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A new Western Mediterranean Sea EBSAs proposal based on quantitative information of key criteria

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ABSTRACT

Marine ecosystems are increasingly threatened by multiple anthropogenic pressures, leading to biodiversity loss, habitats degradation and resources deterioration. To address these challenges, international and regional policy frameworks have established conservation targets. Ecologically or Biologically Significant Marine Areas (EBSAs), designated by the Convention on Biological Diversity based on multiple criteria, can guide spatial conservation and play a vital role in maintaining ocean health. In this study, we provide a quantitative, systematic approach to refine existing EBSAs within the Western Mediterranean Sea via spatially explicit proxies for the internationally agreed protection criteria. Spatial prioritization was conducted and included environmental stability to account for ecological resilience under climate change. Our results reveal a pronounced spatial imbalance in the representation of EBSA criteria within internationally agreed protection schemes (Natura2000 sites, Ramsar sites, Specially Protected Areas of Mediterranean Importance and proposed Sites of Community Importance), ranging from 2.2 % to 63.9 %, providing relevant information for the study area. There is a marked bias toward the northern part of the basin, with current EBSAs covering 47 % of the study area, while existing protected spatial features correspond to 19.7 % of the study area. This spatial bias may undermine the effectiveness of marine biodiversity conservation and highlights the need for more equitable and data-driven spatial planning approaches. By redefining existing EBSAs and evaluating their alignment with internationally agreed protection schemes, our work provides a scientific basis to inform future conservation strategies and support the development of ecologically coherent transnational networks of protected areas aligned with global and regional goals.

1. Introduction

The Mediterranean basin, which covers less than 0.8 % of the global ocean surface, is a major marine biodiversity hotspot. It hosts approximately 7.5 % of the world's marine biodiversity, with around 17,000 marine species, and is characterized by a high rate of endemism, with over 29 % of its species being endemic [1–3]. However, the ecosystems of the Mediterranean Sea are severely affected by the combined effects of human pressures, including overexploitation of commercial marine resources, high fisheries discarding and by-catch rates of non-commercial and vulnerable species, and climate change impacts. Among these, intense sea warming, particularly the increasing frequency, duration and intensity of marine heatwaves compared to other oceanic regions [4,5], has caused severe ecological disruptions, including mass mortality due to the surpassing of species' physiological thresholds [6] and significant alterations in community structure [7]. Additional stressors such as ocean acidification, changes in primary production [2,8–10], habitat degradation, pollution, and the introduction of invasive species further challenge the effective management of this basin [11–15]. In this context, strengthening protection and conservation efforts is essential to support marine biodiversity, the recovery of exploited marine resources and to enhance overall ecosystem health. However, the feasibility and effectiveness of such measures depend on balancing conservation priorities with social, economic and cultural criteria [16], which can pose significant challenges for spatial planning in this region [17].

A range of frameworks has emerged to integrate ecological goals with socio-economic needs [16,18]. Among these, Marine Protected Areas (MPAs) are the primary tool for conserving marine biodiversity and promoting ecosystem health by reducing anthropogenic threats

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such as overfishing, habitat loss and pollution [19–22]. Over the past decades, numerous international and regional commitments have been established to support the protection and conservation of key marine regions. The EU Biodiversity Strategy for 2030, for instance, aims to protect 30 % of EU marine areas by 2030, with at least one-third under strict protection [23]. This aligns with the global goals adopted by the Convention on Biological Diversity (CBD) in December 2022 [24] that was reinforced by the new Agreement under the United Nations Convention on the Law of the Sea (UNCLOS) on the Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdiction [25], the General Fisheries Commission for the Mediterranean (GFCM) 2030 Strategy for sustainable fisheries and aquaculture in the Mediterranean and the Black Sea [26], and COP23 of the Barcelona Convention's Mediterranean Action Plan [27]. Despite these commitments, current levels of MPA extent, regulation and enforcement in the Mediterranean Sea remain limited [28,29]. Only 6 % of the basin is covered by protection, similar to the global average, and just 0.23 % is under full or high protection [28–30]; thus, compromising the effectiveness of the MPAs in protecting marine biodiversity from multiple stressors and the achievements of policy targets.

Achieving these ambitious commitments requires the identification of biodiversity hotspots and other ecologically significant areas where conservation and spatial planning measures can be effectively implemented. To facilitate this process, the CBD launched an initiative in 2008 to identify and describe Ecologically or Biologically Significant Marine Areas (EBSAs). These areas aim to support the maintenance, protection and conservation of global marine biodiversity through a biogeographically representative network of ecologically coherent areas. The definition of EBSAs is based on seven scientific criteria: (i) Uniqueness or rarity, (ii) Special importance for life-history stages of species (iii) Importance for threatened, endangered or declining species and/or habitats, (iv) Vulnerability, fragility, sensitivity, or slow recovery, (v) Biological productivity, (vi) Biological diversity, and (vii) Naturalness [31]. Meeting just one of these criteria can be sufficient for an area to be designated as an EBSA [32]. These areas can be located within or beyond national jurisdictions, and their identification does not entail mandatory conservation or management measures by States [33–35]. The EBSA identification process is conducted through regional workshops organized by the CBD Secretariat, where experts participate in their individual capacity following a selection process based on nominations submitted by Parties and relevant organizations. These workshops aim to integrate scientific knowledge with national and regional assessments, and the resulting EBSA descriptions are not legally binding but serve as technical inputs to support marine spatial planning and biodiversity conservation [22,34,36,37].

The identification of EBSAs has faced several limitations, including (i) a reliance on qualitative data assessments for designation, overly broad spatial boundaries; (ii) limited updates following ecological changes; (iii) absence of standardized thresholds for EBSA criteria; and (iv) weak integration into legal frameworks [21,22,34,38]. As a result, there are few examples of actual implementation, revision or integration of EBSAs into marine policy and management [39,40]. One notable exception is the RAMOGE International Agreement, under which activities since 2015 have been based on the outcomes of the CBD/UNEP-MAP process conducted in 2014 [37]. Three oceanographic campaigns have led to proposals for the designation of new Natura2000 deep-sea sites within the EBSA of the north-western basin [41–43]. In complex regions such as the Western Mediterranean Sea, where multiple, diverse and overlapping pressures exist across jurisdictional boundaries [44], effective management becomes even more challenging. There is therefore an urgent need for updated, data-driven approaches that can enhance the scientific robustness and practical utility of EBSAs in marine policy and planning.

To date, more than 300 EBSAs have been identified globally. In the Western Mediterranean Sea, three transboundary EBSAs have been recognized: the North-western Mediterranean Pelagic Ecosystems, the North-western Mediterranean Benthic Ecosystems and part of the Sicilian Channel (https://www.cbd.int/ebsa/). In this study, we propose a novel, systematic and revisable approach to redefine EBSAs in the Western Mediterranean Sea by integrating the best available quantitative data across the seven EBSA criteria. To strengthen the long-term viability of conservation priorities, we also incorporate environmental stability into the assessment. Environmental stability is a critical factor for sustaining ecosystem resilience, particularly in the face of accelerating global change. Areas with greater environmental stability are more likely to maintain ecological functions and biodiversity over time, making them strategic targets for long-term effective conservation planning. This approach aims to provide valuable information to support future CBD workshops and assist participants from countries conducting assessments, in alignment with the guidance received from their respective national authorities. To do so, we first evaluate the spatial overlap of EBSA criteria with existing conservation designations, including current EBSAs and other internationally agreed protection schemes such as Natura2000 sites, Ramsar sites, Specially Protected Areas of Mediterranean Importance (SPAMIs) and proposed Sites of Community Importance (SCIs) at the regional level. Then, using a spatial optimization framework, via two separate analyses we identify the most relevant areas that meet EBSA criteria across different scenarios: a) at the regional scale and b) within each Exclusive Economic Zone (EEZ) when declared, balancing the weight of each criterion and minimizing prioritization costs. Finally, we assess the extent to which the EBSA criteria targets are being achieved and the proportion of prioritized areas in each scenario in the Western Mediterranean Sea.

2. Material and methods

2.1. Study area

The Western Mediterranean Sea covers an area of approximately 846,000 km^2 and includes waters from European countries (France, Italy, Spain and Principality of Monaco) as well as North African countries (Algeria, Morocco and Tunisia). It corresponds to FAO subarea 37.1 (including divisions 37.1.1, 37.1.2 and 37.1.3) and ranges in depth from 0 to about 3500 m (Fig. 1).

This region is the most biologically productive area of the Mediterranean Sea, particularly along the continental shelf of the northwestern part, which is influenced by major rivers and deltas such as Rhône and Ebro [45]. It supports a high diversity of Mediterranean habitats and species, including many endemic and threatened taxa, such as seabirds, marine mammals, chondrichthyans, invertebrates, among others [2,46].

Despite its ecological importance, the region faces significant pressures, including intensive maritime activities and a highly urbanized coastline, leading to pollution, waste accumulation, and resource degradation [15,16,46,47]. The impacts of overfishing and habitat loss are further exacerbated by climate-induced environmental changes, which are expected to intensify more rapidly in this region than the global average [6,48,49].

Several regional and international political commitments, processes and institutions are in place to support the implementation of spatial management with different levels of protection [16,28]. To assess the spatial representation of existing marine internationally agreed protection schemes, we compiled geospatial data from regional and international sources, including Natura2000 sites, Specially Protected Areas of Mediterranean Importance (SPAMIs), Ramsar sites, and other region-specific management measures (Fig. 1). These datasets were selected to reflect the transboundary nature of this study and the EBSA framework, which emphasizes ecological coherence across jurisdictions. National MPAs were not explicitly included in this version of the analysis, as the focus of this study is methodological and regional in scope. The proposed framework is designed to be flexible and replicable, allowing for the integration of additional protection layers, such as national MPAs, when relevant to the planning context and when reliable

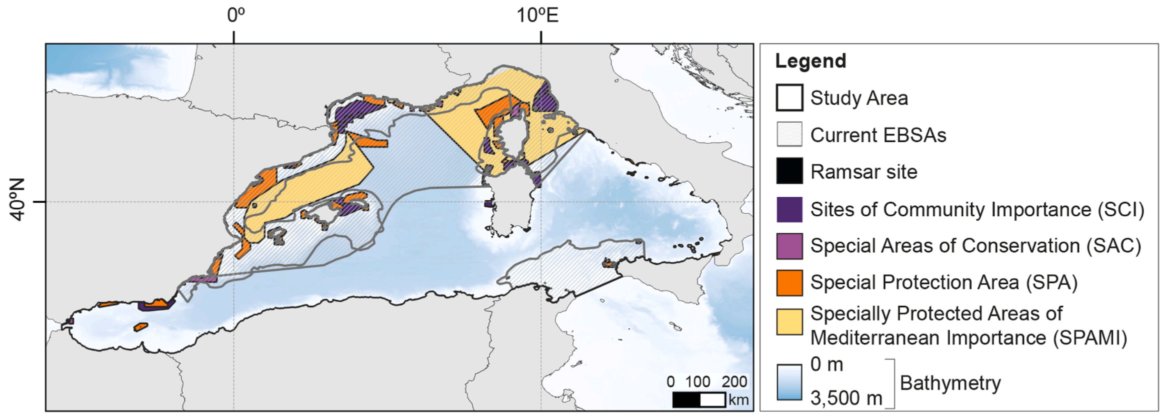

Fig. 1. Map illustrating the study area boundaries and identifying current internationally agreed protection schemes in the Western Mediterranean Sea, including Ecologically or Biologically Significant Marine Areas (EBSAs), Ramsar sites, Natura2000 sites such as Sites of Community Importance (SCI), Special Areas of Conservation (SAC) and Special Protection Areas (SPA), and Specially Protected Areas of Mediterranean Importance (SPAMI).

spatial data are available.

For the prioritization analyses based on EEZs, the EEZ of the Principality of Monaco was integrated into the French EEZ to simplify the spatial framework, given that the Principality of Monaco represents only 0.03 % of the total study area.

2.2. Data selection and quality

We selected the best available quantitative spatial datasets representing species, habitats, productivity, biodiversity richness, maritime activities and biogeochemical variables, according to the definition of each EBSA criterion (Table 1). Each dataset was assigned to the relevant EBSA criterion. In addition, we incorporated a layer of environmental stability to identify areas that have remained more stable over time in terms of sea temperature, marine heatwaves and primary productivity (see Section 2.3 for more details).

To ensure robustness, all geospatial layers followed a quality assessment using the Fitness for Use Score (FUS) approach [50], based on seven indicators grouped into three components [50]. The FUS for each dataset was calculated as the mean of the relevant indicator scores and was applied uniformly across the spatial extent of that layer. FUS values were computed for each dataset and then aggregated to calculate mean FUS scores per indicator and across all criteria. To evaluate statistical differences among FUS indicators and across criteria, we used the Kruskal-Wallis H-test, followed by Dunn's test for multiple comparisons with Bonferroni correction. All EBSA criteria met the predefined quality threshold (FUS $\geq$ 2 on a 0–3 scale). FUS scores are reported in Table S1.

Spatial data on existing EBSAs and other international spatial protection areas were also compiled for this region (see Table 2).

2.3. Data preparation

First, we selected (see Section 2.2) and processed the spatial datasets corresponding to each of the EBSA criteria (Table 1 and Fig. 2). All layers were then re-projected to the EPSG:3035 (LAEA Europe) coordinate reference system, clipped to the study area and, for raster data, resampled to a 5 $\times$ 5 km resolution where necessary.

For the environmental stability criterion, specifically for layers related to temperature and primary productivity (Table 1), we first calculated the absolute values of the obtained slopes, as a proxy for the magnitude of environmental changes occurring on a per-pixel basis [52]. For the marine heatwave layers (Table 1), we calculated the accumulated intensity by summing the intensity values of all marine heatwave events occurring within each pixel over the study period [53].

Standardization was necessary since some layers were presence/absence data and others contained continuous data. For standardization, the continuous spatial layers (e.g., temperature, productivity, species richness) were expressed as quartiles to ensure comparability across datasets with different units and scales (Fig. 2). Then, all spatial layers associated with each EBSA criterion were aggregated into a single composite layer per criterion by summing the values of the overlapping quartiles (Fig. 2). These composite layers for each criterion were then rescaled into quartiles again to allow comparison across criteria, as the number of data layers associated with each criterion varied (see Table 1).

For naturalness and environmental stability criteria, we applied an inverse approach to identify areas with lower levels of human maritime activity and regions that have remained more stable in terms of environmental changes, respectively. Finally, we extracted only the top quartile (Q4) from each composite criterion layer, representing the areas with the highest values or relevance for that criterion (Fig. 2). These final layers (containing cells corresponding to Q4) were then converted into binary presence/absence maps (1/0) for use in the subsequent spatial overlap and prioritization analyses (Fig. 2).

All these steps were conducted using R version 4.3.1 and the "terra" R package [54] and the Tikta software (version 2.0.3) developed under the GES4SEAS EU project (https://www.ges4seas.eu/).

2.4. Analyses

2.4.1. Spatial overlap

To assess how all EBSA criteria are represented within existing internationally agreed protection schemes and current EBSAs, we calculated the percentage of spatial overlap between each criterion (binary layers) and: (i) current EBSAs, (ii) existing internationally agreed protection schemes, including Natura2000 sites (Special Area of Conservation or SAC and Special Protection Areas or SPA), Ramsar sites and Specially Protected Areas of Mediterranean Importance (SPAMIs), and (iii) the combination of existing internationally agreed protection schemes (included in ii) and proposed Sites of Community Importance (SCI; see Fig. 2 and Table 2), respectively. Including SCIs in spatial planning and prioritization scenarios is particularly important, as they represent existing conservation commitments that can guide future management strategies, ensure coherence with the Natura2000 sites network and support the achievement of EU biodiversity objectives, especially the protection of ecologically valuable marine habitats and species. Additionally, we quantified the percentage of spatial overlap of current EBSAs, existing internationally agreed protection schemes, and the combination of existing internationally agreed protection schemes and proposed SCIs, with the total area of the Western Mediterranean Sea. These analyses were performed using QGIS Desktop, version 3.34.12-Prizren.

Table 1
EBSA criteria, including environmental stability, and the corresponding data used for each criterion to conduct the analysis. Definitions of each criterion [31], the temporal resolution of the data, the metrics used and their sources are also provided.

Criterion	Definition	Data	Temporal resolution	Metrics	Source
Uniqueness or rarity	Area contains either (i) unique ("the only one of its kind"), rare (occurs only in few locations) or endemic species, populations or communities, and/or (ii) unique, rare or distinct, habitats or ecosystems; and/or (iii) unique or unusual geomorphological or oceanographic features (Annex I of COP 9 Decision IX/20)	Seamounts	2015 and 2023	Binomial: 0/1	GFCM database on sensitive benthic habitats and species (2023 version). Available at: https://www.fao.org/gfcm/data/maps/sbhs/en/; Rovere, M., & Würtz, M. (2015). Atlas of the Mediterranean seamounts and seamount-like structures. In Atlas of the Mediterranean seamounts and seamount-like structures. IUCN International Union for Conservation of Nature. Available at: https://doi.org/10.2305/IUCN.CH.2015.07.EN
		Spawning areas of *Galeus melastomus* Nursery areas of *Galeus melastomus* Nursery areas of *Raja clavata*	2013		Giannoulaki, M., Belluscio, A., Colloca, F., Fraschetti, S., Scardi, M., Smith, C., Panayotidis, P., Valavanis, V., & Spedicato, M. T. (2013). Mediterranean Sensitive Habitats (MEDISEH). https://www.vliz.be/imisdocs/publications/ocrd/277421.pdf. MEDISEH project: https://imbriw.hcmr.gr/mediseh/)
		Larus audouinni *Puffinus mauretanicus*	2023		BirdLife International and Handbook of the Birds of the World (2023) Bird species distribution maps of the world (2023.1 version).
Special importance for life-history stages of species	Areas that are required for a population to survive and thrive (Annex I of COP 9 Decision IX/20)	Spawning areas of *Merluccius merluccius* Spawning areas of *Mullus barbatus* Spawning areas of *Pagellus erythrinus* Spawning areas of *Eledone cirrhosa* Spawning areas of *Illex coindetii* Spawning areas of *Aristaeomorpha foliacea* Spawning areas of *Aristeus antennatus* Spawning areas of *Parapenaeus longirostris* Spawning areas of *Nephrops norvegicus* Nursery areas of *Merluccius merluccius* Nursery areas of *Pagellus erythrinus* Nursery areas of *Eledone cirrhosa* Nursery areas of *Illex coindetii* Nursery areas of *Aristaeomorpha foliacea* Nursery areas of *Parapenaeus longirostris* Nursery areas of *Nephrops norvegicus* Eggs *Engraulis encrasicolus* Eggs *Sardina pilchardus* Juveniles *Engraulis encrasicolus* Juveniles *Sardina pilchardus* Juveniles *Trachurus mediterraneus* Juveniles *Trachurus trachurus*	2013	Binomial: 0/1	Giannoulaki, M., Belluscio, A., Colloca, F., Fraschetti, S., Scardi, M., Smith, C., Panayotidis, P., Valavanis, V., & Spedicato, M. T. (2013). Mediterranean Sensitive Habitats (MEDISEH). https://www.vliz.be/imisdocs/publications/ocrd/277421.pdf. MEDISEH project: https://imbriw.hcmr.gr/mediseh/)
Importance for	Area containing habitat for the survival and recovery of endangered,	Coralligenous	2013 and 2023	Binomial: 0/1	Coralligenous and other calcareous bioconcretions in the Mediterranean (2023 version). Available at: htt

(continued on next page)

Table 1 (*continued*)

Criterion	Definition	Data	Temporal resolution	Metrics	Source
threatened, endangered or declining species and/or habitats	threatened, declining species or area with significant assemblages of such species (Annex I of COP 9 Decision IX/20)				https://emodnet.ec.europa.eu/en + Giannoulaki, M., Belluscio, A., Colloca, F., Fraschetti, S., Scardi, M., Smith, C., Panayotidis, P., Valavanis, V., & Spedicato, M. T. (2013). Mediterranean Sensitive Habitats (MEDISEH). https://www.vliz.be/imisdocs/publications/ocrd/277421.pdf. MEDISEH project: https://imbriw.hcmr.gr/mediseh/)
		Seagrass meadows	Version 2023		Seagrass cover in Europe (2023 version). Available at: https://emodnet.ec.europa.eu/en as Unique resource identifier: 39746d9c-4220–425c-bc26–7cb3056c36a5
Vulnerability, fragility, sensitivity, or slow recovery	Areas that contain a relatively high proportion of sensitive habitats, biotopes or species that are functionally fragile (highly susceptible to degradation or depletion by human activity or by natural events) or with slow recovery (Annex I of COP 9 Decision IX/20)	*Isidella elongata*	2023 and 2024 version, respectively	Binomial: 0/1	GFCM database on sensitive benthic habitats and species (2023 version). Available at: https://www.fao.org/gfcm/data/maps/sbhs/en/
		Carcharias taurus *Galeorhinus galeus* *Sphyrna mokarran* *Eretmochelys imbricata* *Leucoraja melitensis* *Rhinoptera marginata* *Glaucostegus cemiculus* *Squatina aculeate* *Squatina oculate* *Squatina squatina* *Aetomylaeus bovinus* *Rhinobatos rhinobatos* *Myliobatis aquila* *Anguilla anguilla* *Pinna nobilis*			IUCN (International Union for Conservation of Nature) 2024. The IUCN red list of threatened species. Critically endangered species in the Mediterranean Sea. Version 2022-6.3. Available at: https://www.iucnredlist.org/en. Downloaded on 06 February 2024.
Biological productivity	Area containing species, populations or communities with comparatively higher natural biological productivity (Annex I of COP 9 Decision IX/20)	Primary production	2021	Continuous data	MEDSEA_MULTIYEAR_BGC_006_008. E.U. Copernicus Marine Service Information (CMEMS). Marine Data Store (MDS). Available at: https://doi.org/10.25423/cmcc/medsea_multiyear_bgc_006_008_medbfm3 Downloaded on 29 August 2024.
Biological diversity	Area contains comparatively higher diversity of ecosystems, habitats, communities, or species, or has higher genetic diversity (Annex I of COP 9 Decision IX/20)	Kempton's richness	2015	Continuous data	Coll, M., Lynam, C.P., Corrales, X., Espasandín, L., Ortega, M., Puntila-Dodd, R., Steenbeek, J., Szalaj, D., Tomczak, M., Butenschon, M., Andonegi, E., Castro, M. D., Heye, S., Kristiansen, T., van Duren, L., Vilmin, V., & Peck, M. 2024. Mechanistic projections for changing species and ecosystems: preliminary projections and report. FutureMARES Deliverable Report. https://www.futuremares.eu/deliverables
Naturalness	Area with a comparatively higher degree of naturalness as a result of the lack of or low level of human-induced disturbance or degradation (Annex I of COP 9 Decision IX/20)	Energy windfarms	2023	Binomial: 0/1	EMODnet_HA_Energy_WindFarms. Available at: https://emodnet.ec.europa.eu/en Downloaded on 24 November 2023.
		Maritime traffic (All vessels route density)	2017–2023	Continuous data	Maritime traffic (All vessels route density) (2023 version). Available at: https://emodnet.ec.europa.eu/en
		Marine Litter	2015–2021		Arias, M., Cózar, A., Suaria, G., Viejo, J., Aliani, S., Koutroulis, A., Delaney, J., Bonnery, G., Macías, D., de Vries, R., Sumerot, R., Morales-Caselles, C., Turiel, A., González-Fernádez, D., & Corradi, P. (2024). Mediterranean Sentinel-2 Litter Windrows Catalogue (Jun. 2015 - Sept. 2021) v1.0 (1.0) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.11045944
		Artisanal powered fishing Artisanal unpowered fishing Industrial fishing	2017		Rousseau, Y., Blanchard, J.L., Novaglio, C. et al. A database of mapped global fishing activity 1950–2017. Sci Data 11, 48 (2024). Available at: https://doi.org/10.1038/s41597–023–02824–6
Environmental stability	Area where environmental variables such as temperature and productivity have been stable in the last decades	Temperature (0–150 m)	1987–2023	Continuous data	Escudier, R., Clementi, E., Omar, M., Cipollone, A., Pistoia, J., Aydogdu, A., Drudi, M., Grandi, A., Lyubartsev, V., Lecci, R., Cretí, S., Masina, S., Coppini, G., & Pinardi, N. (2020). Mediterranean Sea Physical Reanalysis (CMEMS MED-Currents) (Version 1) [Data set]. Copernicus Monitoring Environment Marine Service (CMEMS). https://doi.org/10.25423/CMCC/MEDSEA_MULTIYEAR_PHY_006_004_E3R1
		Temperature (bottom)	1987–2021		Escudier, R., Clementi, E., Omar, M., Cipollone, A., Pistoia, J., Aydogdu, A., Drudi, M., Grandi, A., Lyubartsev, V., Lecci, R., Cretí, S., Masina, S., Coppini,

(*continued on next page*)

Table 1 (*continued*)

Criterion	Definition	Data	Temporal resolution	Metrics	Source
					G., & Pinardi, N. (2020). Mediterranean Sea Physical Reanalysis (CMEMS MED-Currents) (Version 1) [Data set]. Copernicus Monitoring Environment Marine Service (CMEMS). https://doi.org/10.25423/CMCC/MEDSEA_MULTIYEAR_PHY_006_004_E3R1
		Primary production	1999–2021		Teruzzi, A., Di Biagio, V., Feudale, L., Bolzon, G., Lazzari, P., Salon, S., Coidessa, G., & Cossarini, G. (2021). Mediterranean Sea Biogeochemical Reanalysis (CMEMS MED-Biogeochemistry, MedBFM3 system) (Version 1) [Data set]. Copernicus Monitoring Environment Marine Service (CMEMS). https://doi.org/10.25423/CMCC/MEDSEA_MULTIYEAR_BGC_006_008_MEDBFM3
		Marine heatwaves (surface)	1993–2022		Global Ocean Physics Reanalysis. E.U. Copernicus Marine Service Information (CMEMS). Marine Data Store (MDS). https://doi.org/10.48670/moi-00021
		Marine heatwaves (bottom)	1993–2022		Global Ocean Physics Reanalysis. E.U. Copernicus Marine Service Information (CMEMS). Marine Data Store (MDS). https://doi.org/10.48670/moi-00021

Table 2
Data from current EBSAs and existing internationally agreed protection schemes.

Data	Source
Current EBSAs area in shapefile	World Wide Fund for Nature (05/07/2024 version). Available at: https://hub.arcgis.com/maps/d164b5bd8f29430783eabf1593e1c94b/about
Existing protected spatial features under Convention on Wetlands, Habitats and Birds Directive and Barcelona Convention: Ramsar Site; Sites of Community Importance; Special Areas of Conservation; Special Protection Area; Specially Protected Areas of Mediterranean Importance.	UNEP-WCMC and IUCN [51]

2.4.2. *Spatial prioritization*

Areas of ecological importance that meet the EBSA criteria and exhibit environmental stability, thus candidates for conservation priority, were identified using spatial conservation prioritization (SCP) with the *prioritizr* R package (https://prioritizr.net/) [55] and *HiGHS* solver [55,56], based on the EBSA criteria and environmental stability layer distribution (binary layers) provided in previous steps (Fig. 2). This algorithm optimizes conservation priority areas based on the spatial distribution of features (i.e., EBSA criteria layers), user-defined conservation targets (ecological objectives to be achieved), constraints (e.g., areas that must be included in the solution) and penalties (e.g., costs associated with selecting certain planning units). In our analysis, we set conservation targets to retain at least 10 % and 30 % of planning units for each EBSA criterion, including the environmental stability criterion as well.

We implemented three prioritization scenarios with the mentioned conservation targets separately. The first was conducted at the regional scale, applying a constraint to lock in existing internationally agreed protection schemes (including the combination of Natura2000 sites, Ramsar sites, SPAMIs and SCI; hereafter referred to as "MPA in"), to identify additional areas that should be incorporated into the current internationally agreed protection schemes network to achieve conservation targets for EBSA criteria. The second scenario, also at the regional scale, was performed without considering existing internationally agreed protection schemes (hereafter referred to as "MPA out") to explore an optimal prioritization solution unconstrained by current spatial designations. The third scenario was conducted at the EEZ scale to evaluate country-level conservation priorities within the Western Mediterranean Sea region. While we refer to maritime zones beyond territorial waters as EEZs, in line with the terminology established by the United Nations Convention on the Law of the Sea (UNCLOS), it is important to acknowledge that in the Western Mediterranean, these zones are only partially declared. Several EEZs overlap or remain subject to dispute, reflecting ongoing geopolitical complexities and the absence of mutually agreed maritime boundaries among some coastal states [44]. In this case, countries with existing internationally agreed protection schemes (France, Italy and Spain) were run with the MPA locked-in constraint ("MPA in"), while countries without such protected spatial features (Algeria, Morocco, and Tunisia) were run with the MPA locked-out approach ("MPA out").

The *prioritizr* R package provides multi-objective optimization tools to identify the best trade-offs among different conditions. Since the best trade-off depends on multiple factors (e.g., available budgets, species' connectivity requirements and management capacity), finding the best balance can be challenging. We used a hierarchical approach across all scenarios, generating a series of incremental prioritizations until the final solution met all predefined objectives.

We first calculated the total cost of the initial prioritization using the *eval_cost_summary()* function (from the *prioritizr* R package), which sums the area of all selected planning units. The total area of each planning unit was used as a proxy for cost, following standard practice in spatial conservation planning. Based on this initial cost, we then established a series of cost thresholds (up to four times the initial cost) to reduce spatial fragmentation in subsequent prioritization scenarios. For each threshold, we generated prioritizations aimed at minimizing total boundary length while ensuring that (i) the total cost did not exceed the threshold, (ii) representation targets for all features were achieved, and (iii) additional constraints (e.g., "MPA in") were satisfied.

We evaluated the resulting candidate prioritizations using performance metrics: total cost and total boundary length (a proxy for spatial fragmentation). To select the most suitable trade-off, we plotted and qualitatively assessed the relationship between these metrics.

After identifying the optimal solution, we assessed the relative importance of selected planning units using an incremental rank approach [57]. All prioritization problems were solved using *HiGHS* with a 0 % optimality gap, relative targets of 0.1 or 0.3 and a boundary penalty of 1. All scenarios used 20-km resolution, except the regional-scale "MPA out" scenario (50 km) due to computational limits.

3. Results

3.1. *Quality of the data*

The quality assessment of the dataset used in this study indicated a relatively high overall data quality, with an average Fitness for Use

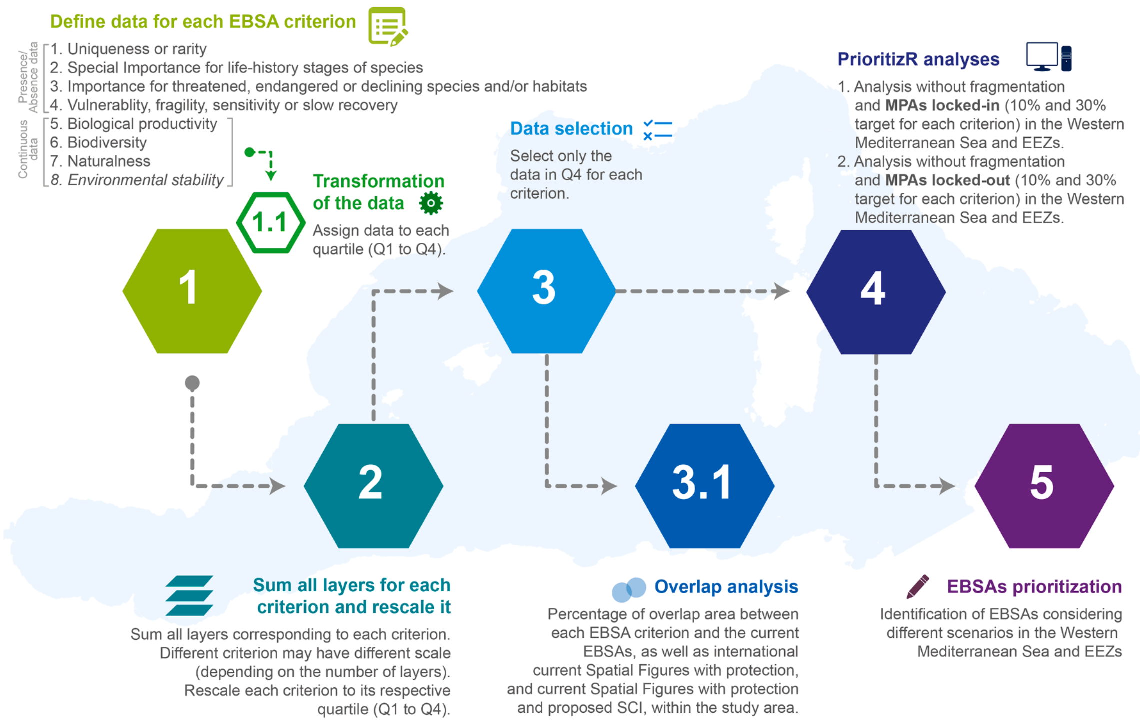

Fig. 2. Workflow diagram illustrating all steps conducted in this study. The first step involved defining the data corresponding to each Ecologically or Biologically Significant Marine Areas (EBSA) criterion. Continuous data were transformed into quartiles. In the second step, all layers for each criterion were summed and then rescaled into quartiles. In the third step, only the highest quartile (Q4) was selected for further analysis. The subsequent steps included overlap and prioritization analyses, resulting in the identification of prioritized EBSAs in the final step.

Score (FUS) of 2.8 out of 3. Among the indicators assessed, "Period of data coverage" received the lowest average score (2.0; Figure S1A). This was the only indicator that showed statistically significant differences compared to the others (Kruskal-Wallis test, $p < 0.01$; Dunn's test, $p < 0.01$; Figure S1A). No significant differences in FUS values were observed across the EBSA criteria (Kruskal-Wallis test, $p = 0.5$; Figure S1B). The criterion "Biological diversity" had the lowest average FUS among the EBSA criteria (mean = 2.6; Figure S1B). Despite these variations, all criteria had FUS values above 2.0, indicating acceptable data quality. Therefore, all datasets were retained for subsequent spatial analyses.

3.2. *Spatial distribution of EBSA criteria*

The spatial distribution of the different EBSA criteria varied across the study area. The uniqueness or rarity criterion (Fig. 3A) covered approximately half of the Western Mediterranean Sea, occurring in both coastal and offshore areas, with a strong presence in the southern part of the region. The special importance for life-history stages of species criterion (Fig. 3B) was mainly concentrated in the northern and coastal waters. The importance for threatened, endangered, or declining species and/or habitats criterion (Fig. 3C) had the least spatial representation, limited to a few coastal areas near the Balearic Islands and Italy. The vulnerability, fragility, sensitivity, or slow recovery criterion and biological diversity (Figs. 3D and 3F) were both primarily distributed along the coastal waters throughout the study area. The biological productivity criterion (Fig. 3E) was concentrated in the southwestern part of the region. The naturalness criterion (Fig. 3G) was mainly found in offshore and deeper waters, while the environmental stability criterion (Fig. 3H) was distributed throughout the study area, with a stronger presence in the southern part and offshore waters.

3.3. *EBSA criteria and their spatial overlap with existing EBSAs and internationally agreed protection schemes*

The percentage of overlap between each EBSA criterion and the current EBSAs, the existing internationally agreed protection schemes, and the combination of internationally agreed protection schemes and proposed SCIs varied significantly. The uniqueness or rarity criterion showed the highest representation across all categories (Table S2). In contrast, the importance for threatened, endangered, or declining species and/or habitats and biological productivity criteria was the least represented (Table S2). The vulnerability, fragility, sensitivity, or slow recovery and biological diversity criteria exhibited moderate representation (Table S2). Overall, the current EBSAs covered 47.01 % of the Western Mediterranean Sea, while the existing internationally agreed protection schemes and the combination of the existing internationally agreed protection schemes and proposed SCIs covered 19.72 % and 21.02 %, respectively (Table S2).

3.4. *Prioritized areas based on EBSA criteria*

Different threshold values were selected in each scenario to run the prioritization analysis, reducing the fragmentation and minimizing the total prioritization cost (see selected thresholds in Figure S2 and Table S3).

Under the "MPA in" scenario, the additional prioritized areas were mainly located in the southwestern offshore part of the study area (Fig. 4A.a). In contrast, under the "MPA out" scenario, the prioritized areas shifted to the southeastern part, including a large portion of the offshore Western Mediterranean Sea, while largely excluding the northern regions, except for the northeastern coast of Corsica (Fig. 4A.b).

Considering the EEZs, for the northern countries of the Western Mediterranean Sea, specifically Italy and Spain, prioritized areas were selected in offshore zones, in addition to the existing combination of

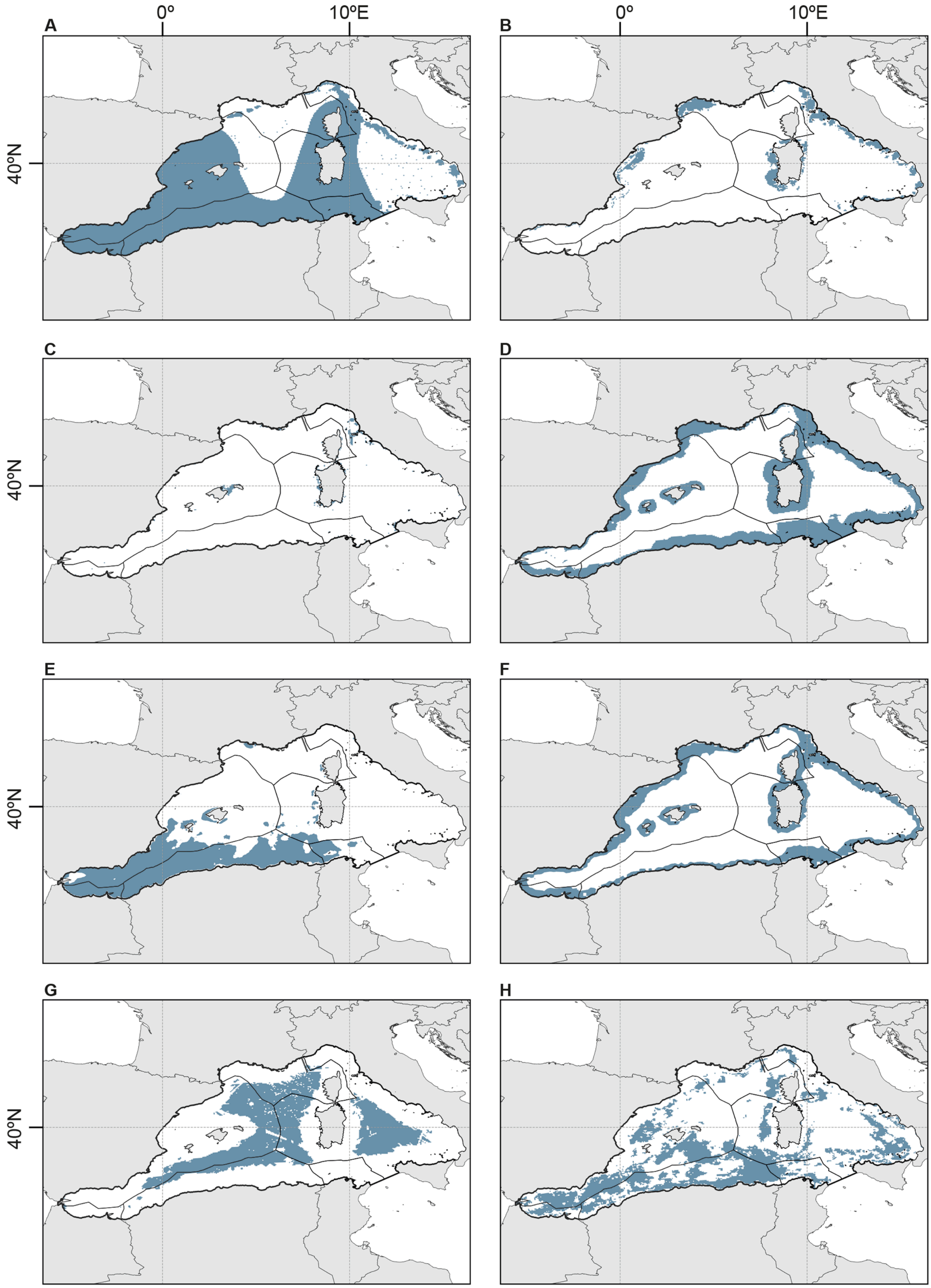

Fig. 3. Distribution of top areas for each EBSA criterion: (A) Uniqueness or rarity; (B) Special importance for life-history stages of species; (C) Importance for threatened, endangered or declining species and/or habitats; (D) Vulnerability, fragility, sensitivity, or slow recovery; (E) Biological productivity; (F) Biological diversity; (G) Naturalness; and (H) Environmental stability criterion.

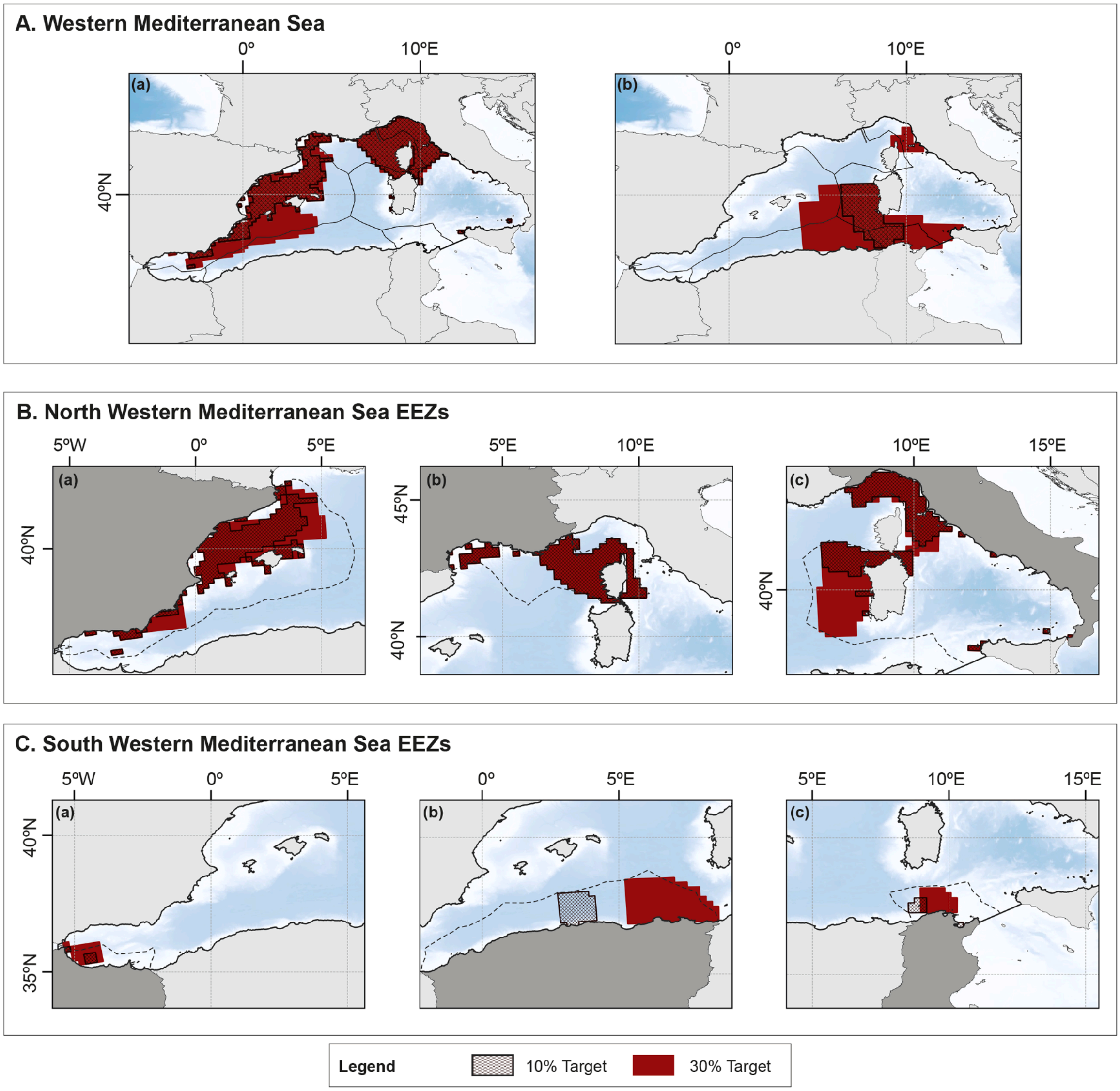

Fig. 4. Maps of prioritized areas under different scenarios: (A) Western Mediterranean Sea with (a) "MPA in" and (b) "MPA out"; (B) North Western Mediterranean Sea EEZs with "MPA in" for (a) Spain, (b) France, and (c) Italy; (C) South Western Mediterranean Sea EEZs with MPA out for (a) Morocco, (b) Algeria, and (c) Tunisia. Different conservation targets 10 % (black striped) and 30 % (red) are shown.

internationally agreed protection schemes and proposed SCIs (Fig. 4B.a and 4B.c). In the case of France, no additional areas were prioritized, as the conservation targets had already been met through existing internationally agreed protection schemes and proposed SCIs (Fig. 4B.b).

For the southern countries of the Western Mediterranean Sea, the prioritized areas in Morocco were selected in the western part of its EEZ (Fig. 4C.a). In Algeria, they were located in the eastern part (Fig. 4C.b), and in Tunisia, in the central and western parts of its EEZ (Fig. 4C.c).

In all cases, the areas prioritized under the 10 % conservation target were contained within those prioritized under the 30 % target, except in the Algerian EEZ scenario. This divergence arises from the fact that the prioritization analyses for the 10 % and 30 % conservation targets were conducted independently, without enforcing spatial overlap between solutions. As a result, the areas selected under each target reflect distinct optimization outcomes based on EBSA-relevant features and the absence of locked-in constraints.

When evaluating the percentage of high-value areas for each criterion covered in the evaluated scenarios against the associated targets so-called conservation targets (at least 10 % and 30 % of coverage per criterion, respectively), in general, all targets were met or exceeded (Fig. 5). From a regional scenario, under the "MPA in" scenario, the criteria of uniqueness or rarity, special importance for life-history stages of species, importance for threatened, endangered or declining species and/or habitats and biological diversity exceeded their minimum targets (Fig. 5A and Table S4). In contrast, under the "MPA out" scenario, only the criterion importance for threatened, endangered or declining species and/or habitats surpassed its target (Fig. 5A and Table S4).

From the EEZ scenario, in countries where the "MPA in" scenario was applied, all criteria met or exceeded both the 10 % and 30 % conservation targets, often with high values (Fig. 5B and Table S4). In contrast, in EEZs where the "MPA out" scenario was applied, all criteria met the targets and, in some cases, even exceeded them (Fig. 5C and Table S4). However, some criteria were not represented in certain EEZs. For instance, special importance for life-history stages of species and importance for threatened, endangered or declining species and/or habitats were not represented in Algeria and Morocco, while special importance for life-history stages of species and naturalness were absent in Tunisia (Fig. 5C and Table S4).

After running the scenarios, we assessed the proportion of the study area covered by priority areas for conservation, based on the proposed

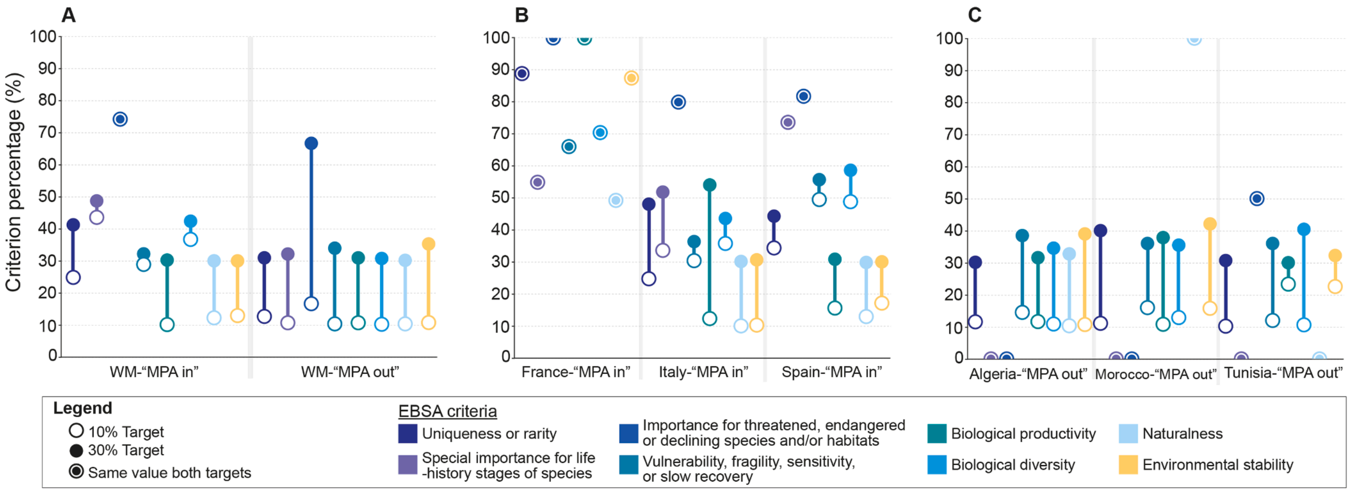

Fig. 5. Percentage of area achieved per criterion, based on the proposed conservation targets (at least 10 % and 30 % target per each criterion, shown as circles), for: (A) Western Mediterranean Sea under "MPA in" (left) and "MPA out" (right) scenarios; (B) Exclusive Economic Zones (EEZs) "MPA in" scenario (France, Italy, and Spain); and (C) EEZs "MPA out" scenario (Algeria, Morocco, and Tunisia). Each color represents a different EBSA criterion. Circles with a white center indicate the 10 % target, while fully colored circles correspond to the 30 % target. When both targets meet the same percentage, a circle with an outline is shown. For example, in panel A, under the "MPA in" scenario and using the proposed 10 % minimum target, the criterion of uniqueness or rarity reached between 20 % and 30 %.

feature targets (at least 10 % and 30 % per criterion). Regarding the areas prioritized for protection and conservation in the Western Mediterranean Sea under different scenarios, when applying the "MPA in" scenario, the prioritized area at the regional level exceeded both the 10 % and 30 % thresholds relative to the total area of the Western Mediterranean Sea (Fig. 6). Similarly, from the EEZ perspective, the prioritized areas also surpassed these thresholds for both conservation targets. For instance, in France, more than 50 % of its EEZ was prioritized for conservation (Fig. 6).

In contrast, under the "MPA out" scenario, the total prioritized area at the regional level remained below both the 10 % and 30 % thresholds relative to the Western Mediterranean Sea area (Fig. 6). However, when analyzed by EEZ, the prioritized areas in each country's EEZ exceeded both the 10 % and 30 % thresholds based on their respective EEZ areas (Fig. 6).

4. Discussion and conclusions

The recognition of EBSAs can play a crucial role in global ocean governance, providing a scientific basis for designating MPAs and other conservation measures to safeguard marine biodiversity. The original EBSA boundaries in the Western Mediterranean Sea were broad and may hinder the prioritization and implementation of targeted conservation measures [37]. While such broad definitions may be appropriate at a global scale, they are less effective for maritime spatial planning and management at regional or national levels [34,40]. Refining these boundaries is therefore essential to guide protection efforts and ensure that EBSAs can be meaningfully integrated into national and regional management strategies [16,40,58]. COP16 [59] has enabled the update of existing EBSA descriptions based on new scientific information, as well as the identification of new areas through approaches beyond the

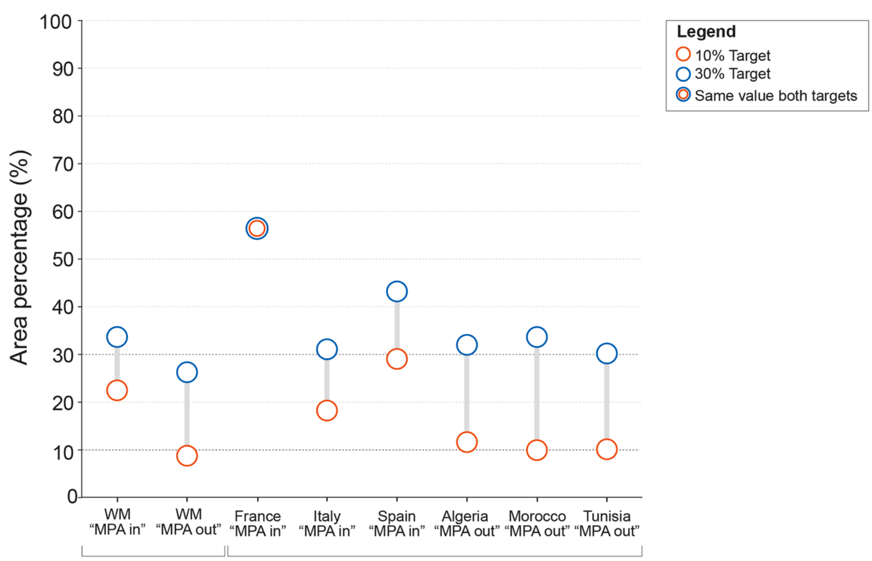

Fig. 6. Proportion of the study area (Western Mediterranean Sea) and the Exclusive Economic Zones (EEZs) covered by the selected priority areas for conservation under each scenario, considering the proposed criterion targets (at least 10 % and 30 % per criterion, shown as circles). Orange circles indicate the 10 % target, while blue circles represent the 30 % target. When both targets reach the same percentage, a circle with an outline is shown. For example, from a regional perspective, when applying the "MPA in" scenario and considering a conservation target of at least 30 % per criterion, more than 30 % of the Western Mediterranean Sea is prioritized for protection.

traditional regional workshops. This ensures that EBSA information remains aligned with the best available science and knowledge, reinforcing its relevance for planning and management.

Our study responds to this challenge by proposing a robust data-driven approach for refining EBSA boundaries and identifying areas that meet the EBSA criteria at a spatial resolution relevant to national and regional planning contexts. This methodology provides a transparent and reproducible framework that complements existing expert-based processes, enhancing the credibility and utility of EBSAs identification.

The EBSA framework has emerged as a powerful tool for informing decisions on how to balance biodiversity conservation with the sustainable use of marine resources [32,34]. One of its key advantages is that they are based on a set of criteria designed to identify ecologically important areas, while representing one of the few globally recognized conservation frameworks with strong international support and commitment [34]. This international endorsement is particularly relevant in transboundary marine regions, such as the Western Mediterranean Sea, where most ecologically significant areas span the jurisdictions of two or more countries, sometimes under conflicting situations [44]. In these contexts, EBSAs may offer a shared, science-based foundation for cooperative conservation planning [16], supporting multi-stakeholder dialogue and adaptive management. Therefore, international cooperation is essential to address the complex challenges of marine biodiversity conservation in such regions, and scientific frameworks like EBSAs play a pivotal role in enabling this collaboration.

Despite their political and ecological strengths, the application of EBSA criteria poses significant practical challenges, particularly in balancing the relative importance of each criterion. The broad scope of the criteria introduces ambiguity when multiple criteria are met to varying degrees within a given area, as there is limited guidance on how to evaluate or prioritize among them [33]. The CBD [31] advises that all criteria should be considered of equal weight, but this approach can be problematic in practice due to the identification of a high number of candidate areas, making it difficult to distinguish ecological relevant sites from those meeting only minimal thresholds [33]. These issues underscore the need for more nuanced methodologies and clearer operational guidance when using the EBSA framework in real-world planning contexts.

Here, we applied a structured and balanced approach to evaluating all EBSA criteria, including environmental stability, ensuring that all data used to describe each criterion meets good quality standards [50] and each criterion has the same weight. This integrative methodology allowed us to move beyond the limitations associated with unweighted or qualitative assessments often applied in previous EBSA exercises. While no formal thresholds exist for EBSA criteria [34,38], our strategy aimed to establish a consistent and evidence-based standard across candidate areas. Such a quantitative integration supports greater transparency and comparability between sites, in contrast to the traditional EBSA framework, where a site may qualify based on only one criterion, leading to inconsistencies in size and ecological significance.

While traditional EBSA criteria provide a solid foundation for identifying ecologically significant areas, they do not systematically account for the long-term impacts of environmental changes on marine biodiversity and ecosystem functioning [60]. Yet, there is growing recognition that environmental changes will likely diminish the effectiveness of protected areas unless explicit adaptation and resilience measures are embedded in their design and management [20,61,62]. In the Mediterranean Sea, intense sea warming, particularly marine heatwaves, has caused severe ecological disruptions, including mass mortality events and shifts in community structure [4–7]. Primary productivity also plays a key role in sustaining biodiversity and ecosystem services, while long-term temperature trends are critical for species persistence. The inclusion of environmental stability as another ecological criterion (this study) acknowledges the critical role that environmentally stable areas can play in facilitating the persistence of species under threat from human-induced climate change and anthropogenic stressors [63]. Moreover, a long-term planning perspective is essential to anticipate ecological shifts and support strategic conservation responses [20,36,60,61,63]. By integrating this criterion, we align with recent calls for protected area networks to not only represent biodiversity as it is today but to also serve as adaptive instruments for a rapidly changing future [64]. Our approach represents a step toward operationalizing climate-informed conservation, highlighting environmental stability as a new and key element in the next generation of EBSA assessments.

After applying balanced weights to each criterion and accounting for environmental stability, the prioritized areas identified in this study align with previously recognized spatial conservation priorities in the Western Mediterranean Sea [16]. Our results confirm the need to increase the conservation efforts in the southern and eastern parts of the basin [16,46]. This reflects both higher anthropogenic pressures in this region [46], and stronger political commitments and implementation resources available in northern EU countries [16]. However, under the “MPA out” regional scenario (which does not account for existing internationally agreed protection schemes), newly prioritized areas shift toward the southeastern part of the study area, including extensive offshore zones. This highlights both the ecological value of the southern Western Mediterranean and a conservation bias towards northern, nearshore regions. In contrast, the “MPA in” scenario results in additional prioritizations remaining concentrated in the southwestern offshore areas. These findings emphasize how existing internationally agreed protection schemes influence spatial prioritization and demonstrate the potential for expanding conservation beyond current internationally agreed protection schemes. Applying this method in a complex transboundary region further underscores the need for coordinated conservation efforts across national borders to safeguard shared marine ecosystems [36].

From an Exclusive Economic Zone (EEZ) perspective, our results show that France already potentially meets its spatial conservation targets (EU Biodiversity strategy 2030) through existing internationally agreed protection schemes and proposed SCIs. However, many of these areas are considered unprotected [28], highlighting the need to improve management and enforcement to ensure conservation goals are truly achieved. In contrast, Italy and Spain require complementary spatial prioritizations, especially in offshore areas, to meet their targets and to improve management measures within their protected areas, which currently have low levels of protection [28,29]. Notably, southern countries such as Morocco, Algeria, and Tunisia, long recognized as underrepresented in conservation efforts [16], also encompass ecologically significant areas where most EBSA criteria targets are met, underscoring their importance in future conservation planning.

While our study provides valuable insights into the prioritization of marine areas for conservation in the Western Mediterranean Sea, several limitations need to be acknowledged. Firstly, as with any broad classification system, the generality of the EBSA criteria can sometimes lack specificity when applied to individual taxa. The inclusion of more species-specific data, particularly at higher spatial resolutions, would significantly enhance the accuracy of prioritization. This issue requires further refinement to improve the precision of our conservation recommendations for specific species or ecological features [34]. Secondly, data availability remains a significant limitation. Despite the extensive datasets used in this analysis, there are still notable gaps, particularly in the southern region of the Western Mediterranean Sea. For instance, data deficiencies can impede the full understanding of biodiversity distribution across the region [21,65]. These gaps are also reflected in the underrepresentation of certain regions in our prioritization, which was also found by other studies [2,16]. Further analyses may consider the inclusion of additional protection layers, such as national MPAs or Fishing Restricted Areas (FRAs), to enhance the representativeness and applicability of the prioritization results. The proposed framework is flexible and allows for the integration of new and updated datasets, provided that spatial data are available, enabling comparative and iterative assessments across jurisdictions. Additionally, some criteria, such as uniqueness, are based on data that may cover large, generalized areas, leading to coarse-scale assessments that could overlook more localized ecological features. Another limitation stems from the temporal and spatial scale of available data. While this analysis draws on a substantial body of information, an extended temporal data coverage would better capture dynamic ecological patterns and improve the reliability of conservation targets over time. Furthermore, the non-nested nature of the 10 % and 30 % solutions is a direct consequence of independent optimization runs, which prioritize complementarity and cost-efficiency rather than strict expansion of initial selections. While this may appear counter-intuitive, it reflects ecological trade-offs inherent in systematic conservation planning. If sequential implementation is required, nestedness can be enforced by locking in core areas during subsequent runs. Finally, while we use all existing internationally agreed protection schemes being implemented or proposed, we do not consider into our analyses their effectiveness. Since the protection effectiveness of MPAs in the Mediterranean Sea is very low [28–30], this issue has to be considered when implementing conservation measures in the study area, prioritizing fully and highly protected areas to achieve desired management outcomes that are beneficial for nature and society [19].

Despite these limitations, our study represents an important first step in identifying areas that meet EBSA criteria for marine conservation in the Western Mediterranean Sea, and could be the baseline for future conservation and management prioritization efforts. With the inclusion of new and more detailed datasets, the analysis can be refined and updated, ensuring that conservation strategies evolve to better address emerging challenges in the Western Mediterranean Sea. Ultimately, this work serves as a foundation for ongoing research and policy action aimed at preserving marine biodiversity in a rapidly changing environment.

CRediT authorship contribution statement

Jeroen Steenbeek: Writing – review & editing, Visualization, Data curation. **Miquel Ortega:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Francisco Ramírez:** Writing – review & editing, Visualization, Validation, Software, Formal analysis. **Maria Bas:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Marta Coll:** Writing – review & editing, Validation, Supervision, Resources, Funding acquisition, Conceptualization.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2026.107075.

Data availability

All data used in this study is available for download via the references listed in Table 1 and Table 2

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