modelling outcomes to the international scientific community working in marine biogeochemistry, coastal ecology, and environmental modelling. Additional dissemination activities were carried out within the scientific outreach event “DEB Of Science,” organized by the Department of Ecological and Biological Sciences (DEB) of the University of Tuscia (<https://www.unitus.it/dipartimenti/deb/impatto-sociale-deb/eventi-e-incontri-deb/deb-of-science-i-edizione/>). The initiative aimed to present ongoing PRIN-funded research activities to teachers and high school students from the Viterbo area, illustrating the project's objectives, methodologies, and main environmental implications in order to promote knowledge transfer and awareness of climate change and marine natural capital. The final project results are currently being consolidated into a scientific manuscript intended for submission to an international peer-reviewed journal.

Additional dissemination activities are planned by UniParthenope. In particular, the study on the ecosystem accounting assessment of the carbon sequestration service provided by *Posidonia oceanica* meadows have been accepted for oral communication at the 6th prestigious international conference of the Ecosystem Services Partnership (ESP), one of the leading scientific forums dedicated to ecosystem services research and applications (<https://www.espconference.org/europe2026/>). The presentation will focus on the methodological framework based on the SEEA Ecosystem Accounting (SEEA-EA) system

and on the spatially explicit assessment of the carbon sequestration service, contributing to disseminating the project results within the international scientific community working on ecosystem services assessment, natural capital accounting, and sustainability science.

In addition, dissemination and knowledge transfer activities will be promoted at the local and regional level aimed at engaging policy makers, coastal managers, and other relevant stakeholders. These initiatives will focus on communicating the ecological importance of *Posidonia oceanica* ecosystems, their current status along the Italian coasts, and their contribution to human well-being through climate regulation and other ecosystem services. These activities will also raise awareness about the need for integrated management strategies capable of combining ecological conservation objectives with socio-economic considerations, supporting evidence-based decision-making for the sustainable management of coastal ecosystems.

The project findings will also be disseminated through scientific publications in Open Access high-impact international peer-reviewed journals (Q1), ensuring broad visibility within the scientific community.

Any relevant attached document which includes the abovementioned details

SECTION 2 – PROGRESS OF ACTIVITIES

With regard to the activities completed during the project's duration, it is below provided:

- a) detailed description of activities carried out by each operational unit with a focus on the timeframe for their implementation

The project relied primarily on spatial ecological descriptors of *Posidonia oceanica* meadows estimated by the machine learning modelling component developed by the University of Rome “Tor Vergata” (UniRoma2). On the basis of those results and other information, the Parthenope University of Naples (UniParthenope) and the University of Tuscia (UniTuscia) carried out other activities foreseen in the project proposal, focusing on carbon sequestration. While the first focused on the implementation of an integrated environmental-economic accounting framework for meadows along the Italian coastline, the latter focused on scenario-based modelling based on the analysis of cumulative anthropogenic pressures. The work followed the methodological structure defined in the proposal and integrated ecosystem accounting approaches, spatial ecological indicators, and geospatial analyses to support the assessment of carbon sequestration services.

WP1 – Data Collection by Desk Study

During the initial phase of the project (0-6 months), all the partners focused their preparatory activities on the review of the scientific literature, the identification of relevant datasets, and the conceptual development of the analytical framework supporting the subsequent ecosystem accounting and spatial analyses. A targeted literature review was conducted to consolidate current knowledge on carbon sequestration processes in seagrass ecosystems and to identify appropriate parameters and methodological approaches for the quantification of the carbon sequestration service provided by *Posidonia oceanica* meadows.

The predictive variables that were candidate to model *Posidonia oceanica* shoot density and rhizome primary production were selected to represent key environmental drivers, including geomorphology, hydrography, water column optics, and anthropogenic pressures.

The primary source for geomorphometric data was the EMODnet Digital Bathymetry (DTM 2024), which provides a 1/16 arc-minute resolution grid (EMODnet Bathymetry Consortium, 2024). From this foundational dataset, we directly extracted depth. Subsequently, a suite of terrain attributes was derived using the GDAL Raster Analysis tools within QGIS (QGIS Development Team, 2024). These attributes included slope, aspect, Terrain Ruggedness Index (TRI), Topographic Position Index (TPI), roughness, and hillshade. Geographic coordinates (latitude and longitude) were mapped onto the same EMODnet raster structure to ensure spatial coherence. The distance of the 200 m isobath from the shoreline was also calculated from the EMODnet bathymetry using GIS processing.

Oceanographic variables were incorporated to account for water column properties. The yearly average of phytoplankton primary production was obtained from a global model (Scardi, 2001), as referenced in the model intercomparison study by Carr et al. (2006). This dataset, originally at a ¼ arc-minute resolution, was interpolated and remapped onto the

EMODnet bathymetry grid. The diffuse attenuation coefficient was sourced from the Bio-ORACLE dataset (Tyberghein et al., 2011), which is based on satellite-derived ocean color data (Feldman and McClain, 2010), from which the euphotic depth was also derived.

To represent terrestrial inputs, several hydrological variables were computed. The number of river or stream mouths within a 1.5 nautical mile radius of each grid cell was determined through GIS analysis. The influence of freshwater input was further quantified by calculating a distance-weighted mean of riverine discharge for rivers with an average flow exceeding 10 m³/s, using publicly available data. The distance to the nearest river mouth was calculated based on data from ESRI (2012) and the Global Self-consistent, Hierarchical, High-resolution Shoreline (GSHHS) database (Wessel and Smith, 1996).

Finally, variables representing anthropogenic pressures were included. The distance to the nearest port was calculated using the World Port Index (NG-IA, 2011). A measure of cumulative human impact was incorporated using the global map of population pressure developed by Halpern et al. (2008).

Simultaneously, spatial datasets potentially relevant for the analyses were identified by UniParthenope and collected, including information related to anthropogenic pressures such as ports, river inputs, pollution sources, and maritime traffic indicators. These datasets were organized and harmonized in order to ensure their compatibility with the spatial analytical framework that would later integrate ecological modelling outputs with ecosystem accounting indicators.

A specific effort during this phase was devoted to the conceptual modelling of the analytical workflow linking ecological descriptors, ecosystem accounting components, and spatial risk indicators. In particular, the methodological structure for the implementation of the SEEA Ecosystem Accounting (SEEA-EA) framework was defined, identifying the relationships between ecosystem extent, ecosystem condition, carbon sequestration service provision, economic valuation, potential ecosystem services loss and the replacement cost of the service. All geospatial processing and analytical procedures were prepared using GRASS GIS 7.8, ensuring methodological consistency and reproducibility through standardized raster-based workflows that would support the subsequent integration of spatial ecological modelling outputs produced within the project.

During the initial phase of the project, UniTuscia significantly contributed to the collection, critical review, and harmonization of the datasets required for the implementation of carbon accounting modelling. In addition to systematizing parameters related to carbon stocks in above-ground and below-ground biomass, spatial data concerning the main anthropogenic disturbance sources considered in the study were collected and standardized. These included:

- coastal engineering works and port infrastructures;
- boat anchoring activities;
- aquaculture facilities;
- urban and industrial effluents;
- urbanization and agriculture within coastal watersheds;
- coastline erosion;
- coastal population density;
- artisanal fisheries.

For each pressure, spatial datasets were acquired from national and European institutional sources, subsequently normalized and harmonized onto a common grid in order to ensure the development of consistent and comparable thematic maps. In parallel, the biophysical parameters required to feed the InVEST Coastal Blue Carbon model were selected and standardized, including carbon content values ($\text{t CO}_2 \text{ ha}^{-1}$) and annual carbon accumulation rates.

WP2 – Sampling design, field and lab activities

Sampling activities on *Posidonia oceanica* meadows have been carried out at different sites, in 30 sampling stations, which have been selected among those collected from other projects carried out by UniRoma2 to fill the gaps in existing data sets or to support model validation. Selected sites included several locations along the coastline of the Calabria region as well as some locations of the Ischia Island.

Using data obtained from other projects at sites where additional information was needed allowed minimizing the impact of the inherently destructive sampling procedures to be carried out on *Posidonia oceanica* meadows (accordingly, no sampling or lab expenses have been accounted for by UniRoma2). This also allowed full compliance with the DNSH (Do No Significant Harm) principle, as no environmental impact was caused by this project.

WP3 – Assessment of Carbon Sequestration and Storage

UniRoma2 assessed the carbon sequestration based on spatially explicit estimated primary production of *Posidonia oceanica* meadows. Conversion from modelled rhizome production, which was validated against observed values obtained from lepidochronological analyses to overall production was carried out according to available literature. The latter was also used as the source for conversion coefficients from dry weight to carbon units and from overall production to long term sequestration. While carbon sequestration was estimated as the result of a series of conversions, it relied upon accurate estimates of rhizome production, which in turn were based on hundreds of field records. As direct measurements of carbon sequestration are very expensive and time consuming, only a handful of them are available and therefore large scale estimates can only be obtained by modelling. From this viewpoint, we deem our results as state of the art.

UniTuscia implemented the InVEST Coastal Blue Carbon model to quantify current carbon stocks and future carbon dynamics in Italian *Posidonia oceanica* meadows.

Within this framework, the following outputs were produced:

- spatial maps of individual anthropogenic disturbances, modelled through spatial decay functions representing impact intensity from each source;
- normalized pressure maps;
- a cumulative impact map, derived from the weighted integration of individual pressures according to habitat vulnerability.

The cumulative impact map constituted the basis for defining habitat state transitions (healthy *Posidonia*, degraded *Posidonia*, absence of *Posidonia*), which were fundamental for constructing the three prospective scenarios:

- Business-as-Usual (BAU);
- Sustainable (SS);
- Non-Sustainable (NSS).

By applying differentiated increases in cumulative impact values across scenarios, future meadow dynamics up to 2050 were simulated. Based on the scenario maps, changes in

carbon stocks and the net CO₂ balance over the period 2025–2050 were estimated, highlighting substantial differences among management trajectories.

WP4 – Ecosystem Accounting

Uniparthenope implemented the SEEA - EA framework for *Posidonia oceanica* meadows. In accordance with SEEA-EA principles, the analysis addressed the assessment of ecosystem extent and condition of *Posidonia oceanica*, and the biophysical and economic evaluation of ecosystem service of carbon sequestration. The framework also included the evaluation of the exposure of *Posidonia oceanica* to anthropogenic pressures and the assessment of potential service losses and related replacement costs. Within this accounting framework, the extent account was derived from national habitat distribution data describing the spatial coverage of *Posidonia oceanica* meadows. The condition account was assessed using spatial indicators of shoot density and rhizome primary production generated within the project through a machine-learning modelling component. These indicators were used to characterize the ecological status and productive capacity of the meadows at regional scale, through an aggregate index. The service account quantified carbon sequestration at the national scale by integrating meadow extent with spatial estimates of rhizome productivity. Results were expressed using both intensive metrics (per unit area) and extensive metrics (total sequestration), ensuring comparability across coastal regions and consistency at national level. The benefits account translated biophysical estimates into monetary values through two complementary valuation approaches: a market-based assessment based on carbon credit prices and a damage-based assessment based on the social cost of carbon. To evaluate pressures affecting ecosystem service provision, a cumulative spatial risk assessment was developed by integrating multiple anthropogenic proxies, including proximity to commercial and recreational ports, river inputs representing sediment and nutrient loads, spatially explicit pollution sources, and anchoring pressure inferred from vessel density indicators derived from maritime traffic data. The resulting risk maps enabled the identification of pressure hotspots and supported the definition of potential ecosystem service loss and the cost for the replacement of the services via reforestation.

UniTuscia developed the economic valuation component associated with changes in carbon stocks by applying the Social Cost of Carbon (SCC) to the biophysical outputs derived from the modelling scenarios.

Estimated emissions and sequestration were aggregated over five-year intervals and converted into monetary values, generating spatially explicit maps of net economic value. This activity enabled the quantification of social costs associated with non-sustainable scenarios and the economic benefits resulting from conservation-oriented management strategies.

WP5 – Modelling and GIS Mapping

UniRoma2 carried out machine learning modelling aimed at assessing *Posidonia oceanica* density and rhizome primary production at Italian national scale. The modelled domain was the entire extent of the Italian *Posidonia oceanica* meadows as mapped in EUSeaMap products. The spatial resolution was defined after the latest Emodnet bathymetric model, i.e. at 1/16 of minute in latitude and longitude, which is approximately as large as a football

pitch (Italian *Posidonia oceanica* meadows include more than 330000 1/16 minute spatial units).

A machine learning approach based on a Multi-Layer Perceptron (MLP) neural network was implemented to identify the most influential environmental predictors for *Posidonia oceanica* shoot density. The entire procedure, from model training to feature selection, was carried out using the PyTorch, scikit-learn, and SHAP libraries in Python.

The predictive model for shoot density was a feedforward Multi-Layer Perceptron (MLP) implemented using the PyTorch library. The network architecture consisted of an input layer with a size corresponding to the number of predictive features, two hidden layers with 64 and 32 neurons respectively, and a single neuron in the output layer for the regression task. The Rectified Linear Unit (ReLU) was used as the activation function for the hidden layers to introduce non-linearity.

Model training was performed using the Adam optimizer and the Mean Squared Error (MSE) as the loss function. To ensure the robustness and generalizability of the evaluation, a 5-fold cross-validation scheme was employed. For each fold, the data was partitioned into training and testing sets. The model was trained for 100 epochs on the training data, and its performance was subsequently evaluated on the held-out test set. The final reported loss for any given set of features was the average MSE across all five folds. The computations were performed on a CUDA-enabled GPU when available, otherwise defaulting to a CPU.

A recursive feature elimination (RFE) procedure was implemented to rank the predictors based on their contribution to the model's output. The process began by training an MLP model on the complete set of 18 initial environmental features. The importance of each feature was then quantified using SHapley Additive exPlanations (SHAP), a game-theoretic approach to explain the output of any machine learning model.

Specifically, the `shap.KernelExplainer` was used to compute the SHAP values for each feature's contribution to the model's predictions on a subset of the data. The feature with the lowest mean absolute SHAP value was considered the least important and was subsequently removed from the set of predictors. This iterative process—training a new model on the reduced feature set and removing the least important remaining feature—was repeated until only a single feature remained. This procedure provided a full ranking of the features based on their contribution to the prediction of *P. oceanica* shoot density, with the test loss (MSE) recorded at each step of the elimination.

The final model for shoot density was based on input data about: average river discharge, seafloor roughness, seafloor slope, seafloor Terrain Ruggedness Index (TRI), euphotic depth, distance from rivers, longitude, density of river mouths, distance from ports and depth (in inverted order of relevance).

The model for rhizome primary production was developed using the same procedure, but the two hidden layers had 38 and 19 neurons respectively, while the final architecture preserved only four inputs, namely average river discharge, phytoplankton production, depth and shoot density. While data sets for those input variables were available for neural network training and test, modelled shoot density was passed to the rhizome primary production model, using a cascaded approach that allowed to obtain spatially explicit estimates.

Estimated shoot density, rhizome primary production and carbon sequestration were provided as GeoTIFF GIS layers and are available at www.posidoniacarbon.it, where another GeoTIFF layer, obtained from a different model, based on a Random Forest, contains estimated habitat suitability for *Posidonia oceanica*.

UniParthenope also produced several GIS maps related to:

- *P. oceanica* ecosystem extent along the Italian coasts;
- *P. oceanica* ecosystem condition along the Italian coasts;
- Spatialized biophysical and monetary carbon sequestration capacity;
- Spatialized ecosystem services loss

UniTuscia was responsible for the production of GIS layers and raster maps related to:

- individual anthropogenic disturbances;
- cumulative impact;
- future distribution of meadows under the three scenarios;
- carbon sequestration and emissions;
- associated economic value.

These cartographic products ensured a high-resolution, spatially explicit representation of results, providing an operational tool for environmental planning and policy assessment.

WP6 – Dissemination

All partners contributed to the dissemination of project results through presentations in international scientific contexts, outreach initiatives, and knowledge transfer activities directed toward stakeholders and the broader scientific community.

The web site of the project is aimed at providing general information about the project and at distributing its products (GIS layers, documents, data sets, etc.). The results of the project will be also presented at forthcoming congresses and workshops, both national and international.

WP7 – Reporting

In the final phase of the project, all partners actively participated in technical and scientific reporting activities, contributing to the preparation of the final project report, the consolidation of modelling results, and the preparation of the documentation required for scientific accountability. Furthermore, the preparation of a scientific manuscripts for submission to an international peer-reviewed journal was initiated, with the aim of disseminating both the adopted methodology and the main project outcomes.

- b) description of potential changes to what has been originally approved mentioning the impacts on the aim of the intervention, on the achievement of long- term goals, on the proposed actions for improvement;

Overall, the activities carried out by the participating research units remained fully consistent with the objectives and methodological framework originally approved in the project proposal. Only minor adjustments were introduced during the implementation phase in order to optimize specific operational aspects without affecting the achievement of the planned scientific outcomes.

Project activities were carried out in accordance with what was originally approved, without substantial modifications to the scientific objectives, methodological framework, or expected outcomes.

As for UniRoma2, the only change in the planned activities was about field data collection, which was obtained from other ongoing projects. Accordingly, while dedicated resources had been allotted, no sampling or lab expenses have been accounted for by UniRoma2

With regard to the dissemination activities planned for the Reserch Unit of the University of Tuscia (UNITUS), the event initially envisaged as a national workshop was implemented as a local outreach initiative, primarily addressed to teachers and high school students in the surrounding area. This adjustment strengthened the educational and third-mission dimension of the project. This change had no impact on the project's objectives or on the achievement of its long-term goals, which have been fully attained. Scientific, modelling, and publication activities were conducted as planned, ensuring the overall consistency of the project with its original aims.

With regard to the activities carried out by the University of Naples "Parthenope" (UniParthenope), no substantial deviations from the originally approved scientific objectives occurred during the implementation of the project. The overall aims of assessing the ecosystem functioning of *Posidonia oceanica* meadows and supporting conservation-oriented spatial analyses were fully maintained throughout the project duration.

Minor methodological adaptations were introduced in order to optimize the integration between spatial modelling outputs and the ecosystem service assessment workflow. In particular, the downstream analyses were based directly on spatially predicted layers of shoot density and rhizome productivity produced by the modelling unit, rather than on independently derived ecological datasets. This adjustment ensured methodological consistency across project components and enabled the development of a coherent spatial workflow at national scale.

The use of model-derived ecological descriptors strengthened the linkage between habitat modelling outputs and ecosystem service assessment, reinforcing the analytical framework originally proposed. Rather than altering the project objectives, this methodological refinement improved the capacity to quantify carbon sequestration and to derive spatially explicit economic and risk indicators aligned with the project's long-term goals.

No changes affecting the achievement of the long-term scientific objectives were identified. On the contrary, the integration of modelling outputs within the ecosystem accounting analyses enhanced the scalability and transferability of the methodological framework, supporting its potential application in future national and Mediterranean-scale assessments.

No corrective actions were required during project implementation. The methodological refinements introduced represent improvements aimed at increasing analytical consistency and policy relevance, without modifying the core objectives or expected outcomes of the project.

c) description of potential challenges encountered and of the proposed actions for improvement;

During project implementation, several technical and scientific challenges were identified, mainly related to data availability and homogeneity, as well as to uncertainties inherent in predictive modelling. A primary limitation concerned the lack of uniform, high-resolution datasets at the national scale regarding the conservation status of *Posidonia oceanica* meadows and key biophysical parameters (shoot density, primary production, and soil carbon stocks). In some regional contexts, updated and spatially detailed data were limited, inevitably introducing uncertainty into spatially explicit estimates. Additional challenges were associated with the reconstruction and standardization of cumulative anthropogenic pressures. Spatial datasets derived from heterogeneous sources, characterized by different scales and formats, required substantial harmonization and normalization efforts. Moreover, defining habitat transition thresholds across future scenarios involved uncertainties linked to the complexity of ecological dynamics and the difficulty of fully representing non-linear

interactions among multiple pressures. Future projections to 2050 are necessarily based on assumptions regarding the evolution of anthropogenic pressures and the effectiveness of management measures. Although grounded in a robust methodological framework, such assumptions cannot fully capture all potential socio-economic and climatic drivers influencing coastal ecosystem trajectories. To address these limitations, several improvement actions are proposed: periodic updating of spatial datasets through the integration of high-resolution remote sensing and coastal observation systems (currently being implemented within the EU-funded PNRR Marine Ecosystem Restoration – MER – project); refinement of cumulative impact models through the incorporation of non-linear relationships and probabilistic approaches; and the development of dynamic scenarios integrating anthropogenic pressures with climate projections and socio-economic pathways. Despite these challenges, the results provide a robust quantitative assessment of the role of *Posidonia oceanica* meadows in the national CO₂ balance and of the implications associated with alternative management trajectories. The identified limitations do not compromise the overall validity of the methodological framework but represent priority areas for further research and model refinement.

Some methodological and operational challenges were encountered during the implementation of the project, primarily related to the integration of heterogeneous spatial datasets and the development of a consistent national-scale analytical framework. A first challenge concerned the harmonization of spatial datasets originating from different sources and resolutions. Predicted ecological layers, environmental pressure datasets, and ancillary geographic information required alignment within a common spatial grid to ensure analytical consistency. This issue was addressed through systematic pre-processing and raster harmonization procedures implemented within a reproducible GIS workflow. A second challenge involved the translation of model-derived ecological descriptors into ecosystem service indicators. The conversion of rhizome productivity into carbon sequestration estimates required the adoption of conversion factors (e.g., carbon fraction and stoichiometric coefficients) that inherently introduce uncertainty. To mitigate this limitation, conservative and literature-supported parameter values were adopted, ensuring methodological transparency. Future developments may incorporate uncertainty analyses and sensitivity testing to refine carbon sequestration estimates. Additional challenges were associated with the representation of anthropogenic pressures through spatial proxies. Certain pressures, such as anchoring activity or diffuse pollution inputs, cannot be directly measured at national scale and therefore required proxy indicators derived from vessel density datasets and environmental monitoring information. While these proxies provide a consistent approximation of pressure intensity, future improvements could include higher-resolution datasets or direct observational monitoring to increase accuracy. The integration of multiple economic valuation frameworks also required careful interpretation, as different approaches reflect distinct dimensions of ecosystem value (market-based, societal, and restoration-based). The adoption of complementary valuation methods was therefore considered an improvement rather than a limitation, allowing a multidimensional representation of ecosystem services. Overall, the challenges encountered did not affect the achievement of project objectives but instead contributed to refining the analytical workflow. The proposed improvements mainly concern future expansion toward uncertainty quantification, enhanced data standardization, and integration with long-term monitoring initiatives to further strengthen the robustness and policy applicability of the developed framework.

d) brief description of potential publications.

Machine learning modelling of *Posidonia oceanica* shoot density and rhizome

production, which are the basis for carbon sequestration estimates, are also of interest to a broader audience. Therefore, they are the subject of a manuscript in advanced preparation by UniRoma2.

Among the main outcomes of the project is the preparation by UNITUS of a scientific contribution intended for publication in an international peer-reviewed journal. The paper will focus on the spatially explicit assessment of blue carbon sequestration and storage in *Posidonia oceanica* meadows along the Italian coasts, with particular emphasis on the development of future scenarios up to 2050 (Business-as-Usual, Sustainable, and Non-Sustainable), the analysis of cumulative anthropogenic pressures, and the quantification of the associated biophysical and economic implications under different management trajectories. The publication will be addressed to the fields of marine ecology, ecosystem services, and environmental modelling, with the aim of disseminating both the adopted methodological framework and the main quantitative results, thereby contributing to the international scientific debate on the role of blue carbon ecosystems in climate change mitigation.

Other scientific contributions will be provided by UniParthenope. In particular, the results obtained within the project are currently being consolidated into two main scientific publications under preparation for submission to international peer-reviewed journals. The first publication focuses on the implementation of the SEEA Ecosystem Accounting (SEEA-EA) framework for the assessment of the carbon sequestration ecosystem service provided by *Posidonia oceanica* meadows at national scale. The study applies the SEEA-EA framework to link ecosystem extent and condition indicators with the assessment of carbon sequestration services and their associated economic value. Within this framework, the biophysical estimates of carbon sequestration by *Posidonia oceanica* meadows are translated into economic values through two complementary valuation approaches: (i) a market-based valuation based on carbon credit prices and (ii) a damage-based valuation based on the Social Cost of Carbon. The manuscript discusses the contribution of Mediterranean seagrass ecosystems to climate regulation and their role within standardized blue carbon ecosystem accounting frameworks. The second publication addresses the spatial assessment of ecosystem service risk, analysing the potential loss of carbon sequestration capacity associated with anthropogenic pressures affecting *Posidonia oceanica* meadows and the replacement costs of the service. By integrating cumulative pressure indicators derived from coastal infrastructure, riverine inputs, pollution sources, and anchoring activity proxies, the study identifies spatial hotspots where the carbon sequestration service provided by *Posidonia oceanica* is most exposed to human pressures. The analysis estimates the potential biophysical loss of the carbon sequestration service under pressure conditions and subsequently evaluates the economic cost required to restore the lost service through a replacement cost approach, approximated using reforestation-based carbon offset interventions. The work supports marine spatial planning and conservation prioritization through a risk-informed ecosystem service assessment. All scientific outputs resulting from the project will be disseminated in accordance with Open Access principles and relevant national and European research policies, ensuring broad accessibility of the results to the scientific community and to stakeholders involved in coastal management and climate mitigation strategies.

Any relevant attached document which includes the abovementioned details

SECTION 3 – COMMON INDICATORS

Below the updates on the indicator RRFCI 8 – “*Number of researchers who work in research centres which are recipients of financial support (women; men; non-binary)*” – as per the description in the guidelines included in the n.34 MEF notification from the 17th of October 2022.

Common indicators	Planned value	Implemented value
Researchers who work in research centers which are recipients of financial support (women)	2	2
Researchers who work in research centers which are recipients of financial support (men)	4	4
Researchers who work in research centers which are recipients of financial support (non-binary)	0	0

SECTION 4 – PREDICTIVE ANALYSIS AND FINAL COMMENTS

Below it is provided a description of the forecast scenario on the development of the project, any potential change which is deemed necessary for the future as well as comments on the document.

1) Predictive analysis

The forecast scenario for the further development of the project is based on the consolidation and updating of the modelling framework implemented, with particular emphasis on the integration of more recent and higher-resolution datasets concerning anthropogenic pressures and the conservation status of *Posidonia oceanica* meadows. Future developments are expected to include the incorporation of climate projections and socio-economic pathways in order to enhance the robustness and dynamic nature of the scenarios up to 2050. Any necessary adjustments will mainly concern the refinement of cumulative impact models and the periodic updating of biophysical parameters. No substantial modifications to the originally defined methodological framework are deemed necessary. Any future adjustments will be incremental and aimed at improving predictive accuracy and the operational transferability of the results.

The results achieved within the project provide a solid basis for future developments aimed at supporting the long-term conservation and management of *Posidonia oceanica* ecosystems. The spatial framework developed during the project can be extended to simulate potential changes in carbon sequestration capacity under different anthropogenic pressure scenarios, including increasing coastal urbanization, maritime traffic, and pollution inputs. Such analyses may enable the identification of areas where ecosystem services are more vulnerable and where conservation actions should be prioritized.

From a methodological perspective, further improvements may include uncertainty quantification associated with ecological predictions and carbon conversion parameters, as well as the integration of higher-resolution monitoring datasets to refine spatial indicators of anthropogenic pressures. The analytical workflow developed within the

project may also represents a baseline framework for the assessment of additional ecosystem services provided by *Posidonia oceanica* meadows, supporting more comprehensive ecosystem accounting and marine spatial planning applications.

2) Final comments

The Research Unit of the University of Rome Tor Vergata (UniRoma2) has provided estimates of shoot density and rhizome primary production in *Posidonia oceanica* meadows at the national scale, on which all further work has been based. These estimates, until now not available in a spatially explicit form, are also of interest to the scientific community, even beyond the topic of carbon sequestration.

The Research Unit of the University of Tuscia (UniTuscia) fully achieved its assigned objectives by developing a spatially explicit assessment of blue carbon sequestration in *Posidonia oceanica* meadows, based on prospective scenarios up to 2050 derived from the analysis of cumulative anthropogenic pressures. The results obtained, integrated with an economic valuation component, provide a robust and methodologically advanced quantitative framework, suitable for supporting sustainable management strategies and climate change mitigation policies.

The Research Unit of the University of Naples “Parthenope” (UniParthenope) successfully achieved the main project objectives by developing an integrated and spatially explicit framework for assessing the carbon sequestration ecosystem service provided by *Posidonia oceanica* meadows along the Italian coasts. The project combined ecological modelling outputs, ecosystem accounting approaches, economic valuation, and spatial risk assessment to generate a coherent set of indicators supporting conservation planning and ecosystem-based management.

The results provide a robust quantitative basis for understanding the role of *Posidonia oceanica* ecosystems in supporting ecosystem service provision and for identifying areas where anthropogenic pressures may threaten their functioning. The methodological framework developed during the project represents a transferable tool that can support future environmental assessments and the evaluation of additional ecosystem services within marine ecosystem accounting frameworks. These findings represent a scientifically grounded knowledge base that may support evidence-based decision-making in coastal management, conservation planning, and the integration of marine ecosystem services into environmental policy frameworks.

*Legal Representative
(digital signature)*

ATTACHMENTS

The below documents are also attached to the technical – scientific report:

Att. 2 – Declaration of compliance with DNSH principle and compliance with other principles as per the Environment code.