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Research Article

Keywords: biodiversity conservation, climate-smart reserves, northern Mediterranean, benthic habitats, soft bottoms, spatial prioritization

Posted Date: November 25th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11166417/v1

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Additional Declarations: No competing interests reported.

Protecting Vulnerable Marine Ecosystems in the Mediterranean: Systematic Conservation Planning Toward the 2030 Horizon

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Abstract

Protecting 30% of the ocean by 2030 (the "30x30" target of the Kunming-Montreal Global Biodiversity Framework), requires prioritizing conservation networks that maximize ecological benefits while minimizing socio-economic costs. The protection of Vulnerable Marine Ecosystems (VMEs) is particularly urgent on the Mediterranean seafloor, which is exposed to multiple human pressures, notably intense bottom trawling and accelerating climate change. This study applied Systematic Conservation Planning (SCP) to identify priority conservation areas for VMEs across the soft-bottom habitats of the northern Mediterranean under multiple management scenarios. Up-to-date spatial data on the current distribution and climate refugia of VMEs and biogeographic patterns of megabenthic invertebrate communities were integrated with information on human uses (e.g., bottom trawling activity, offshore wind farm projects, oil and gas infrastructures), in a spatial prioritization algorithm. Across scenarios, the continental shelves and upper slopes of the Gulf of Lion, the Catalan Sea, and the Strait of Sicily consistently emerged as priority areas for VMEs conservation. The slopes of the eastern Ligurian Sea, northern Ionian Sea, and southwestern Adriatic Sea emerged as areas of conservation interest, although their selection varied among scenarios. Substantial gaps were identified in the current networks of Fisheries Restricted Areas (FRAs) and Marine Protected Areas (MPAs), with 56% of the conservation priority areas identified in our study lacking these protection measures. This study provides a portfolio of conservation priority areas that can support stakeholder and policymaker discussions on Mediterranean basin-scale management plans for VMEs. It contributes to the development of more climate-smart, representative, and cost-effective conservation networks.

Key words: biodiversity conservation; climate-smart reserves; northern Mediterranean; benthic habitats; soft bottoms; spatial prioritization

Introduction

The continental shelves and slopes of the Mediterranean Sea host diverse topographic features including submarine canyons and seamounts, which sustain high local biodiversity (Bo et al., 2010;

Cartes et al., 2004; Fanelli et al., 2018; Rovere & Würtz, 2015). Within these environments, habitat-forming taxa such as cold-water corals, sea pens, and sponges enhance the structural complexity of otherwise predominately bare soft-bottom habitats, creating refugia for a wide range of associated fauna (Buhl-Mortensen et al., 2010; Chimienti et al., 2019b). These biogenic structures are thought to function as Essential Fish Habitats (EFHs), supporting commercially valuable species, including the European hake *Merluccius merluccius*, the two red shrimps *Aristeus antennatus* and *Aristaeomorpha foliacea*, and the Norway lobster *Nephrops norvegicus*, by providing feeding grounds, nursery, and spawning areas (Colloca et al., 2004; D'Onghia et al., 2012; Sardà et al., 2004).

The most intense bottom-trawling pressures in Europe occur on Mediterranean continental shelves (Amoroso et al., 2018; Eigaard et al., 2017; Hiddink et al., 2026; Korpinen et al., 2021), severely damaging megabenthic invertebrate communities, through seabed scraping and sediment resuspension (Buhl-Mortensen et al., 2016; Clark et al., 2016; Kaiser, 2019). Recognition of the vulnerability of such ecosystems to adverse impacts caused by bottom fishing contributed to the international framework for identifying and protecting Vulnerable Marine Ecosystems (VMEs) following United Nations General Assembly Resolution 61/105 (UNGA, 2006). Significant declines in VME indicator taxa have been recorded, including sea pens (e.g., *Funiculina quadrangularis*, *Pennatula rubra)*, crinoids *(e.g., Leptometra phalangium),* and deeper Cold-Water Corals (CWCs) (e.g., *Madrepora oculata*, *Desmophyllum pertusum,* and *Isidella elongata*) (Carbonara et al., 2022; González-Irusta et al., 2022; Pierdomenico et al., 2018). However, operational conservation and management at the Mediterranean scale remain limited. In addition, Mediterranean VMEs are exposed to other human-induced pressures, present and future oil and gas infrastructure (Mangano & Sarà, 2017; Wilson-Ormond et al., 2000), and the expansion of Offshore Wind Farms (OWFs) (Benjamins et al., 2014; Faraggiana et al., 2024; Soukissian et al., 2017). Although risk assessments are still developing, available studies highlight potential negative effects of these installations on benthic habitats (Lloret et al., 2022, 2025). Climate change adds a further, potentially interacting, pressure on Mediterranean marine ecosystems, and severely accelerates their degradation. Deep-water warming has been observed since

68 the mid-20th century (Bethoux et al., 1990; Lejeusne et al., 2010), alongside ocean acidification and
69 changes in stratification and water mass circulation (Danovaro, 2018; Jones et al., 2014; Sweetman et
70 al., 2017). Climate-driven habitat shifts and losses of VME indicator taxa have been predicted in
71 response to rising temperatures in the Mediterranean (Georges et al., 2024, 2026; Millot et al., 2024,
72 2026a) while ocean acidification may further affect the biocalcification of CWCs (Morato et al., 2020).

73 In this context, international and regional policies are essential to support ecosystem-based
74 management of demersal resources and the protection of benthic habitats. The Kunming–Montreal
75 Global Biodiversity Framework calls for the effective conservation and management of at least 30% of
76 terrestrial, inland-water, coastal and marine areas by 2030 ("30x30") (CBD, 2022), while EU Biodiversity
77 Strategy for 2030 calls for at least 30% of EU seas to be protected with one third of protected areas
78 (10% of EU seas) under strict protection (Directorate-General for Environment (EC), 2021). These
79 objectives remain far from being achieved in the Mediterranean, where less than 10% of the basin is
80 designated as MPAs, and only 0.03% is fully protected (Claudet et al., 2020; Gomei et al., 2019).
81 Mediterranean MPAs are predominantly coastal and generally focus on shallow species and habitats,
82 resulting in limited overlap with deeper VMEs. Fisheries Restricted Areas (FRAs) implemented by the
83 General Fisheries Commission for the Mediterranean (GFCM) also provide protection for some VMEs,
84 but their spatial coverage remains limited. Although trawling and dredging have long been prohibited
85 below 1,000 and a shallower 800 m restriction has been recommended (GFCM, 2024b), depth-based
86 measures alone do not protect the majority of VMEs occurring on shelves and upper slopes (Chimienti
87 et al., 2019; Georges et al., 2024, 2026; Millot et al., 2024, 2026a) . Moreover, current protected area
88 networks may lack resilience under changing climatic conditions (Kyprioti et al., 2021). The EU Nature
89 Restoration Regulation (EU, 2024) provides an additional regulatory framework by requiring Member
90 States to develop National Restoration Plans in 2026 that will assess extent, status, and priorities for
91 restoration of degraded habitat types, including Mediterranean deep-sea coral habitats that
92 characterize VMEs. The Regulation has precise incremental targets for filling in knowledge gaps (extent
93 and status) and habitat improvement/restoration over the next 25 years. Restoration measures may

include passive approaches and could include area protective measures such as MPAs and FRAs. Therefore, a scientifically informed and climate-aware network of spatial protection measures is needed to safeguard Mediterranean VMEs from the combined effects of bottom trawling and climate change.

Reconciling marine biodiversity conservation with sustainable economic activities requires explicit identification of tradeoffs and priorities. Systematic Conservation Planning (SCP), is a useful decision-support tool for identifying priority networks of conservation areas (Giakoumi et al., 2025; Harris et al., 2019; Holness et al., 2022; Knight et al., 2010; Pressey & Bottrill, 2009; Zaucha & Gee, 2019). SCP uses prioritization algorithms to select sets of areas that meet quantitative conservation goals while minimizing socio-economic costs (Margules & Pressey, 2000). Originally developed for terrestrial reserve design (Balmford, 2003; Christodoulou et al., 2021; Cowling et al., 2003; Rodrigues et al., 2004), SCP has been increasingly applied in marine environments (Álvarez-Romero et al., 2018; Boussarie et al., 2023; Combes et al., 2021; Delavenne et al., 2012; Giakoumi et al., 2013; Lombard et al., 2007; Metcalfe et al., 2013, 2015). SCP can be used to design protected area networks that satisfy several key principles including; the representativeness of the full range of biodiversity, prioritizing threatened and vulnerable features, promoting the long-term persistence of biodiversity, maintaining ecological connectivity, complementing existing protection, minimizing conflict or opportunity costs associated with human activities, and providing alternative spatial solutions for stakeholder engagement and decision-making (Giakoumi et al., 2025; Kukkala & Moilanen, 2013). More recently, incorporating climate change into SCP has become a key recommendation for identifying climate-resilient areas and improving the long-term effectiveness of conservation networks (Arafeh-Dalmau et al., 2023; Buenafe et al., 2023; Carter et al., 2020; Keppel et al., 2015; Levin et al., 2020; Magris et al., 2014; O'Regan et al., 2021). Advances in Habitat Suitability models now allow projected distributional responses to future climate conditions to inform the identification of areas where suitable environmental conditions are expected to persist (Anderson et al., 2022; Araújo et al., 2011; Combes et al., 2021; Pacifici et al., 2015).

SCP exercises have been conducted in the Mediterranean, either at the regional scales (Maiorano et al., 2009), with a focus on coastal habitats (Giakoumi et al., 2013), or by extending approaches developed at broader ocean-basin scales (Combes et al., 2021). Several conceptual frameworks and criteria have also been proposed to prioritize the conservation of Mediterranean vulnerable habitats (Abdulla et al., 2009; de Juan & Lleonart, 2010; Fanelli et al., 2021; Manea et al., 2020; Micheli et al., 2013). However, spatially explicit assessments aimed specifically at protecting VMEs across the Mediterranean have been constrained by incomplete knowledge of their distribution and biogeographic patterns and by uneven information on human uses and associated socio-economic costs (Combes et al., 2021; Manea et al., 2020; Wright et al., 2021).

This study develops the first basin-scale systematic conservation planning approach for VMEs in the northern Mediterranean Sea by integrating novel spatially explicit data on the distribution, sensitivity and composition of megabenthic communities. Priority conservation networks were designed to be: (1) representative, by capturing the diversity of megabenthic assemblages using biogeographical surrogates (Millot et al., 2026b); (2) targeted, by prioritizing hotspots of the most sensitive megabenthic taxa to bottom trawling, including VME indicator species (Millot et al., 2026c); (3) climate-smart, by prioritizing areas predicted to act as climate refugia for VME indicator species under future climate scenarios (Georges et al., 2024, 2026; Millot et al., 2024, 2026a) and (4) complementary to existing MPAs and FRAs and (5) cost-aware, by accounting for selected human uses and infrastructure. Multiple scenarios varying in conservation targets, representation requirements, costs and constraints were tested to provide a set of alternative conservation solutions. This flexible and transparent framework is intended to support discussion with a wide range of stakeholders on priority areas for VMEs conservation at the Mediterranean scale, while recognizing that basin-scale priorities require further refinement and participatory evaluation at national and local scales before implementation.

Materials and Methods

Systematic Conservation Planning framework

The SCP exercise followed six steps, summarized in **Figure 1** to address a set of conservation scenarios. Spatial prioritization was performed using an exact integer linear programming (ILP) algorithm implemented in the open source *Prioritizr R* package (Hanson et al., 2025) in R version 4.5.0. *Prioritizr* addresses conservation-planning problems comparable to those tacked by widely used tools Marxan and Zonation (Ball et al., 2009; Moilanen et al., 2009). Unlike heuristic approaches, ILP can identify mathematically optimal solutions for a specified objective and set of constraints, subject to the solver settings and optimality gap used (Rodrigues & Gaston, 2002).

Planning region and planning units

The planning region covered the continental shelves and upper slopes of the northern Mediterranean Basin **(Figure 2)** from 10 to 1,000m depth encompassing fishing grounds intensively exploited by bottom trawling. Southern and eastern sectors were excluded due to the lack of accurate spatial data on the distribution of benthic communities and VMEs. The planning region was divided into a grid of 5 × 5 km cells, each representing a Planning Unit (PU). PUs intersecting terrestrial areas or falling outside the selected bathymetric range were excluded, resulting in 24,114 PUs covering approximately 602,850 km².

Conservation features

Six types of spatially explicit conservation features were integrated **(Table 1)**. Four were biological components: (1) biomass hotspots of sensitive taxa to bottom trawling, (2) a sensitivity index of benthic communities, (3) present-day habitat suitability for six VME indicator species (e.g., the pennatulids *Funiculina quadrangularis, Pennatula phosphorea, Pennatula rubra, Pteroides griseum,* the coral *Isidella elongata* and the crinoid *Leptometra phalangium)*, and (4) potential future climate refugia for these species. Habitat components were represented by (5) geomorphological indicators of VMEs (submarine canyons and seamounts). Finally, (6) bioregions of megabenthic communities were

included as additional conservation features in specific scenarios. The associated spatial layers were obtained from multiple sources summarized in **Table 1**, with details of layer construction and data sources provided in **Supplementary Material SM1**. These up-to-date spatial layers were mainly derived from benthic observations collected through the MEDiterranean International Trawl Survey (MEDITS), an annual bottom trawl survey conducted by EU Mediterranean countries (Spedicato et al., 2019). All raster layers were projected using an Albers Equal Area projection, centered on the Mediterranean, to ensure consistent area representation and reduce spatial distortion in area-based analyses.

Setting conservation targets and scenarios

Quantitative conservation targets were set for each conservation feature and expressed as a percentage of its distribution within the planning region. They represent the minimum proportion of each feature distribution to be included in the conservation solution. Depending on the conservation scenario, targets were either set uniformly across features at 10%, 30% or weighted to reflect relative conservation priority, according to predefined decision rules. In the weighted approach, a baseline target of 10% was assigned to biological features and 60% to habitat features. The higher baseline for habitat features reflected the small number of geomorphological elements considered (submarine canyons and seamounts) and the intention to ensure their strong representation in the solutions. Feature-specific targets were then adjusted using the criteria in **Table 2**: + 10–20% based on taxon sensitivity to bottom trawling (as defined in Millot et al., 2026c), + 10% for climate-refugia features, + 10% for features with limited spatial extent (<10% of the total planning region), and - 10% for features with broad spatial extent (>50% of the total planning region). Targets for bioregions were set at 10%. These features were included to ensure a balanced spatial representation of the main megabenthic invertebrate assemblages rather than to express differences in conservation priority.

Costs and constraints

To test alternative conservation scenarios, five spatial cost layers were developed: (1) a constant area-based cost, and varying cost layers accounting for (2) existing conservation areas, (3) bottom-trawling activity, (4) OWF plans and, (5) the combined effects of existing conservation measures and human uses. In addition, (6) a constraint layer representing oil and gas installations and constructed wind farms was used to "lock out" the corresponding PUs (i.e., exclude them from the selection).

Area-based cost layer

An Area-based cost layer was obtained by assigning to each PU a constant cost equal to 1 (P) **(Figure 2)**. For scenarios based on this layer, the cost of the conservation solution corresponds to the number of selected PUs, which is equivalent to the total area of the solution. As such, solutions with a smaller extent are favoured.

Existing conservation areas

Existing conservation areas are often locked into SCP solutions to ensure complementarity with current conservation networks. As these measures provide heterogeneous and generally incomplete VME protection, they were not locked-in but their cost was reduced. The distribution of existing conservation areas was extracted from the MAPAMED database (https://www.mapamed.org/) and complemented with additional data from GFCM or national regulations, among which three levels of potential protection for VMEs were distinguished. The highest level was assigned to GFCM FRAs targeting VMEs, the permanent fishing closures in the Gulf of Lion, and the GFCM recommendation for an 800 m depth trawling ban (GFCM, 2024b). The second level included FRAs targeting EFHs and seasonal fishing closures in the Gulf of Lion. The lowest level was attributed to marine Natura 2000 sites designated under the EU Habitats Directive (EU, 1992) and national MPAs. The wide "Cetacean Migration Corridor" and Natura 2000 sites designated under instruments not specifically targeting benthic habitats (i.e., EU Birds and Marine Mammals Directives), were excluded. Other MPAs may also not specifically protect benthic communities, but no further filtering was applied, because information

on management objectives was incomplete and their spatial extent was generally small. Ecologically or Biologically Significant Areas (EBSAs), which are only indicative areas and not subject to fishing regulations, were not included. Each PU overlapping a conservation area by at least 50% was assigned a protection score of 1 (low), 2 (moderate), or 3 (high); when several measures overlapped, the maximum score was retained. The resulting raster layer (C) was rescaled between 0 and 0.8, and the conservation cost layer (C-cost) was calculated so that PUs associated with higher existing protection has lower costs **(eq. 1)**. The rescaling was performed between 0 and 0.8 rather than between 0 and 1 to prevent PUs with the highest level of existing protection from becoming cost-free to select.

C-cost = P* (1-C) **(eq. 1)**

With P, the PU raster layer; C, the conservation area layer.

Bottom trawling activities

Due to the lack of data on the economic or social value of fisheries in the Mediterranean, fishing activity was used as a proxy for potential fisheries-related opportunity cost in this SCP exercise. Bottom-trawling activity was recently re-estimated across the Mediterranean basin by Global Fishing Watch (https://globalfishingwatch.org/) using satellite-based Synthetic Aperture Radar (SAR) imagery (Marsaglia et al., 2024). SAR vessel detections from 2017 to 2021 were matched with AIS data when available to be converted into bottom-trawling hours and the relationship was then extrapolated across the basin using a modelling approach (Marsaglia et al., 2024). The resulting raster layer (T) was rescaled between 0 and 0.8 (consistently with the rescaling applied to the conservation layer), and used to calculate a bottom-trawling cost layer (T-cost) was calculated **(eq. 2)**.

T-cost = P * (1+T) **(eq. 2)**

With P, the PU raster layer; T, the bottom-trawling activity layer.

Offshore wind farm plans

Considering that OWF plans may be incompatible with the designation of conservation areas, we limited their selection by increasing their cost. Boundaries of four OWF proposals in French waters (AO06, AO10, and OWF projects for 2030 and 2050) were extracted from www.geolittoral.developpement-durable.gouv.fr, and OWF proposals in Spanish waters were obtained from EMODnet (EMODnet Human Activities, Energy, Wind Farms). The localisation of OWF proposals in Italian waters was not considered because it was not publicly available at the time of the study. Since these installations are planned and not yet constructed, the cost of PUs covered by at least 50% of an OWF project was doubled (equal to 2), but not locked out. The resulting raster layer (OWF) was used to calculate the OWF cost (OWF-cost) **(eq. 3)**.

OWF-cost = P * (1 + OWF) **(eq. 3)**

With P, the PU raster layer; OWF, the OWF installations layer.

Combined cost layer

A global cost layer (G-cost) was calculated by accounting for existing conservation areas (C), bottom-trawling activity (T), and OWF installations (OWF). The cost of PUs was decreased by the presence of existing conservation areas to favour their selection, and increased by anthropogenic activities to penalize the selection of economically important grounds **(eq. 4)**.

G-cost = P * (1 – C + T + OWF) **(eq. 4)**

With P, the PU raster layer; C, the conservation areas layer; T, the bottom-trawling activity layer; and OWF, the OWF installations layer.

Energy production infrastructure

The locations of oil and gas installations, including offshore platforms and boreholes, were extracted from EMODnet (products “EMODnet Human Activities, Oil and Gas, Wells”, “EMODnet Human Activities, Oil and Gas, Offshore Installations”), together with pilot wind turbines already

constructed in the Gulf of Lion (product "EMODnet Human Activities, Energy, Wind Farms"). PUs containing at least one of these installations were locked out of scenarios that included the energy-infrastructure constraints.

Boundary penalty

A "boundary penalty" parameter was fixed to discourage the spatial fragmentation of conservation solutions. This factor is equivalent to the boundary length modifier (BLM) used in Marxan (Ball et al., 2009) which penalize solutions that are excessively fragmented by favoring the spatial aggregation of PUs. Preliminary analyses were performed by assessing the cost of conservation solutions associated with varying boundary penalties values ranging from 0.00001 to 0.01 (encompassing the 0.0001 value used in Combes et al., 2021). The boundary penalty was then fixed at a value that provided a trade-off between spatial connectivity of the conservation network and cost-efficiency.

Setting and implementation of conservation scenarios

A total of 10 conservation scenarios were developed to explore how alternative conservation targets, biodiversity representation objectives, existing conservation areas, human-use costs and constraints influence the prioritization of areas for conservation. All scenarios were implemented using the PrioritizR package (Hanson et al., 2025). Calculations were performed on the MARBEC-GPU High-Performance Computing (HPC) server and parallelized to reduce computation time. Scenarios varied by conservation features, targets, costs, and constraints. The attributes of three "base scenarios", three "bioregional scenarios", and three "management scenarios" were summarized in **Table 3**.

The prioritization software Gurobi (Gurobi Optimization, LLC, 2024) was selected to solve the conservation problems because of its high performance (Hanson et al., 2025). The objective function *prioritizeR::Add_min_set_objectif* was used to identify solutions that met all conservation targets and constraints, and minimize total cost. Solutions were generated with an optimality gap set to 0.1, which defines the acceptable deviation from the true optimal solution. This means the solver could stop when

it found a near-optimal solution within 10% of optimality. This approach allows for the generation of contrasting solutions that are slightly less cost-efficient than the optimal one, yet still meet a large proportion of the conservation targets. A portfolio of 100 solutions was generated for each scenario, and the 30 lowest-cost solutions were retained to calculate PUs selection frequency (i.e., the number of times a PU is selected within each set of solutions) over the planning region. This can be interpreted as a measure of the irreplaceability of each PU to meet the optimal conservation solution.

While the cost of the solutions under the "base" and "bioregional" scenarios was equal to the number of selected PUs, the cost of the solutions under the "management" and "global" scenarios was weighted by the presence of conservation areas and human uses. Because these scenarios used different cost surfaces, their raw objective values are not directly comparable. To ensure comparison, the cost of each solution was expressed as a percentage of the total cost summed over all PUs of the planning region. The total cost therefore varied according to the cost layer used in each scenario (i.e, the number of PUs in the whole planning region for S1 to S6, the conservation cost layer for S7, the bottom-trawling cost layer for S8, the OWF cost layer for S9 and the global cost layer for S10).

Post-hoc analyses: Complementarity of the conservation priority network and existing protected areas

To assess the complementarity between the conservation priorities identified in this study and existing protected areas, a priority conservation network was delineated from the "global management" scenario by retaining only PUs with a selection frequency ≥ 80%. This arbitrary threshold was used to define highly recurrent PUs. The percentage overlap between this high-frequency priority network and each of the three protection levels described under "Costs and constraints - Existing conservation areas", was then calculated. Particular attention was given to the Gulf of Lion and the Strait of Sicily where existing conservation measures are concentrated.

Results

Boundary penalty calibration and target settings

An optimal trade-off between cost efficiency and the fragmentation of conservation solutions was achieved with a boundary penalty parameter of 0.0001 for all scenarios **(Figure SM2.1)**. This value was fixed to solve the 10 scenarios. Higher boundary penalties substantially increased costs and produced overly clustered networks, whereas lower values resulted in too fragmented networks **(Figures SM2.2, SM2.3 and SM2.4)**.

Weighted conservation targets ranged from 10% to 70% across conservation features **(Table SM3.1)**. The highest targets were assigned to canyons and seamounts (60% and 70%, respectively) to favour their selection given the small number of geomorphological features considered and the limited spatial extent of seamounts. Climate refugia features were set at 50% for *L. phalangium* and 40% for the five other VME indicator taxa. The present-day distribution features of VME indicator taxa were assigned a conservation target of 30%. Targets for the biomass of taxa sensitive to bottom trawling ranged from 20% to 40%, increasing with both spatial extent and degree of sensitivity. The baseline target of 10% was maintained for the benthic community sensitivity index feature **(Table SM3.1)**, as well as for the sixteen bioregions as they were not concerned by the decision rules.

Cost layers spatial patterns

When accounting for existing conservation areas across the basin, the majority of PUs with the lowest cost were located below 800 m depth, corresponding to the actual recommendation from the GFCM for a bottom-trawling ban. In the Gulf of Lion (French waters), the cost of almost all PUs was reduced due to the presence of several seasonal and permanent fishing closures **(Figure SM2.5A)**. PUs with high costs related to bottom-trawling activity were mainly found in the Catalan Sea, northern Adriatic, and northern Aegean Sea **(Figure SM2.5B)**. While PUs in the Gulf of Lion and the northern Alboran Sea were associated with medium costs in terms of bottom-trawling activity, their cost values were increased by the overlap with OWF plans, as well as in the northern Alboran Sea **(Figure SM2.5C)**.

The global cost layer was very similar to the bottom-trawling cost layer, as it covered the entire Mediterranean basin, whereas the influence of existing conservation areas and OWFs was very localized. Nevertheless, the Gulf of Lion exhibited the most contrasting cost patterns, with PU costs increased by OWF plans but reduced in surrounding areas due to fishing closures **(Figure SM2.6A)**. Finally, constrained PUs (i.e., selection locked out) were mainly located in the northern Adriatic, where most oil and gas infrastructures are found, and sporadically in the Strait of Sicily and Ionian Sea. Some PUs in the Gulf of Lion were also constrained due to the presence of pilot OWFs **(Figure SM2.6B)**.

Costs of conservation solutions

Overall, the number of selected PUs and cost variability among the 30 lowest-cost solutions within each scenario was low **(Figures 3A and B)**. The number of selected PUs remained relatively consistent across most scenarios, generally ranging from 6,000 to 7,000. The main exceptions were the solutions under the 10% target-based scenarios (S1 and S4), where fewer or around 2,000 PUs were selected **(Figure 3A)**. Relative solutions cost (expressed as a percentage of the total value of the corresponding cost layer across the planning region) varied considerably among scenarios, from less than 10% in S1 and S4 to 30-32% in S8 and S10. Under the “base” (S1, S2, S3) and “bioregional” (S4, S5, S6) scenarios, cost was generally proportional to the number of selected PUs **(Figures 3A and B)**. Under the “management” scenarios (S7, S8, S9, S10), the number of selected PUs remained broadly similar, but relative costs differed. The scenario penalizing trawling overlap (S8) and the “global management” scenario (S10) presented solutions with the highest costs (30-32%), whereas solutions under scenarios facilitating the selection of existing conservation areas (S7) and accounting for energy production areas (S9) had slightly lower costs (24-26%) **(Figure 3B)**.

Conservation priorities among scenarios

Only maps of selection frequency for each scenario are presented, while the PUs' selection of the best solution (i.e., the most cost-efficient) for each scenario is shown in supplementary material, **Figure**

SM2.7. The percentages of conservation targets achieved for each feature by the best solutions were detailed in **Table SM3.2**. Spatial overlaps among broad feature categories (e.g., biomass of sensitive taxa and climate refugia) are shown in **Figure SM2.8** to help identify the features associated with recurrent PU selection.

Base scenarios

Our results show that PUs located in the western Gulf of Lion and the western Strait of Sicily were highly selected across the solutions, indicating their irreplaceability for achieving the 10% conservation target of all conservation features **(Figure 4A)**. Surrounding PUs in these two regions, as well as in the Catalan Sea, were also frequently selected, but with greater flexibility among solutions. To achieve the 30% target, PU selection became more spatially constrained across the entire Gulf of Lion, the Catalan Sea, and the Strait of Sicily **(Figure 4B)**, meaning that a greater number of PUs are irreplaceable. Under priority-weighted targets, the most frequently selected PUs were located on the continental shelf and upper slope of the Gulf of Lion, as well as in the northern Catalan Sea and the Ligurian Sea off the Italian coast **(Figure 4C)**. The selection of PUs in the Adriatic Sea and the Aegean Sea was more flexible across the SCP solutions. Some PUs from these regions were selected **(Figure SM2.7)**, but in different combinations across solutions, explaining their low selection frequency.

Bioregional scenarios

The inclusion of bioregions as additional conservation features maintained a frequent selection of PUs in the Gulf of Lion and the Strait of Sicily, while increasing selection frequency in the Ligurian, Adriatic, and Aegean Seas **(Figure 5)**. Under the 10% target-based scenario, selection of these regions was concentrated in relatively small areas **(Figure 5A)**. When the conservation target increased to 30%, PU selection became more flexible across the basin, although distinct areas of consistently high selection frequency remained within each region **(Figure 5B)**. Under the priority-weighted scenario, selection frequency remained highest in the western basin, particularly in the Gulf of Lion and the

382 northern Catalan Sea, compared to the rest of the Mediterranean basin, despite a conservation target
383 of 10% met for all bioregions **(Figure 5C)**.

384 Management scenarios

385 The three "management scenarios" differed from S6 by incorporating more complex cost layers,
386 accounting for existing conservation areas **(Figure 6A)**, bottom-trawling activity **(Figure 6B)**, and energy
387 production infrastructures **(Figure 6C)**. PUs associated with a high score of irreplaceability were
388 concentrated in the Gulf of Lion and the northern Catalan Sea, consistent with the S6 scenario. PU
389 selection frequency increased in the central Gulf of Lion, when existing conservation areas were
390 favoured, particularly within large seasonal fishing closures **(Figure 6A)**. Penalizing heavily trawled
391 areas had relatively little effect on prioritization outputs, as the highest estimated bottom-trawling
392 activity occurred in the northern Adriatic and northern Aegean Seas, where selection frequency was
393 already low, indicating flexible solutions **(Figure 6B)**. Selection frequency increased locally in the south-
394 western grounds of the Strait of Sicily. Finally, accounting for the cost associated with OWF plans
395 reduced PUs selection frequency locally in the central Gulf of Lion. By contrast, excluding areas with oil
396 and gas infrastructure, particularly in the Adriatic Sea, had a negligible impact on the outputs due to
397 the limited spatial extent of these areas **(Figure 6C)**.

398 The "global management scenario" did not differ substantially from the single-factor management
399 scenarios. The highest PU selection frequencies were observed on the continental shelf and especially
400 along the shelf-break of the Gulf of Lion, as well as in the central Catalan Sea and on the continental
401 shelves of the Strait of Sicily. PU selection was also strongly constrained on the slopes of the eastern
402 Ligurian Sea, northern Ionian Sea, and southwestern Adriatic Sea **(Figure 7)**. Overall, PU irreplaceability
403 was higher in the western and central Mediterranean, while selection was more variable across
404 solutions in the Adriatic and Aegean Seas. Central Adriatic and central Aegean Seas were the least
405 selected areas. In the Gulf of Lion, the increased cost of OWF plans was offset by the reduced cost

associated with existing seasonal and permanent fishing closures, resulting in maintained PU selection in this region **(Figure 7)**.

Complementarity of the conservation priority network and existing protected areas

The priority network comprising highly selected PUs (selection frequency ≥ 80%) under the "global management scenario" largely complemented the existing protection network, with 56% of the selected areas not covered by any the protection measures considered here. The network nonetheless accounts for existing protected areas, with 25% of its surface overlapping high protection zones, 8% overlapping moderate protection zones, and 12% overlapping low protection zones **(Figure 8)**.

Discussion

This study provides one of the first SCP applications specifically designed to guide the conservation of VMEs across the northern Mediterranean, and accounting for human-uses pressure and climate change. This study overcomes the former limitations in spatial data by using the latest predictions of distribution for sensitive and VME-indicator taxa, as well as projections of their potential future climate refugia (Georges et al., 2024, 2026; Millot et al., 2024, 2026a). The proposed network of priority conservation areas provides a valuable basis for decision-making aimed at fulfilling European and international conservation commitments by 2030.

Flexible, representative and climate-smart conservation solutions

The objective of the study was not to identify a single optimal solution, but rather to propose a flexible set of alternative networks, supporting stakeholder discussion and reveal areas repeatedly required to meet conservation targets (Giakoumi et al., 2025; Kukkala & Moilanen, 2013). This study integrated two levels of flexibility: first, through scenarios varying in conservation targets, bioregional representativity, and complexity of human-use cost layers; and second, through portfolios of alternative solutions to identify irreplaceable areas required to meet conservation targets.

In addition, a key contribution of this study is the explicit inclusion of bioregional patterns in megabenthic community distributions. Beyond ensuring adequate representation of biological diversity (Howell, 2010; O'Brien et al., 2022; Rice et al., 2011), these scenarios also promote an equitable distribution of priority areas across the Mediterranean seas and consequently among Mediterranean countries. This is particularly relevant in a complex geopolitical context, where biodiversity conservation depends on shared responsibility among states (Sala et al., 2021). Nevertheless, high conservation priorities (with highly irreplaceable areas) were predominantly concentrated in the western basin. This pattern may partly reflect differences in data availability between the western and eastern Mediterranean, with lower species occurrence data in the eastern basin potentially limiting the identification and prediction of VME areas. The concentration of predicted climate refugia in the western basin may also have contributed to this pattern. Replicating conservation targets for each feature within bioregions, rather than treating bioregions as independent features, could be explored in future analyses to strengthen representativeness (Combes et al., 2021; Giakoumi et al., 2013).

A further key strength was the inclusion of climate refugia predictions for six VME indicator species across the northern Mediterranean under the IPCC SSP2-4.5 climate scenario for 2050. These input constrained the identification of priority conservation areas in the Gulf of Lion, the Catalan Sea, and the Strait of Sicily, where the most extensive climate refugia were predicted (Georges et al., 2024; Millot et al., 2024, 2026a). While Species Distribution Model (SDM) projections are highly informative, integrating the specific response of a wide range of species to climate change can be time-consuming. A more integrative approach for incorporating climate change into future SCP frameworks could involve identifying areas of environmental stability using key environmental drivers of megabenthic community distribution, such as temperature, dissolved oxygen concentration, and pH (Buenafe et al., 2023; Wilson et al., 2020).

Priority areas of conservation for Vulnerable Marine Ecosystems

Under all scenarios, the continental shelves and upper slopes of the Gulf of Lion, the Catalan Sea and the Strait of Sicily consistently ranked among the highest-priority areas for VME conservation. These regions support high megabenthic biomass (Millot et al., 2026c), and include submarine canyons hosting large CWC colonies (Fabri et al., 2017, 2025). Upper-slope environments can receive enhanced organic-matter inputs associated with elevated surface productivity and mesoscale oceanographic processes, potentially supporting high megabenthic biomass (Fanelli, 2013; Tecchio et al., 2013). They are also generally less intensively trawled than shallower shelf grounds and were predicted as key climate refugia for several VME indicator taxa, supporting long-term persistence of these ecosystems (Georges et al., 2024; Millot et al., 2024, 2026a). Accounting for trawling activities, energy infrastructures, and existing conservation areas did not strongly constrain the size of the priority networks, with a similar number of PUs selected compared with the baseline scenarios. While accounting for existing conservation areas and OWFs did not result in more costly networks, penalizing the selection of areas subject to trawling increased the overall cost of the selected network. This suggests that, to meet the conservation targets, heavily trawled areas need to be selected. Indeed, the continental shelves of the Gulf of Lion and the Catalan Sea remained the most frequently selected despite trawling activities and the development of OWFs in the region. Largely covered by seasonal fishing closures, MPAs and FRAs, the Gulf of Lion represents a strategic region to reinforce VME conservation measures, at least in areas without conflicts with renewable energy development.

Other areas also appeared as priority interests, although their irreplaceability varied across scenarios. In particular, the slopes in the eastern Ligurian Sea, the northern Ionian Sea, and the southwestern Adriatic Sea seemed relatively cost-efficient areas for implementing new conservation measures. The northern and central Adriatic Sea shelves were rarely selected in the scenarios, probably due to high depletion of megabenthic communities in the region due to decades of intense bottom trawling (Hiddink et al., 2026; Russo et al., 2020), as well as less climate refugia and habitat features. Finally, the central and southern Aegean Sea emerged less often as priority areas, even though they provided good representativity of megabenthic bioregional patterns. Oligotrophic waters may reduce

food export to the seafloor, leading to lower megabenthic invertebrate biomass in these regions and therefore decreasing their contribution to achieving conservation objectives (Coll et al., 2010). Moreover, few climate refugia were predicted in this region, while the number of recorded seamounts and canyons was also limited.

Gaps in the existing MPA and FRA network

When considering only highly irreplaceable PUs, fewer than half of the priority areas identified for VMEs under the "global management" are currently covered by protection measures **(Figure 8)**. Matches between priority areas and existing conservation sites were mainly concentrated in the Gulf of Lion, where MPAs, national fishing closures and GFCM FRAs are already implemented. An overlap was also identified with the EFH-FRA of the "West of Gela Basin" in the Strait of Sicily. Although these FRAs were designated to protect EFHs of demersal stocks (e.g., European Hake spawning aggregation in the Gulf of Lion; Hake nurseries and deepwater rose shrimps in the Strait of Sicily (FAO, 2022)), they may also contribute to the protection of VMEs. However, other GFCM FRAs of the northern Mediterranean were not frequently selected by the prioritization algorithm. For instance, the Jabuka Pomo Pit FRA (central Adriatic) and the two other EFH-FRAs in the Strait of Sicily (East of Adventure Bank and East of Malta Bank) established to protect EFHs for European Hake and deepwater rose shrimps (Carlucci et al., 2009; Garofalo et al., 2011) do not match high biomass of sensitive megabenthic taxa. This result is also observed for the FRA "*Lophelia* reef off Capo Santa Maria di Leuca" intended to protect VME. However, presence records of the CWC *Desmophyllum pertusum* (formerly *Lophelia pertusa*) were not included in our analysis due to a lack of basin-wide data, which likely explains this discrepancy. Small and scattered priority areas were identified deeper than the 800 m trawling ban planned by the GFCM (current ban at 1000 m) (GFCM, 2024b). While raising the trawling ban from 1000 m to 800 m already represents a significant improvement, further consideration could be given to reducing this depth further, since high megabenthic biomasses were concentrated in

shallower waters. Finally, existing MPAs are generally too small and too coastal to provide effective protection for VMEs.

Our results highlight substantial protection gaps in priority VME areas outside the existing conservation frameworks considered here. For instance, no FRAs currently cover the continental shelf and/or the shelf break of the Catalan Sea, despite predicted VME hotspots and climate refugia for seapens, the crinoid *L. phalangium* and the bamboo coral *I. elongata*. Recent GFCM measures have focused on deeper sites (e.g., Bari Canyon (Angeletti et al., 2021), Otranto Channel (GFCM, 2024a)), which, while hosting vulnerable ecosystems, are largely covered by the existing trawling ban below 1000 m. Future VME-FRAs decisions should target shelf-break and upper-slope zones, which support high VME biomass while experiencing less fishing activity than continental shelves and are not currently subject to offshore wind development plans. Strengthening effective protection within existing areas that overlap with VME priorities is also necessary. Indeed, EFH-FRAs do not necessarily impose strict fishing closures and bottom contacting gears permitted (lines and nets) within or adjacent to such areas may still affect VMEs (FAO, 2025). The effectiveness of MPAs and FRAs in protecting VMEs should therefore regularly assessed against both current and projected VMEs distribution, using the best available scientific information (Danovaro et al., 2020; Manea et al., 2020).

It is important to emphasize that this interpretation was based on a single scenario, and used an 80% selection frequency threshold to identify highly selected cells to draw general conclusions about their overlap with existing conservation measures. The threshold is a visualization and diagnostic choice rather than a biological cut-off. Moreover, because the mapped network includes only the most frequently selected cells, it represents only a subset of the areas required to fully meet the defined conservation targets. Lower-frequency areas may therefore still be important areas to consider and should remain part of future negotiation for the implementation of additional management measures.

Limitations on spatial information included in the SCP

Despite relying on up-to-date spatial data on the distribution of VMEs and megabenthic communities, several limitations may affect the prioritization output. Most spatial information was derived from megabenthic invertebrate bycatch recorded during the MEDITS trawl surveys (Spedicato et al., 2019). Surveys are restricted to soft-bottom habitats, resulting in a lack of coverage of rocky or rough seabeds. Moreover, taxonomic expertise is not fully homogeneous among the eight participating countries, resulting in a marked decrease in data quantity and coverage from the western to the eastern Mediterranean basin. In the Aegean Sea, heterogeneous taxonomic identification may therefore underrepresent the diversity of megabenthic communities and soft-bottom VMEs documented by regional studies (Salomidi et al., 2022; Stamouli et al., 2022, 2023). This bias may also explain why planning units were more frequently selected in the western basin than in the Aegean Sea. Consequently, low priority in the present basin-scale analysis should not be interpreted as evidence of low ecological values and a focused regional SCP would be valuable when more spatially consistent data become available.

Cost estimates are also affected by incomplete or uneven spatial data across the basin. Despite improvements in fishing vessel detection (Marsaglia et al., 2024), bottom trawling activity may remain underestimated in some regions. In particular, the non-detection of vessels smaller than 15 m and uncertainty in converting vessel detection into fishing hours, may lead to biased estimates. Data on existing conservation areas and offshore wind farm (OWF) plans were also unevenly available across the planning region. While MPA and FRA localisations were obtained from the international MAPAMED database, only French national fishing closures related to the western Mediterranean management plan (EU, 2019) were accounted for in this SCP analysis. Spanish and Italian permanent closures, although often very small, could not be included due to unavailability of coordinates. Similarly, OWF plans were also mapped with greater spatial precision in French waters, whereas equivalent data for numerous projects in the Strait of Sicily (https://map.4coffshore.com/offshorewind) were not publicly accessible.

Making the SCP more relevant for conservation and management decisions

Optimizing connectivity in conservation networks is key to ensure the persistence of marine communities (Goetze et al., 2021). One approach in SCP is to include connectivity matrices derived from Lagrangian Particle Tracking Models, which simulate larval dispersal among marine reserves (Clavel-Henry et al., 2019; Gary et al., 2020). The cost of the highly connected PUs is reduced to favour their selection, resulting in more connected conservation networks (Combes et al., 2021). Maintaining connectivity under climate change scenarios adds a further challenge in designing climate-smart marine reserves (Giakoumi et al., 2025; Magris et al., 2014; Wilson et al., 2020). Climate change is expected to affect the connectivity of marine populations by altering oceanographic circulation/currents, stratification, and the dispersal distance of species (Gerber et al., 2014). Mechanistic models incorporating projected shifts in oceanographic currents, developed for the Mediterranean, suggest that larval dispersal distance may decrease in response to warming, while connectivity between protected areas could increase as new areas become suitable (Andrello et al., 2015). The major limit to account for connectivity in SCP is the scarcity of data on larval life history traits (e.g., pelagic larval duration, dispersal depths). Only very few studies have been carried out for some gorgonians (e.g., *Paramuricea clavata*) (Coma et al., 1995; Linares et al., 2008) and octocorals (*I. elongata*) (Lauria et al., 2025) and additional research on other megabenthic taxa is needed to investigate these aspects.

Future SCP should also consider the potential consequences of fishing closures on the sustainability of trawling fleets, as well as their positive or negative impacts on other fleets (Ulrich et al., 2025). If total fishing effort is not simultaneously reduced, closures may displace the fishing effort to previously less exploited grounds (Boussarie et al., 2023), potentially shifting pressure toward other sensitive habitats. Mixed-fisheries dynamics simulation models, such as ISIS-Fish (Mahévas & Pelletier, 2004), may help evaluate changes in fleet effort distribution and fish population dynamics under alternative fishing closure designs (Hopkins et al., 2024; Lehuta et al., 2010, 2016; Reecht et al., 2015).

Bioeconomic models can also be useful to simulate the effects of management measures on trawl fisheries, as demonstrated in the central Mediterranean, to assess the economic cost of FRAs and changes to the 1000 m trawling ban (Russo et al., 2019; Sbrana et al., 2025).

The process of protection for VMEs is a relatively low-cost measure when compared to a high intervention restoration activity in the deep sea (reseeding/planting) (Chen et al., 2022; Van Dover et al., 2014). Protection allows for natural recovery, which may still take decades for a degraded seabed (Da Ros et al., 2019). Our SCP analysis does not prioritize degraded VME areas that might be in need of restoration, but future analyses could combine layers of trawling intensity/impact (Hiddink et al., 2026) and habitat suitability modelling with future refugia, to further prioritize management areas, thus fulfilling steps in the EU Nature Restoration Regulation.

By providing a flexible set of priority conservation areas, this basin-scale SCP exercise may support discussion among stakeholders and policymakers on future management strategies for Mediterranean VME conservation. However, the variability and uncertainty associated with spatial prioritization solutions, can be confusing for non-experts in their decision making process (Janßen et al., 2019). Quantifying these uncertainties in future work could improve the transparency and reliability of SCP outputs. Moreover, the development of user-friendly interfaces (e.g., Shiny apps) can facilitate stakeholder engagement and their understanding of the SCP outputs, and therefore strengthening their confidence, which is essential for the implementation of conservation measures (Giakoumi et al., 2025).

Conclusions

This study highlighted how the growing availability of benthic observations and estimates of human activities, combined with robust modelling approaches, can be used to optimize future conservation decisions for VMEs in the Mediterranean. Rather than identifying a single optimal network, the analysis provides alternative priority solutions and highlights areas that recur across scenarios, while also revealing substantial gaps in current protection. The diverse priority conservation

603 solutions could support the discussion among stakeholders and policymakers to optimize basin-scale
604 VME management plans and help reach the 2030 Agenda objectives. These results can support
605 scientific discussion within the GFCM on where additional or strengthened VME conservation
606 measures warrant evaluation. A similar methodology can be refined at regional or local scales to
607 support national initiatives, including MPAs targeting vulnerable ecosystems and climate refugia.
608 Involving local stakeholders (e.g., politicians, NGOs, fishers, and other sea-users) from the early stages
609 of the process, through mediation initiatives, could greatly improve the accuracy of SCP outputs and
610 enhance acceptance of new conservation areas.

611 Acknowledgment

612 We sincerely acknowledge the REDRESS project (https://redress-project.eu/) for providing financial
613 support for this research. We are grateful to DG MARE (European Commission's Directorate-General
614 for Maritime Affairs and Fisheries) for providing free access to the MEDITS database, from which the
615 input layers were derived. We also extend our thanks to the scientific teams from the eight countries
616 (Croatia, Cyprus, France, Greece, Italy, Malta, Slovenia, and Spain) for their contribution to the
617 coordination and implementation of the MEDITS surveys. Finally, we thank DEN MARBEC for providing
618 access to the HPC resources of the MARBEC GPU server, which enabled us to efficiently perform our
619 analyses.

620 Statements & Declarations

621 The first author received support through a PhD studentship funded by IFREMER and authors
622 collaboration was enabled by the European Union under the Horizon Europe project REDRESS
623 (Restoration of Deep-Sea Habitats to Rebuild European Seas, https://redress-project.eu/), Grant No.
624 101135492. The numerical resources used in this work were supported financially by the 2015–2020
625 CPER CELIMER, funded by the French Ministry of Higher Education, Research and Innovation, the

Occitanie Region, Montpellier Méditerranée Metropolis, Sète Agglopole Méditerranée, Ifremer, and IRD.

The authors have no relevant financial or non-financial interests to disclose.

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Figure and table captions

Figure 1: Main steps of a Spatial Conservation Planning framework.

Figure 2: Planning region selected (in planning units, PUs - in blue shading) over which the SCP exercise was conducted, covering soft bottoms of the northern Mediterranean Sea from 10 to 1,000 m depth. The main Mediterranean Seas are numbered.

Figure 3: (A) Number of selected PUs and (B) percentage of total cost for the 30 optimal solutions under the "base scenarios" (S1, S2, S3), the "bioregional scenarios" (S4, S5, S6), the "management scenarios" (S7, S8, S9) and the "global scenario" (S10). For the "base" and "bioregional" scenarios, the cost of a solution is equal to the number of selected PUs, whereas for the "management" scenarios, cost is weighted according to existing conservation areas and human uses. Costs are expressed as a percentage of the total cost summed across the entire planning area to ensure comparability among scenarios. Scenario attributes are summarized in **Table 3.**

Figure 4: Map of PUs selection frequency across the 30 optimal solutions for the base scenarios, with conservation targets (A - S1) set at 10% for all features, (B - S2) set at 30% for all features, and (C - S3) varying among features according to their conservation priority.

Figure 5: Map of PUs selection frequency across the 30 optimal solutions for the bioregion scenarios, with conservation targets (A - S4) set at 10% for all features, (B - S5) set at 30% for all features, and (C - S6) varying among features according to their conservation priority.

Figure 6: Map of PUs selection frequency across the 30 optimal solutions for the management scenarios, with conservation targets varying among features according to their conservation priority and accounting for costs associated with (A - S7) existing conservation areas, (B - S8) bottom-trawling activity, and (C - S9) energy production installations.

Figure 7: Map of PUs selection frequency across the 30 optimal solutions for the global management scenario (S10), with conservation targets varying among features according to their conservation priority and accounting for a global cost of conservation and human activities.

Figure 8: Proposed network for priority conservation of VMEs under the "global management scenario", restricted to planning units (PUs) with a selection frequency ≥ 80%, and their overlap with existing protection measures. Four levels of protection are distinguished in the legend: High protection (GFCM FRAs targeting VMEs, permanent fishing closures in the Gulf of Lion, and the GFCM recommendation of trawling ban below 800 m depth); Moderate protection (GFCM FRAs targeting EFHs and seasonal fishing closures in the Gulf of Lion); Low protection (Natura 2000 sites under the EU Habitats Directive and national MPAs); No protection (areas not covered by any of the above measures). (A) Basin-scale representation of the priority network, with GFCM FRAs outlined in black and the percentage of overlap between the priority network and the four levels of existing protection shown in the pie chart, (B) focus on the Gulf of Lion region with the French FRA (in black), national fishing closures (in brown), offshore wind farm plans (in purple) and MPAs (in green), (C) focus on the Strait of Sicily with FRAs (in black) and MPAs (in green).

Table 1: Attributes of the conservation features included in the SCP analysis (further details of layer construction in **Supplementary Material SM1**).

Table 2: Summary of the decision rules applied to weight conservation targets according to the conservation priority of features listed in **Table 1**.

Table 3: Attributes of the conservation scenarios tested in the SCP analysis, varying in conservation features, conservation targets, costs, and constraints.

Figures

Figure 1 :

- Step 1: *Define the planning region and planning units*

The **planning region** is the area over which the SCP is conducted. It is partitioned into equal-sized spatial grid cells, referred to as **planning units** (PUs), each of which is either selected or not in the **conservation solution**.

- Step 2: *Select the conservation features*

Conservation features correspond to elements of conservation interest (e.g., VMEs refugia, geomorphological features, ect.) that are selected to be protected in a potential conservation network. They need to be spatially defined.

- Step 3: *Fix conservation targets*

Conservation targets are set for each conservation feature. They correspond to the amount of a conservation feature that must be included in the conservation network. These targets are quantitatively set by the user, either based on international conservation objectives or determined heuristically according to several criteria. They are often expressed as a percentage of the feature's original distribution within the planning region.

- Step 4: *Fix costs and constraints*

In an 'area-based cost' scenario, a common **cost** is set for each PU, and the total cost of the solution is equal to the number of selected PUs. In 'management cost' scenarios, costs can be increased by human-uses (e.g,, fishing activity), or reduced by existing conservation measures. Some PUs can be **constrained** to be selected or excluded from the conservation solution (e.g,, oil and gas infrastructure, offshore wind farms).

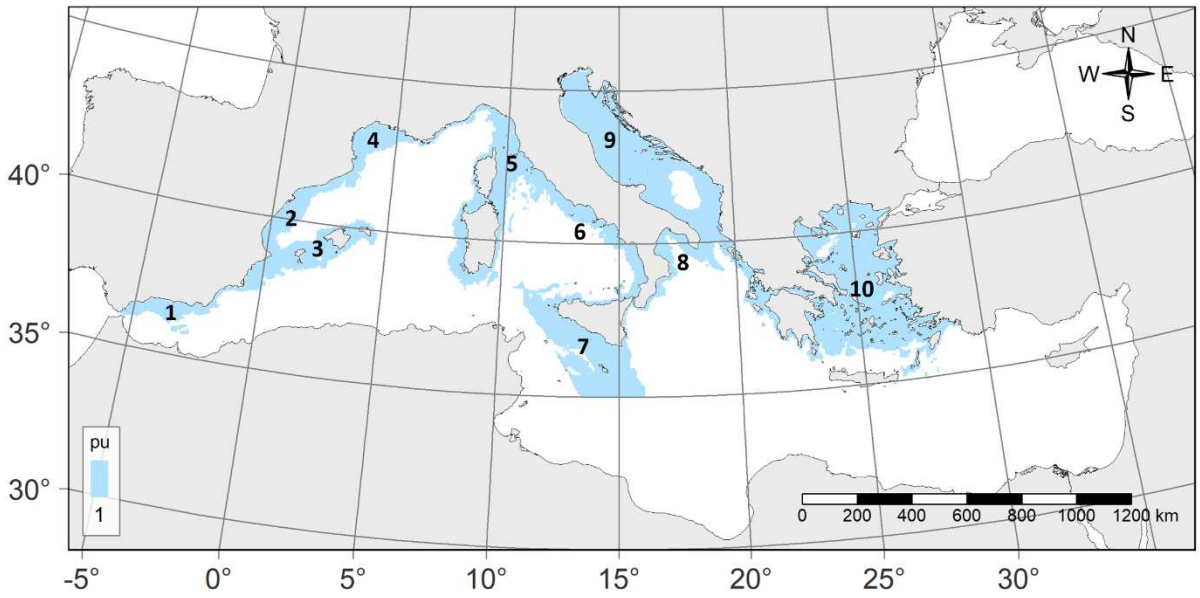
- Step 5: *Fix the penalties*

Penalties are additional criteria that can influence the selection of Pus in the final conservation solution. The function '*PrioritizeR::add_boundary_penalties*' allows penalizing spatial fragmentation of the network. This is similar to the boundary length modifier parameter used in Marxan.

- Step 6: *Solve the conservation problem and generate a portfolio of solutions*

An **objective function** is selected to fix which metric must be maximized or minimized. The *'PrioritizeR::add_min_set_objective'* function enables the full achievement of conservation targets while minimizing total cost. A prioritization algorithm is then selected, along with parameters such as the **optimality gap** (i.e., the difference (in %) between the best and an acceptable near-optimal solution). A **portfolio** of **optimal solutions** is generated for each conservation problem.

Figure 2:



01. Alboran Sea	06. Tyrrhenian Sea
02. Catalan Sea	07. Strait of Sicily
03. Balearic Sea	08. Ionian Sea
04. Gulf of Lion	09. Adriatic Sea
05. Ligurian Sea/Corsica	10. Aegean Sea

Figure 3:

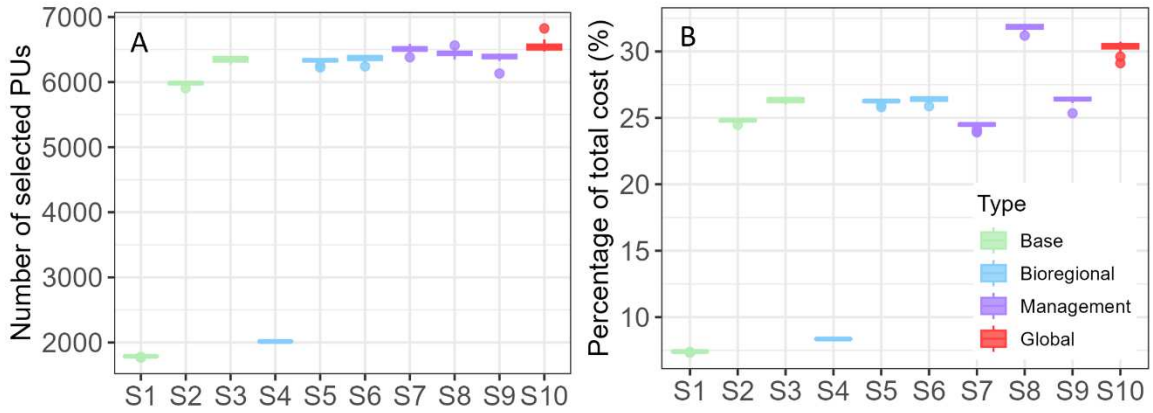
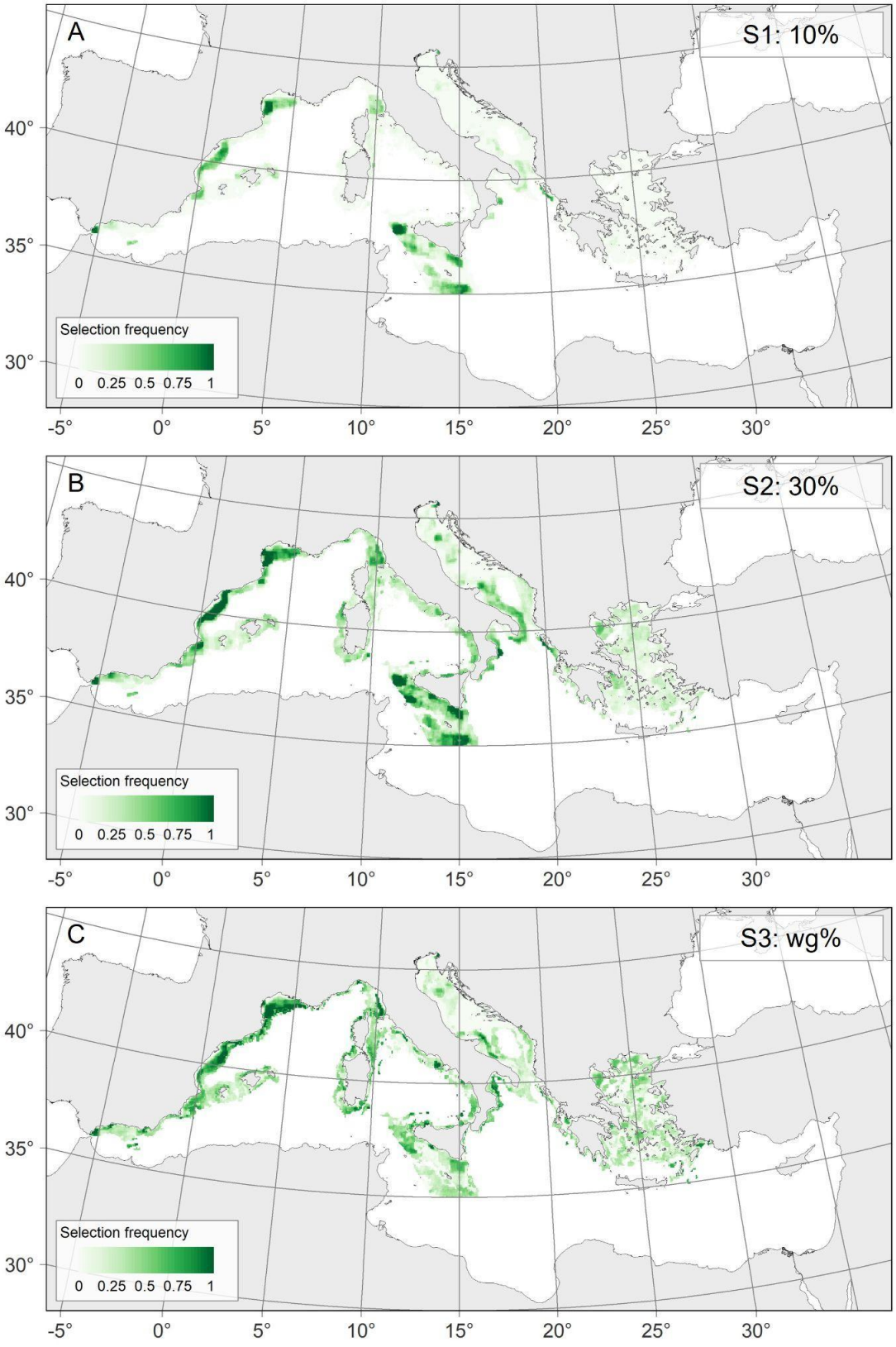


Figure 4:



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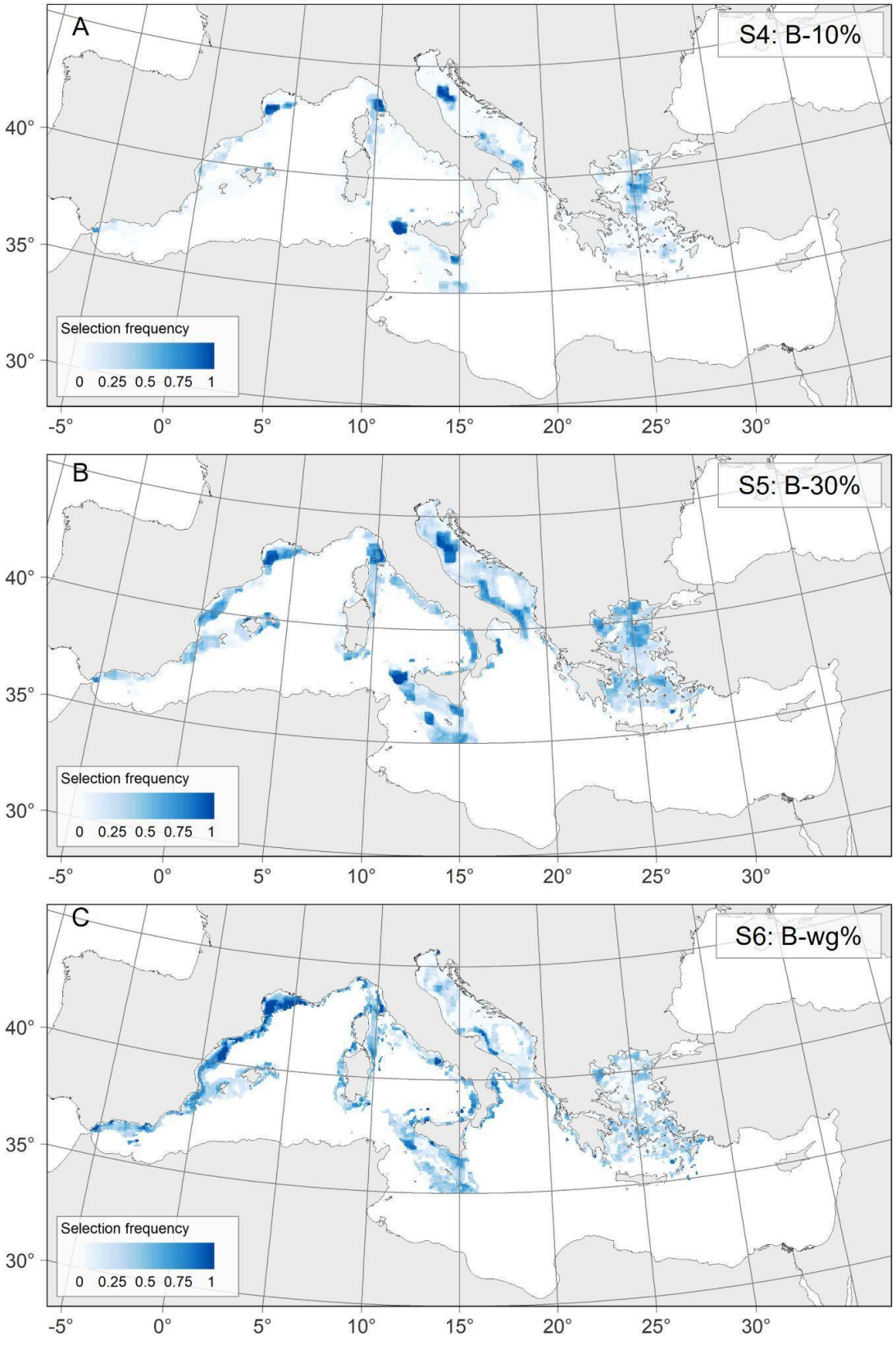
1176 **Figure 5:**



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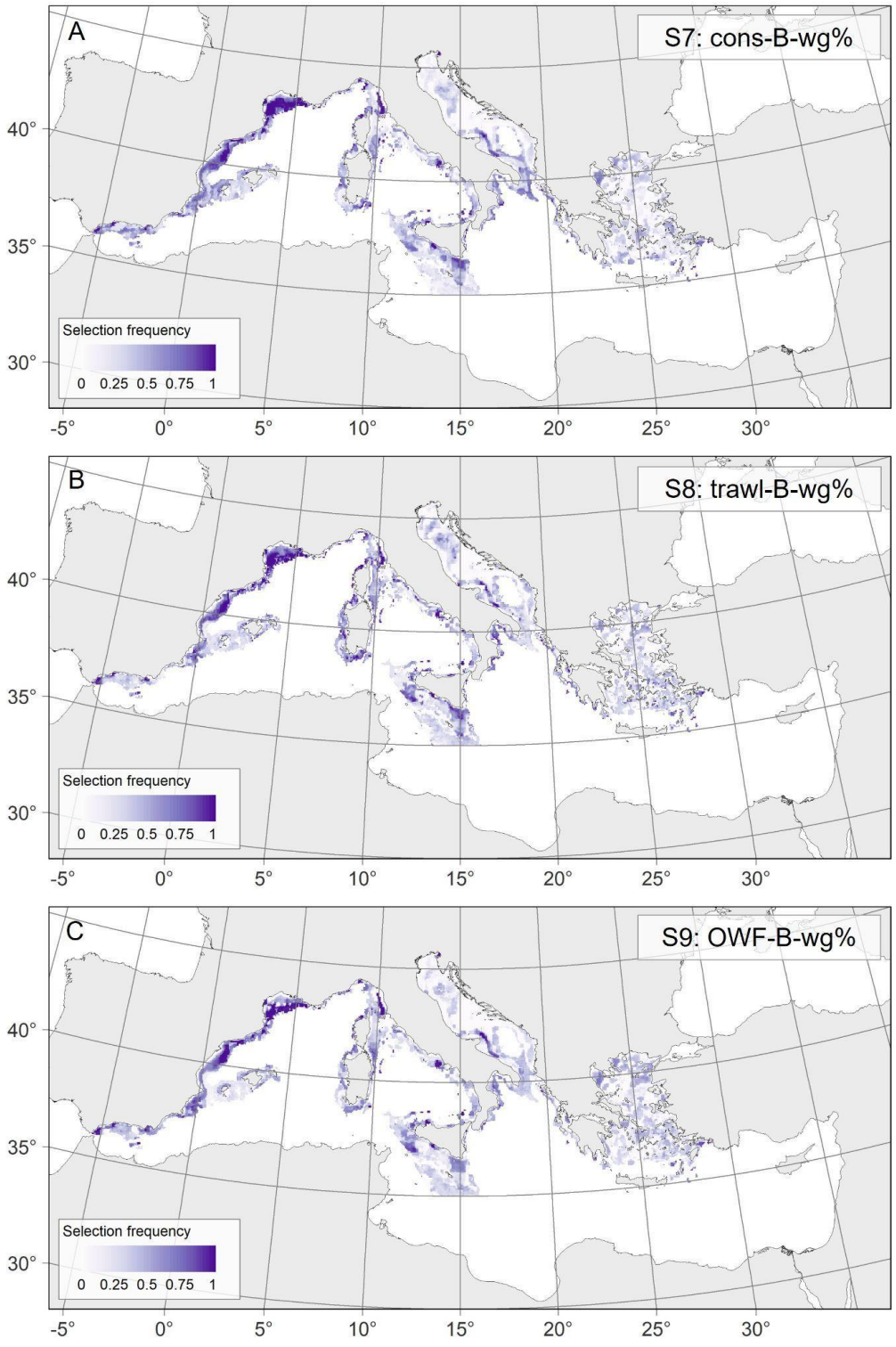
1178 **Figure 6:**



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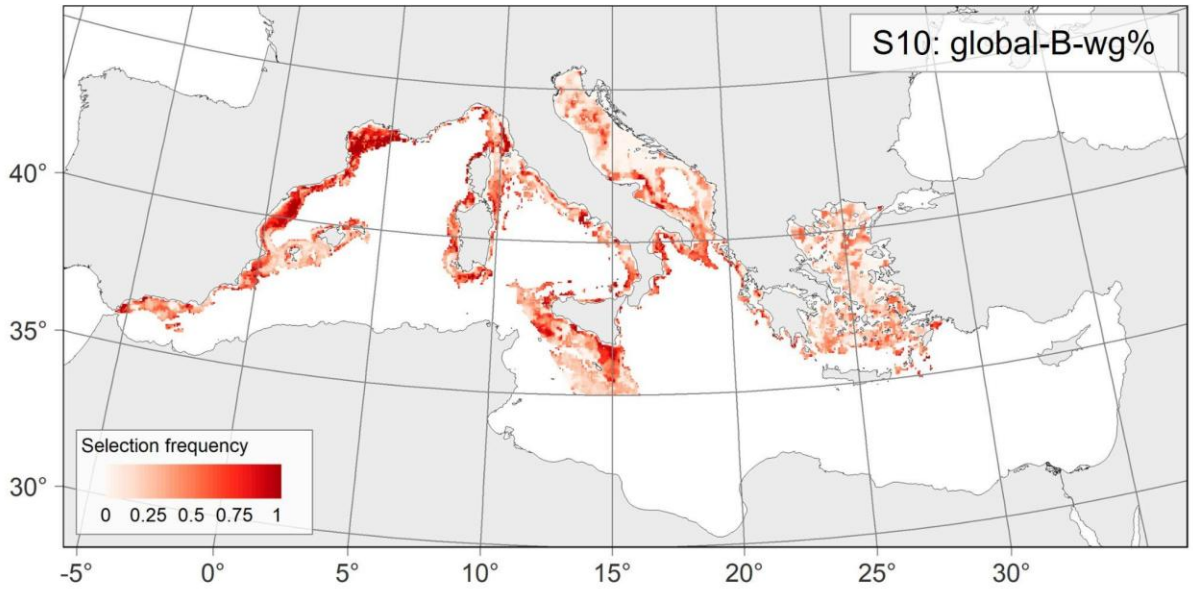
1180 **Figure 7:**



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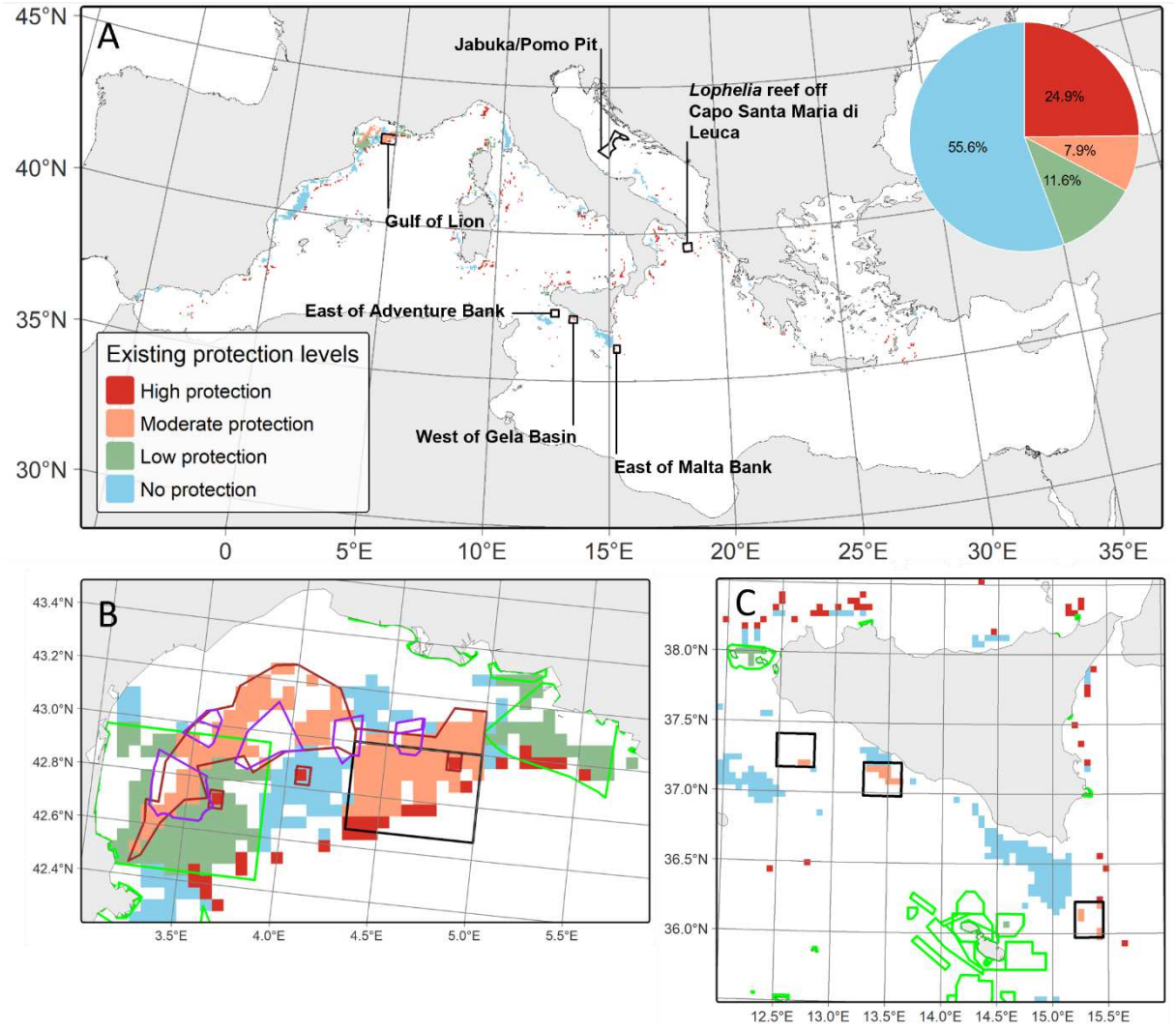
1182 **Figure 8:**



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Tables

Table 1:

Features name	Type	Number	Data type	Source
Biomass distribution of sensitive taxa	Biological	30	Continuous (Biomass)	Millot et al., 2026c
Sensitivity index of megabenthic communities	Biological	1	Continuous (Index)	Millot et al., 2026c
Habitat suitability of VME indicator species	Biological	6	Continuous (Probability of presence)	Millot et al., 2024 Millot et al., 2026a Georges et al., 2024 Georges et al., 2026
Climate refugia of VME indicator species	Biological	6	Binary	Millot et al., 2024 Millot et al., 2026a Georges et al., 2024 Georges et al., 2026
Geomorphological features	Habitat	2	Binary (seamount presence) and continuous (canyon length)	Combes et al., 2021
Megabenthic bioregions	Bioregion	16	Binary	Millot et al., 2026b

1188 **Table 2:**

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	Biological	Habitat	Bioregion
Baseline target	10%	60%	10%
Sensitivity of the taxa	+ 10-20%	-	-
Climate refugia	+10%	-	-
Small extent	+10%		-
Large extent	-10%		-

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1191 **Table 3:**

Scenarios	Scenarios type	Conservation target	Bioregions	Conservation cost	Bottom trawling cost	Planned OWF cost	Energy Production constraint
S1	Base	10%					
S2	Base	30%					
S3	Base	weighted %					
S4	Bioregional	10%	✓				
S5	Bioregional	30%	✓				
S6	Bioregional	weighted %	✓				
S7	Management	weighted %	✓	✓			
S8	Management	weighted %	✓		✓		

S9	Management	weighted %	✓			✓	✓
S10	Management	weighted %	✓	✓	✓	✓	✓

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Supplementary Files

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